Spectrum Sharing Methods in Coexisting Wireless Networks

Dissertation

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Mohammad Muttakin Siddique

from Dhaka, Bangladesh

First Examiner:	Prof. Dr. rer. nat. habil. Carmelita Görg
Second Examiner:	Prof. Dr.-Ing. Andreas Timm-Giel
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I assure, that this work has been done solely by me without any further help from others except for the official support by the Chair of Communication Networks and the project PoSSuM supported by the German Research Foundation (DFG). The literature used is listed completely in the bibliography.

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(Mohammad Muttakin Siddique)

ABSTRACT

Radio spectrum, the fundamental basis for wireless communication, is a finite resource. The development of the expanding range of radio based devices and services in recent years makes the spectrum scarce and hence more costly under the paradigm of extensive regulation for licensing. However, with mature technologies and with their continuous improvements it becomes apparent that tight licensing might no longer be required for all wireless services. This is from where the concept of utilizing the unlicensed bands for wireless communication originates.

As a promising step to reduce the substantial cost for radio spectrum, different wireless technology based networks are being deployed to operate in the same spectrum bands, particularly in the unlicensed bands, resulting in coexistence. However, uncoordinated coexistence often leads to cases where collocated wireless systems experience heavy mutual interference. Hence, the development of spectrum sharing rules to mitigate the interference among wireless systems is a significant challenge considering the uncoordinated, heterogeneous systems. The requirement of spectrum sharing rules is tremendously increasing on the one hand to fulfill the current and future demand for wireless communication by the users, and on the other hand, to utilize the spectrum efficiently. In this thesis, contributions are provided towards dynamic and cognitive spectrum sharing with focus on the medium access control (MAC) layer, for uncoordinated scenarios of homogeneous and heterogeneous wireless networks, in a micro scale level, highlighting the QoS support for the applications.

This thesis proposes a generic and novel spectrum sharing method based on a hypothesis: The regular channel occupation by one system can support other systems to predict the spectrum opportunities reliably. These opportunities then can be utilized efficiently, resulting in a fair spectrum sharing as well as an improving aggregated performance compared to the case without having special treatment. The developed method, denoted as Regular Channel Access (RCA), is modeled for systems specified by the wireless local resp. metropolitan area network standards IEEE 802.11 resp. 802.16. In the modeling, both systems are explored according to their respective centrally controlled channel access mechanisms and the adapted models are

evaluated through simulation and results analysis. The conceptual model of spectrum sharing based on the distributed channel access mechanism of the IEEE 802.11 system is provided as well.

To make the RCA method adaptive, the following enabling techniques are developed and integrated in the design: a RSS-based (Received Signal Strength based) detection method for measuring the channel occupation, a pattern recognition based algorithm for system identification, statistical knowledge based estimation for traffic demand estimation and an inference engine for reconfiguration of resource allocation as a response to traffic dynamics.

The advantage of the RCA method is demonstrated, in which each competing collocated system is configured to have a resource allocation based on the estimated traffic demand of the systems. The simulation and the analysis of the results show a significant improvement in aggregated throughput, mean delay and packet loss ratio, compared to the case where legacy wireless systems coexists. The results from adaptive RCA show its resilience characteristics in case of dynamic traffic. The maximum achievable throughput between collocated IEEE 802.11 systems applying RCA is provided by means of mathematical calculation.

The results of this thesis provide the basis for the development of resource allocation methods for future wireless networks particularly emphasized to operate in current unlicensed bands and in future models of the Open Spectrum Alliance.

KURZFASSUNG

Das Funkspektrum, die fundamentale Grundlage für drahtlose Kommunikation, ist eine endliche Ressource. Die Entwicklung einer größer werdenden Anzahl von funkunterstützten Geräten und Diensten in jüngerer Zeit macht das Spektrum knapp und folglich teurer unter dem Paradigma einer weitreichenden Regulierung mit dem Zweck der Lizenzvergabe. Mit ausgereiften Technologien und ihrer ständigen Verbesserung wird es deutlich, dass eine engmaschige Lizensierung nicht mehr für alle drahtlosen Dienste notwendig ist. Hieraus ergibt sich das Konzept der Nutzung unlizensierter Frequenzbänder für die drahtlose Kommunikation.

Als einen vielversprechenden Schritt, die wesentlichen Kosten für Funkspektrum zu verringern, werden unterschiedliche drahtlose Technologien zur Verwendung in denselben Frequenzbändern eingesetzt, besonders in den unlizenzierten Bändern, woraus sich Koexistenz ergibt. Allerdings führt unkoordinierte Koexistenz oft zu Fällen, in denen benachbarte drahtlose Systeme erhebliche gegenseitige Störungen erfahren. Aus diesem Grund ist die Entwicklung von Regeln zur Aufteilung des Spektrums zum Abschwächen von Störungen zwischen drahtlosen Systemen eine wesentliche Herausforderung, wenn man unkoordinierte, heterogene Systeme berücksichtigt. Der Bedarf an Regeln zum Aufteilen des Spektrums nimmt drastisch zu, auf der einen Seite, um gegenwärtige und zukünftige Anforderungen der Benutzer an drahtlose Kommunikation zu erfüllen, auf der anderen Seite, um das Spektrum effizient zu nutzen. In dieser Arbeit werden Beiträge zur dynamischen und kognitiven Aufteilung des Spektrums für unkoordinierte Szenarien homogener und heterogener drahtloser Netze örtlicher Ausdehnung vorgestellt, mit dem Schwerpunkt auf der Vielfachzugriffs (MAC)-Schicht und unter Berücksichtigung der Dienstgüteanforderungen durch die Anwendungen.

Diese Arbeit schlägt eine generische und neuartige Methode der Spektrumsaufteilung basierend auf einer Hypothese vor: Die regelmäßige Kanalbelegung durch ein System kann andere Systeme unterstützen, Zugriffsmöglichkeiten auf das Spektrum zuverlässig vorauszusagen. Diese Zugriffsmöglichkeiten können dann effizient genutzt werden, woraus sich eine faire Aufteilung des Spektrums sowie ein verbessertes Gesamtleistungsverhalten ergibt im Vergleich zum Fall ohne besondere Behandlung. Das untersuch-

te Verfahren, bezeichnet als Regelmäßiger Kanalzugriff (Regular Channel Access, RCA), wird für Systeme modelliert, die durch die Standards für drahtlose lokale bzw. regionale Netze IEEE 802.11 bzw. 802.16 spezifiziert sind. In der Modellierung werden beide Systeme entsprechend ihrer jeweiligen zentral gesteuerten Kanalzugriffsmechanismen untersucht und die angepassten Modelle werden durch Analyse und Simulation ausgewertet. Das konzeptuelle Modell der Spektrumaufteilung basierend auf dem verteilten Kanalzugriffsmechanismus des IEEE 802.11-Systems wird ebenfalls erörtert.

Um das RCA-Verfahren adaptiv zu gestalten, werden folgende Grundlagentechnologien entwickelt und in den Entwurf integriert: ein RSS-basiertes Detektionsverfahren zur Messung der Kanalbelegung, ein auf Mustererkennung beruhender Algorithmus zur Systemidentifikation, eine wissensbasierte statistische Schätzung des Verkehrsaufkommens und ein Inferenz-Mechanismus zur Rekonfiguration der Ressourcenzuweisung als Antwort auf die Verkehrsdynamik.

Der Vorteil des RCA-Verfahrens wird demonstriert, bei dem jedes konkurrierende benachbarte System für eine Ressourcenzuweisung basierend auf den geschätzten Verkehrsaufkommen der Systeme konfiguriert wird. Die Simulation und die Analyse der Ergebnisse zeigt eine deutliche Verbesserung des aggregierten Durchsatzes, der mittleren Verzögerung und der Paketverlustrate im Vergleich zum Fall, bei dem herkömmliche drahtlose Systeme koexistieren. Die Ergebnisse der adaptiven RCA zeigen die Robustheit im Falle von veränderlichem Verkehr. Der maximale Durchsatz, der sich zwischen benachbarten IEEE 802.11-Systemen bei Anwendung von RCA erzielen lässt, wird mit Hilfe einer mathematischen Berechnung ermittelt.

Die Ergebnisse dieser Arbeit stellen die Grundlage für die Entwicklung von Ressourcenvergabeverfahren für zukünftige drahtlose Netze bereit, insbesondere bezogen auf den Betrieb in den gegenwärtigen unlizenzierten Bändern und in zukünftigen Modellen der Open Spectrum Alliance.

CONTENTS

CHAPTER 1

INTRODUCTION

The only alternative to coexistence is co-destruction.[1] Wireless communication has become an integral part of everyday life today. It has experienced a profound success both technically and commercially in the last few years. It is anticipated that the higher the number of wireless networks in the same vicinity, the more operating spectrum bands are required. Spectrum is, however, on the one hand, a limited resource and on the other hand, not used efficiently and dynamically by current wireless systems. This general fact is the root of the aspiration to share the limited spectrum resource efficiently and carefully among the wireless networks. Wireless Local Area Networks (WLAN) and Wireless Metropolitan Area Networks (WMAN), commercially known as *WiFi (Wireless Fidelity)* and *WiMAX (Worldwide Interoperability for Microwave Access)* respectively, are two key technologies for wireless networks. This thesis proposes a new promising coexistence method, or in other words spectrum sharing method, namely Regular Channel Access (RCA), among the collocated aforementioned wireless networks.

The structure of this chapter is as follows. Section 1.1 introduces the two major emerging wireless technologies WLAN and WiMAX, followed by the key motivation behind this thesis work in Section 1.2. Section 1.3 provides the thesis statement. The main contributions of the thesis are summarized in Section 1.4. The chapter ends with outlining the thesis in Section 1.5.

1.1 Emerging Wireless Technologies

WLAN is one of the popular and commercially successful wireless technologies that provides wireless connectivity for fixed, portable and moving stations within a local area. The Institute of Electrical and Electronics Engineers (IEEE) specified a standard for WLAN which is known as IEEE 802.11 [58]. Various amendments have been added to the base standard IEEE 802.11 by extending the protocol to improve the performance in several contexts, for example, to provide high bandwidth. WLAN operates in unlicensed bands like the Industrial, Scientific and Medical (ISM) band (in

[1] Jawaharlal Nehru, 1954.

2.4 GHz) and the Unlicensed National Information Infrastructure (U-NII) band (in 5.0 GHz) depending on its Physical (PHY) layer protocol. Another emerging wireless technology for broadband WMAN is IEEE 802.16 [60], commercially known as WiMAX. During its early stage, IEEE 802.16 was seen as a wireless alternative to the current static wired Internet connection facility like the Digital Subscriber Line (DSL), however, today technological enhancements make it suitable for mobility. IEEE 802.16 systems can operate between 2-11 GHz where licensed and unlicensed bands are located.

1.2 Motivation and Area of Study

As already mentioned, the radio spectrum is a finite resource, which makes it costly under the concept of traditional spectrum licensing. Due to the high costs of radio spectrum, an increasing number of new radio based services operate in the unlicensed bands which thus provide a large benefit for wireless communications. These new services are appearing in every aspect of human life like health care, entertainment, telephony, environmental sensing, location sensing, etc. In many cases the main driving technology underneath is IEEE 802.11. Considering the economical perspective, following the same path as IEEE 802.11, a new competitor for unlicensed bands are the IEEE 802.16 based networks. Deploying IEEE 802.16 in unlicensed bands is a very promising step in the sense that it would significantly reduce the cost for a service provider, which as an end effect reduces the service cost for the users. However, in this case a scenario could occur where an IEEE 802.11 system starts using the same channel which is occupied by an IEEE 802.16 system or vice versa; as an alternative channel is not available, for example in highly dense urban areas. This is denoted as a heterogeneous networks coexistence scenario. Similar situations also happen in homogeneous scenarios consisting of IEEE 802.11 systems, for example in an 'apartment or office scenario'. As there are new devices, services and applications like Voice over IP (VoIP), audio and video streaming appearing in the market every day which use IEEE 802.11 techniques for communication, this leads to a huge amount of IEEE 802.11 based network traffic located in the same vicinity so that the problem becomes more critical. The audio and video streaming devices wirelessly stream digital music, photos, and videos stored on a network-enabled PC to a home entertainment center, for example.

One of the main drawbacks of an unlicensed band is unpredictable interference, and if the systems do not manage the spectrum properly, then this interference leads to poor performance. Destructive mutual interference between uncoordinated wireless systems severely decreases the spectrum efficiency and performance. The latter can be analyzed from different perspectives, for example, in an overall scenario, on a per system basis or on a per user basis. However, from the user perspective, assured QoS (e.g. throughput, delay, jitter, loss ratio, etc.) is desired. For this reason, there is an increased requirement to efficiently utilize the unlicensed spectrum band by means of spectrum sharing or coexistence methods. The more systems operate within a mutual range, the more they require methods for coexistence or even cooperation.

Considering the above problem, both IEEE 802.11 and IEEE 802.16 systems are investigated in this thesis and spectrum sharing methods by means of MAC scheduling are designed, developed and evaluated. As the focus of this thesis is the IEEE 802.11 system, the more detailed implementation is done for the IEEE 802.11 system. During the investigation, different protocol standards including the legacy IEEE 802.11 system are considered. The challenges like spectrum occupation measurement, processing the measurement data, detection and identification of another radio system and its type in the vicinity, estimation of traffic demand by the own and the other system, self-learning and inferring optimum and fair spectrum sharing rules are covered in this work.

1.3 Thesis Statement

The outcomes of this dissertation in the form of newly developed concepts and methods, designs, models and performance evaluations significantly leverage the ongoing research and state-of-the-art on dynamic spectrum sharing for wireless networks. The contributions of this dissertation have the potential to serve as promising considerations, on the one hand for standardization and regulatory boards and on the other hand, for different stakeholders like network operators and equipment manufacturers, towards cognitive and dynamic spectrum sharing.

1.4 Contributions of the Thesis

To prove the above statement the main contributions of this thesis are summarized as follows:

- Different possible scenarios in coexisting wireless networks, where spectrum sharing would be applied, are investigated, described, and aligned in a multi dimensional scenario matrix. Performance metrics are outlined to be used in this thesis to evaluate coexistence.

- A generic spectrum sharing method, namely the Regular Channel Access (RCA) is proposed.
- The IEEE 802.11e and the IEEE 802.16 MAC layers and their way of packet scheduling are adapted to support the proposed method.
- A comprehensive analysis of spectrum usage patterns by wireless systems, varying a wide number of parameters, is provided. A model for system identification based on spectrum usage patterns is developed and its use in spectrum sharing is shown.
- Methods are developed for estimating the traffic demands by one's own system and by the other system. The acquired estimated results are considered as input to the developed spectrum sharing methods.
- The proposed adaptive regular channel access method is modeled.
- The IEEE 802.11 based simulation is extended for MAC layer scheduling according to the RCA method for evaluating the homogeneous scenarios.
- IEEE 802.16 and IEEE 802.11 are integrated into a combined simulation and the impact for both networks in different coexistence scenarios is analyzed without special protocol extensions.
- The simulation model is extended to support the proposed algorithms. Performance evaluation is done for both wireless networks in coexistence scenarios with proposed extensions and compared against the legacy case, i.e, the case where the proposed extensions are absent.
- The conceptual extensions of the RCA method are proposed in case of homogeneous and heterogeneous scenarios, consisting of more than two systems, and consisting of partially overlapped systems.
- The concept of possible extension and adaptation of the coexistence method for homogeneous and heterogeneous scenarios consisting of legacy IEEE 802.11 WLAN systems, for example adapting the Point Coordination Function (PCF), is described.
- Mathematical calculations are provided for determining the transmission times for different particular frames of the IEEE 802.11 system, considered in this thesis, showing the different parts like protocol overhead and signaling overhead, in the first step. In the second step, the upper boundaries of the throughput for the IEEE 802.11 system are calculated in the case of standalone and coexisting scenarios by taking into account the frame exchange durations.

1.5 Outline of the Thesis

The rest of the thesis is structured as follows:

Chapter 2 provides a background overview about different standards, architectures, channel access methods and physical layer aspects for both IEEE 802.11 and IEEE 802.16 cases. In Chapter 3, the spectrum sharing concept is defined and a summary of the drivers of dynamic spectrum sharing is given. Enabling techniques towards spectrum sharing are also provided.

Chapter 4 contains a detailed description of a possible future coexistence scenario of wireless networks, summarized in a scenario matrix which is considered in the rest of the thesis for evaluation. Spectrum sensing and traffic demand estimation methods are provided in Chapter 5 with a comprehensive analysis on spectrum measurement results.

Chapter 6 is about the spectrum sharing methods developed in the framework of this thesis. In addition, a simulation model is also provided in this chapter. The mathematical calculation for transmission times and the throughput boundaries are provided in Chapter 7. Chapter 8 contains the simulation model and evaluation of the spectrum sharing method between IEEE 802.11 systems and Chapter 9 contains the same for spectrum sharing between IEEE 802.11 and IEEE 802.16 systems.

Finally, chapter 10 provides the summary and conclusion of this thesis and outlines the issues to deal with in future research activities.

CHAPTER 2

WIRELESS NETWORKS

The *starting point* for the development of IEEE 802.11 standard, which standardizes the Wireless Local Area Network (WLAN), is a bit different than the same for the IEEE 802.16 standard, which standardizes the Wireless Metropolitan Area Network (WMAN). Several proprietary solutions for WLAN arrived in the market at the early age of WLAN, just after the time in 1985 when the United States Federal Communications Commission (FCC) made the decision to open up the 900 MHz and 2.4 GHz spectrum for use without a government license [4]. Later, the Institute of Electrical and Electronics Engineers (IEEE) developed an international standard: IEEE 802.11 for WLAN, which is one of the most successful standards ever developed. In contrast, the IEEE 802.16 standard came first in 2001, and later the industry promoted the IEEE 802.16 standard by deploying the networks under the name *WiMAX*.

In this chapter, the MAC and the PHY protocol of IEEE 802.11 and IEEE 802.16 are briefly described, which are considered as the basis for the work done in the framework of this thesis and the basic information for the next chapters. The network architecture models, the protocol reference models, the MAC frame structures, the MAC mechanisms and the physical layer specifications are discussed for both technologies, considering they are the roots of the protocol description. Besides, a generic channel model including the most known influencing factors is discussed. Note that the radio channel is the fundamental basis for wireless communication.

The structure of this chapter is as follows. The chapter begins with a technical description of MAC and PHY layer of IEEE 802.11 based systems in Section 2.1. Section 2.2 gives a similar description for IEEE 802.16 based systems. The chapter ends with the channel model and the wireless ranges in sections 2.3 and 2.4.

2.1 IEEE 802.11

A Wireless LAN (WLAN) is a wireless, pico-cellular access network for flexible data communication between fixed, portable and mobile terminal equipment and an Ethernet/ATM/IP based core network in a limited geographical area using electromagnetic waves [94]. WLANs facilitate to transmit and receive data over the air interface, minimizing the need for wired connections. Thus, WLANs combine data connectivity with user mobility through simplified configuration and enable *movable LANs* [87, 102]. The main benefits of WLAN – mobility, flexibility, ease of installation, scalability, cost saving – make it a highly emerging wireless technology.

As mentioned in the beginning of the chapter, the IEEE specified a standard called *IEEE 802.11* for WLAN. As a reference, note that the European Telecommunications Standards Institute (ETSI) specified another WLAN standard called *HIgh PERformance wireless Local Area Network* (HIPERLAN). Both standards, IEEE 802.11 and HIPERLAN, support data rates of 2 Mbit/s and work in the 2.4 GHz band.

The scope of the standards is to define the specifications for Physical Layer (PHY) and Medium Access Control (MAC), sub-layered in Data Link Control (DLC) layer, of the open system interconnection (OSI) seven-layer reference model for wireless connectivity for fixed, portable and moving stations within WLAN. The basic network architecture for IEEE 802.11 based WLAN is described in the following.

2.1.1 Architecture and Modes of Operation

The primary building block of an IEEE 802.11 based network is called the Basic Service Set (BSS), which is defined as a group of stations (STA) that are located in the same geographical area, using the same frequency channel and under the direct control of a single coordination function (see Section 2.1.4.2). At least two stations are contained in a BSS.

Though the edge of the cell cannot be precisely defined, but the area covered by the BSS, i.e. the coverage area under which the member stations of the BSS remain in communication, is called Basic Service Area (BSA). This is comparable to a cell in a cellular communication network. Generally, all the stations in a BSS can communicate with all other stations in the same BSS. Based on how they can communicate, two modes resulting in two network architectures are defined. They are discussed in the following.

2.1.1.1 Ad hoc Network Architecture

Figure 2.1 shows an ad hoc network consisting of three STAs. In this mode of operation, where a group of STAs can communicate with each other directly, without any infrastructure support, the primary building block is denoted as Independent BSS (IBSS). This type of network is often built without any pre-planning, that is why it is often referred as *ad hoc* network.

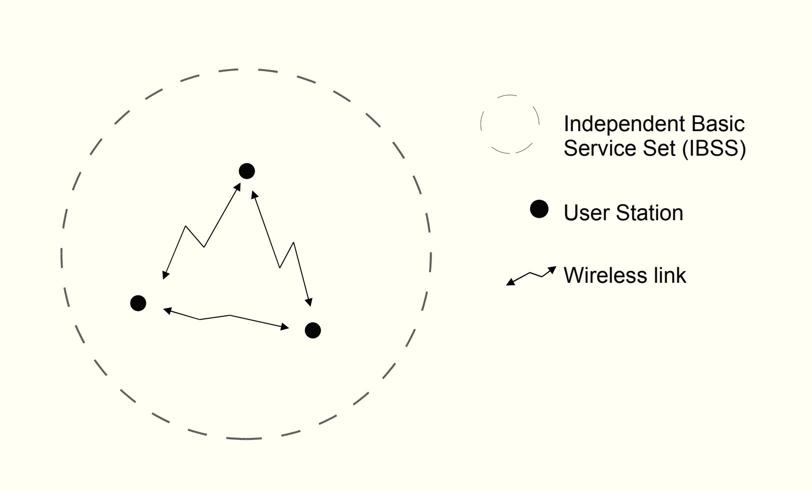


Figure 2.1: Ad hoc network

2.1.1.2 Infrastructure Network Architecture

In the infrastructure network, all stations in a BSS can communicate with all other stations in the same BSS through the central station, which is called Access Point (AP). The stations can move freely under the same BSS. Figure 2.2 shows such an infrastructure network consisting of three BSSs. The other architectural components are described as follows based on the IEEE 802.11 standard.

- **Distributed System (DS)**: If (case 1:) a STA from one BSS needs to communicate with a STA from another BSS, or (case 2:) a STA leaves the BSS and moves to another BSA where it registers itself and needs to communicate with all other stations in its previous BSS, then an architectural component is required to interconnect BSSs. The component which facilitates this objective is introduced and denoted as Distributed System (DS).
- **Extended Service Set (ESS)**: Multiple BSSs are integrated together to form an ESS using a common distribution system (DS). The ESS is a form of geographical range extension by providing the integration points necessary for network connectivity between multiple BSSs. According to the IEEE 802.11 specification, the DS is separated from the ESS from the architectural context and the DS is implementation dependent, so it could be a wired IEEE 802.3 Ethernet LAN, IEEE 802.4 Token Bus LAN, or wireless DS (WDS).
- **Portal**: Wireless users in the BSS can access the Internet through the gateway access device called portal. A portal is a logical entity

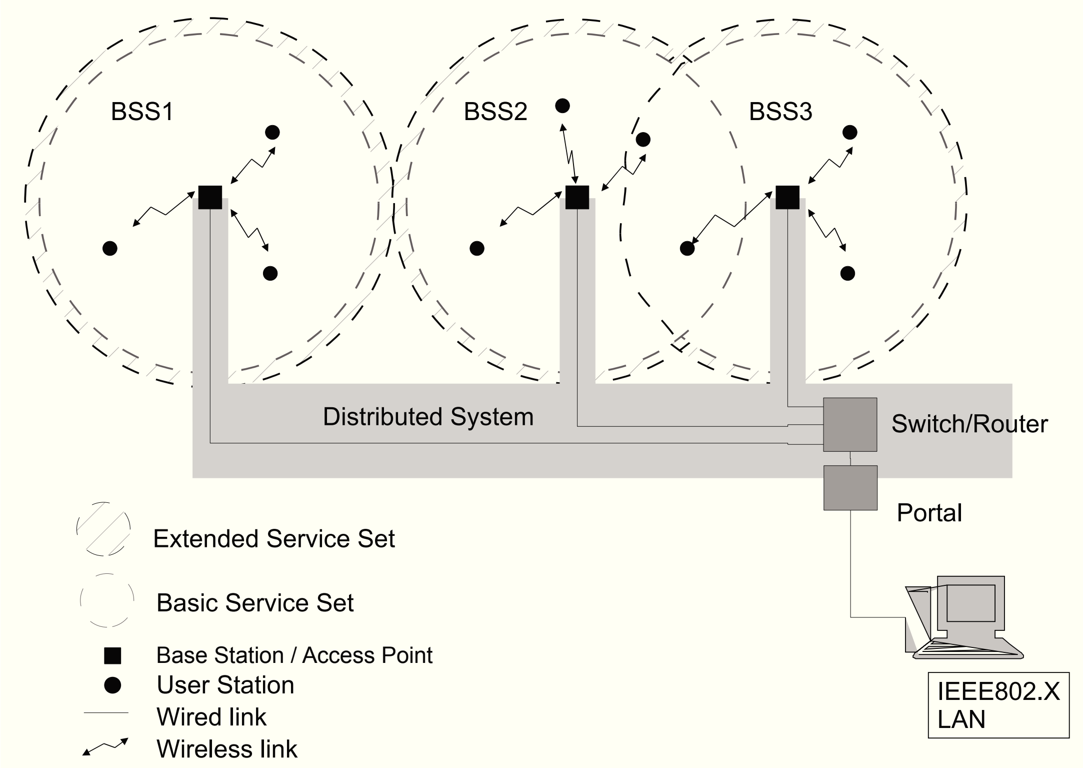


Figure 2.2: Infrastructure network

that specifies the integration point on the DS where both the IEEE 802.11 and non-IEEE 802.11 networks integrate. If the network is an IEEE 802.X, the portal incorporates functions that are analogous to a bridge: that is, it provides range extension and the translation between different frame formats.

A DS is a backbone network that is responsible for MAC-level transport of MAC Service Data Units (MSDU). Therefore, an ESS appears as a *single* BSS to the logical link control layer at any station associated with one of those BSSs.

There are different possibilities existing from the context of the relative physical coverage area of the BSSs. Such as, physically disjoint BSSs (BSS1 and BSS2 in Figure 2.2), partially overlapping BSSs (BSS2 and BSS3 in Figure 2.2), fully overlapping BSSs (shown later in Chapter 4).

2.1.2 The IEEE 802.11 Standards and Amendments

The IEEE put its efforts to standardize wireless local area networks as IEEE 802.11 to overcome and reduce further conflicts concerning the interoperability between the entities (STAs and/or APs) produced by the different manufacturers. The efforts resulted in a specification document known as IEEE 802.11-1999 standard. After that, several working groups and task groups were created by IEEE to enhance the operation of WLAN in several contexts. The final outcomes of the task groups are first published as amendments and later integrated in the main standard. For example, to provide high bandwidth up to 11 Mbps at PHY layer is published as IEEE Std 802.11b-1999 - Amendment 2 and later it is integrated in IEEE Std 802.11-2007 [63]. The accomplishment of even higher PHY speed up to 54 Mbps using OFDM is published as IEEE Std 802.11a (Amendment 1), where WLAN is designed to operate in the 5 GHz band. The IEEE Std 802.11g (Amendment 4) specified the PHY layer using the OFDM technique to achieve the same level of speed at 2.4 GHz. It was accepted by the industry very swiftly due to its backward compatibility with legacy IEEE 802.11b.

In Appendix A.3, an updated list of IEEE 802.11 related standards, task groups and their activity is provided for a brief overview. This thesis is directly or indirectly related with the work from the following groups: TGa (IEEE Std 802.11a), TGe (IEEE Std 802.11e), TGh (IEEE Std 802.11h), TGk (IEEE Std 802.11k), TGu (IEEE Std 802.11u), TGaf (IEEE Std 802.11af).

2.1.3 Reference Model

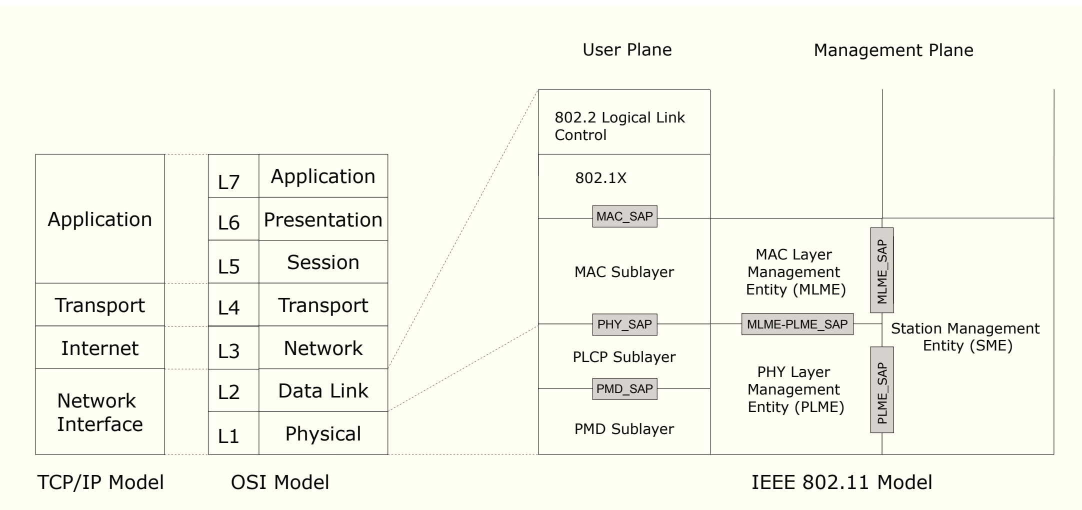


Figure 2.3: IEEE 802.11 reference model

The IEEE 802.11 Standard [63] outlines the reference model of the IEEE 802.11 based system, which is depicted in Figure 2.3. The TCP/IP model and the OSI reference model is included in the figure for reference. Two planes – user and management – are shown.

User plane:

- **Logical Link Control (LLC)**: The LLC layer feeds data frames to the **MAC sublayer** through the MAC-Service Access Point (MAC-SAP). The MAC sublayer is described in more detail in the next section.
- **Physical Layer Convergence Procedure (PLCP)**: The PLCP sublayer provides the convergence functions, i.e., it defines the method of mapping the MAC layer data to the specific frame format suitable for the applied PMD.
- **Physical Medium Dependent (PMD)**: The PMD sublayer has a direct interface with the wireless medium and it facilitates the actual transmission and reception of data over the medium. Different PHY specifications result in different PMD services.

Control plane:

- **MAC Layer Management Entity (MLME)** and **Physical Layer Management Entity (PLME)**: They control the behavior of the MAC and PHY layer respectively in the user plane. For example, timing synchronization among the stations and setting the physical transmission channel respectively are done here.
- **Station Management Entity (SME)**: The SME is a layer independent entity and closely related to MLME and PLME to accomplish the management functions.

According to [104], the definitions of the entities are rather unclear due to the reason that they are implementation dependent and there is no requirement of interoperability among different implementations. This is also one of the main reasons why different interpretations are found in literature, for example as following. According to [32], SME can be residing in a control plane, where as according to [104], MLME and PLME can be residing in a control plane.

2.1.4 Medium Access Control Sublayer

Two of the main functions of the MAC sublayer are to assemble the MAC Protocol Data Unit (MPDU) from the SDUs arriving from the higher layer into the MAC layer and to provide the methods for channel access. The

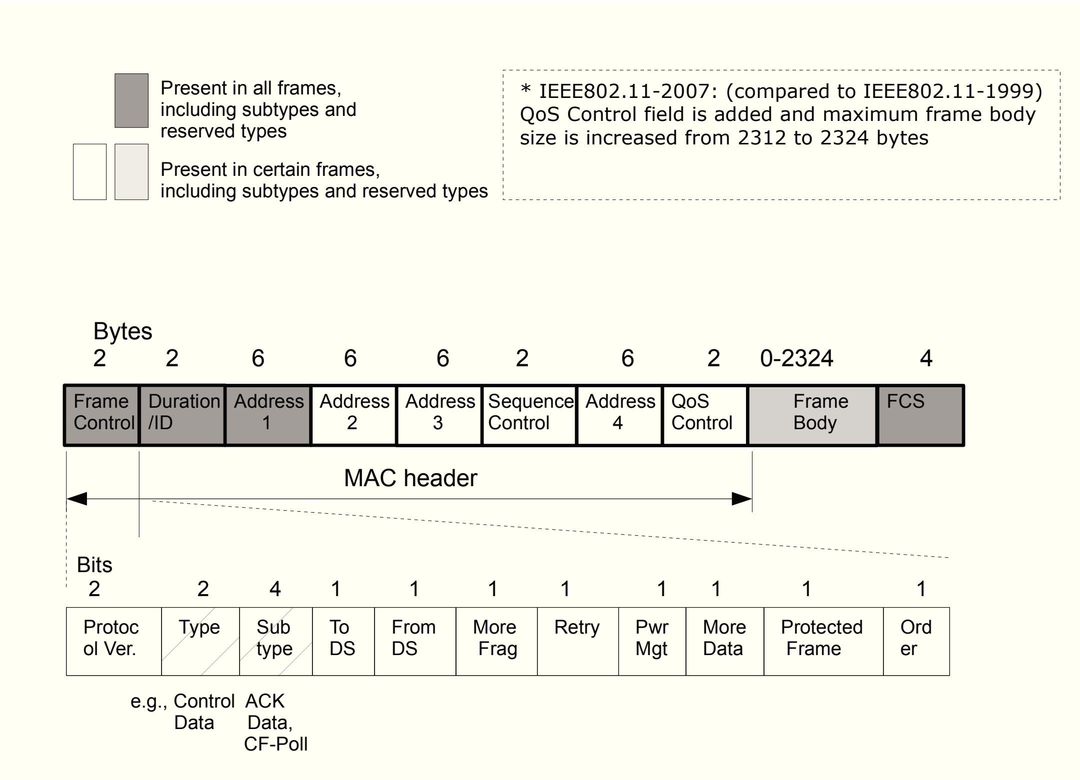


Figure 2.4: IEEE 802.11 MAC frame

MPDU, often called MAC frame, is the fundamental data unit exchanged between the peer MAC layers of the AP and its associated STAs. The MAC sublayer is described in the following focusing on the MAC frame structure and various channel access methods, known as coordination functions.

2.1.4.1 MAC Frame Structure

The basic MAC PDU (MPDU) or frame structure is shown in Figure 2.4, which consists of three fundamental components:

- a MAC header,
- a variable length frame body, and
- a Frame Check Sequence (FCS).

According to the general rule all the stations should be able to validate all received frames and interpret certain fields of the MAC header of all frames. As shown in the figure, any frame must have four fields–Frame Control, Duration/ID, Address 1 and FCS, whereas other fields are only present in certain frames. All the fields are described briefly in the following.

Table 2.1: Type and subtype of frames, used in this thesis

Type	Subtype
Management	Beacon
Control	ACK
Data	Data
Data	QoS CF-Poll (no data)
Data	QoS Null (no data)

- **Frame Control:** The detailed structure of the frame control is shown in Figure 2.4, highlighing two relevant fields. The type field defines the major three types of packets: data, management and control packets and the subtype field defines the sub category as the name implies. Table 2.1 gives a list of IEEE 802.11 frames used in this thesis mentioning their types and subtypes.

Table 2.2: Duration field

Access method	Bit 15	Bit 14	Bit 0-13
CFP under PCF	1	0	0
CP under DCF and EDCA (HCF)	0	0-32767	
CFP and CAP under HCCA (HCF)	0	0-32767	

- **Duration/ID:** This is one of the important frame fields, which provides a general idea about the duration, the station should be silent provided that they can decode the frame. Two practical examples are as following where the duration field value is exploited. When the contents of a received Duration/ID field is less than 32768, regardless of the address, type, and subtype values (even when type or subtype contain reserved values) the duration value is used to update the Network Allocation Vector (NAV) during the procedure like
  - Request to Send/Clear to Send (RTS/CTS) (Figure 8.19), and
  - the allocation of the Transmission Opportunity (TXOP) to a STA through QoS CF-Poll (Figure 2.10).

  The maximum value of the duration is based on the following two factors: The frame is transmitted,
  - in which channel access period, whether it is Contention Period (CP) or Contention Free Period (CFP) (see Section 2.1.4.4), and

  - following which channel access method (see Section 2.1.4.2).

  Table 2.2 gives a more detailed overview on the maximum limit.

- **Address field:** A generic frame has the provision for four address fields. But as mentioned before, they are not required to be present in each frame, rather their usage depends on the frame type. The content of the address field is one of the following
  - Basic Service Set Identification (BSSID)
  - Source Address (SA)
  - Destination Adress (DA)
  - Transmitting STA Address (TA)
  - Receiving STA Address (RA).

  The last two addresses are used in the case where there is an intermediate node between the source and destination, for example in the scenario where the STAs communicate with each other via the AP.
- **Sequence Control field:** This field consists of two subfields, the sequence number and the fragment number. The sequence control field is not present in control frames. Generally each data and management frame is assigned a unique sequence number.
- **QoS Control field:** It is a new addition in IEEE 802.11-2007 standard. It has different QoS-related information elements such as TXOP limit, ACK policy. It is a 16-bit field. Each QoS Control field consists of five subfields, whose content definition is depend on particular sender (AP or STA), frame type, and subtype. The usage of these subfields and the various layouts of the QoS Control fields are listed at page 67 in [63]. In the framework of this thesis, a new layout is proposed and used for QoS Null frame.
- **Frame Body field:** This is a variable length field which contains information based on frame type and subtype. For data frames, this contains the payload.
- **FCS field:** This field contains a 32-bit Cyclic Redundancy Check (CRC).

In the following the structures of three different frame types are given.

Data frame: The top diagram in Figure 2.5 depicts a generic data frame structure. In the bottom, three specific data frames: QoS data, QoS CF-Poll and QoS Null are illustrated with a particular emphasis to show the frame fields used. When the frames have QoS Control fields in their MAC header, they are denoted as QoS data subtypes. Note that, inside the thesis the preterm 'QoS' is usually left out for better readability. These three example

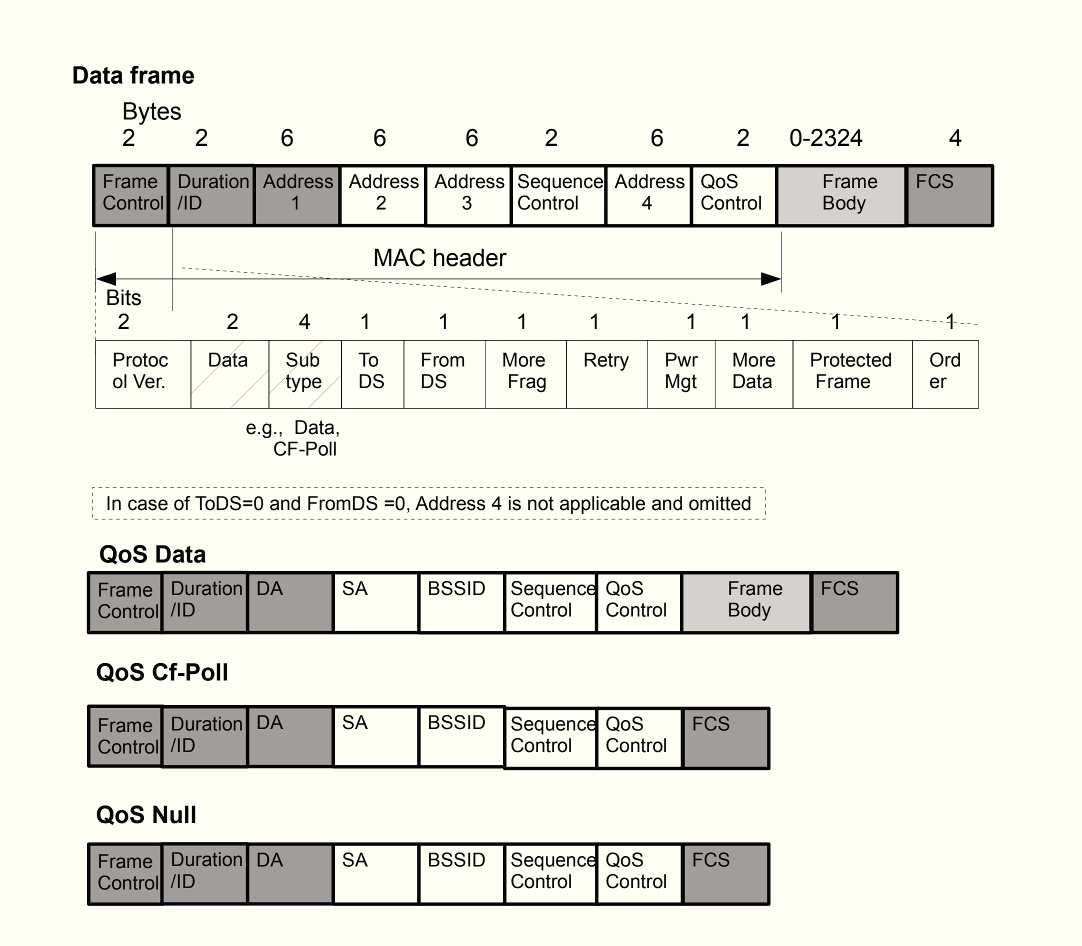


Figure 2.5: IEEE 802.11 MAC Data frame

frames are used for direct communication between AP and STAs in case of the downlink or the uplink. Communication via the Distributed System (DS) is not considered here, and that is why the address 4 field is not used.

Control frame: Figure 2.6 shows the frame structure for an acknowledgement (ACK) frame, which is a control frame. Note that the fields in the *frame control*, containing the '0' value are common to all control frames. Unless fragmentation of data, the duration field is set to 0. The RA field of the ACK frame is copied from the Address 2 field of the immediately previous directed data frame to be acknowledged (i.e., SA).

Management frame: Figure 2.7 shows the frame structure for a Beacon frame, which is a management frame. In case of a Beacon frame, the DA field is the destination of a frame which is a broadcast address. The SA field is the address of the STA transmitting the frame. If the STA is an AP the BSSID field is the address of the AP.

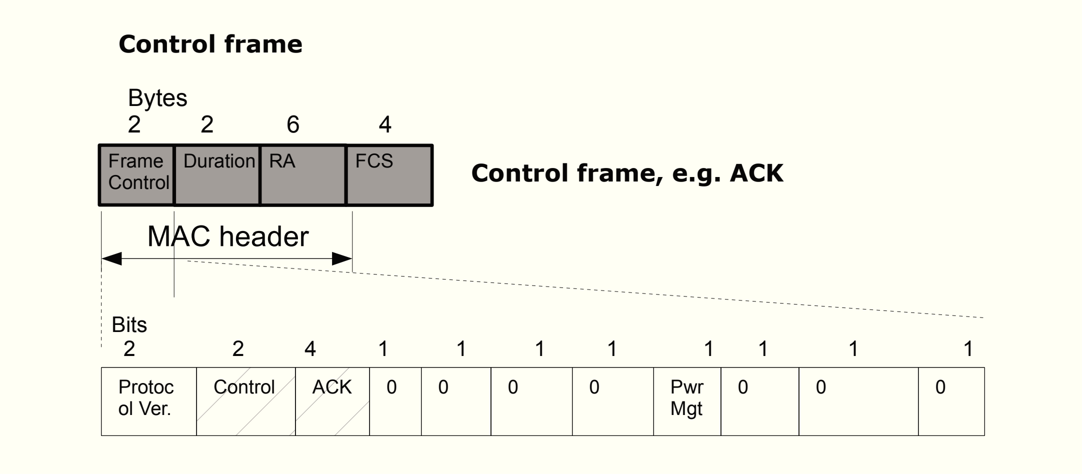


Figure 2.6: IEEE 802.11 MAC Control frame (ACK)

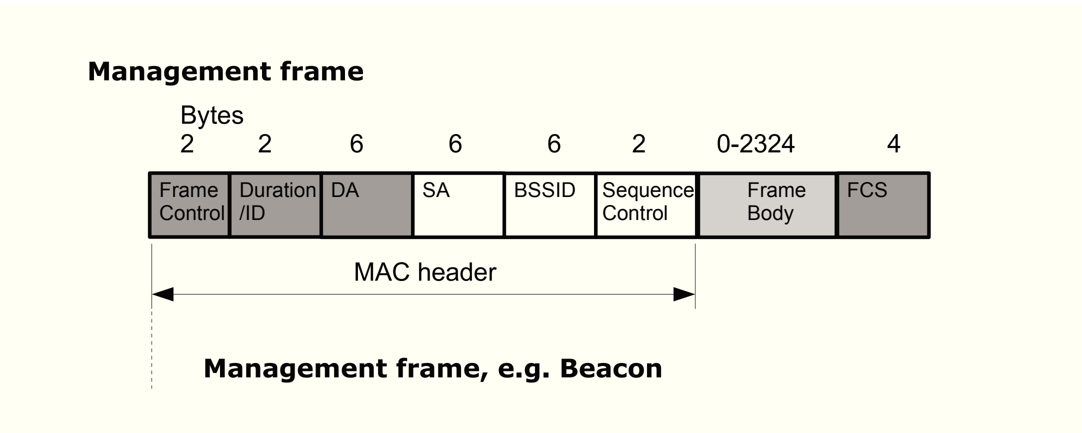


Figure 2.7: IEEE 802.11 MAC Management frame

In general, the frame body of a management frame consists of the information elements according to its subtype. An information element has its own identification (ID). If any station does not identify any element ID, it should ignore that and proceed to parse the other recognizable IDs. The Beacon frame has a list of information elements as defined in the standard. Some of them, related to this thesis, are described in the following.

- Beacon Interval: This provides the duration between two consecutive Beacon frames.
- Quiet Element: It is used to silent the transmission in the current channels. It has the following fields.
  - Quiet Count field: It contains the number of Target Beacon Transmission Times (TBTT) until the intended beacon interval during

which the next quiet interval shall start. A value of 1 indicates the quiet interval shall start during the beacon interval starting at the next TBTT.
  - Quiet Period field: It contains the number of beacon intervals between the start of regularly scheduled quiet intervals. A value of 0 indicates that no periodic quiet interval is defined.
  - Quiet Duration field: It contains the duration of the quiet interval.
  - Quiet Offset field: It contains the offset of the start of the quiet interval from the TBTT specified by the Quiet Count field. The value of the Quiet Offset field shall be less than one beacon interval.
- Measurement Request Element: It contains a request that the receiving station can perform. One of the fields in the measurement request element is measurement type which contains, for example, the Clear Channel Assessment (CCA) request type and there is a provision to *introduce new measurement types*. Just after the measurement type, there is a field of variable length called measurement request, which is correlated to the measurement type. For example, for the CCA request, there are three sub-fields under measurement request: Channel number, measurement starting time and measurement duration.

2.1.4.2 MAC Architecture

The IEEE 802.11-1999 standard defines two channel access mechanisms for WLAN namely the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). IEEE 802.11e introduced the Hybrid Coordination Function (HCF), which is integrated in IEEE 802.11-2007.

2.1.4.3 Distributed Coordination Function

The DCF is a contention based random channel access scheme based on the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol and the random backoff procedure. Carrier sense facilitates the first degree of collision avoidance where the backoff does the second degree. Figure 2.8 shows the channel access method of IEEE 802.11 in DCF mode.

Before describing the DCF method, some required IEEE 802.11 fundamentals are briefly provided below.

Carrier Sense (CS) Mechanism: It is used to determine the channel state. Two types of CS mechanism – physical CS (PCS) and virtual CS

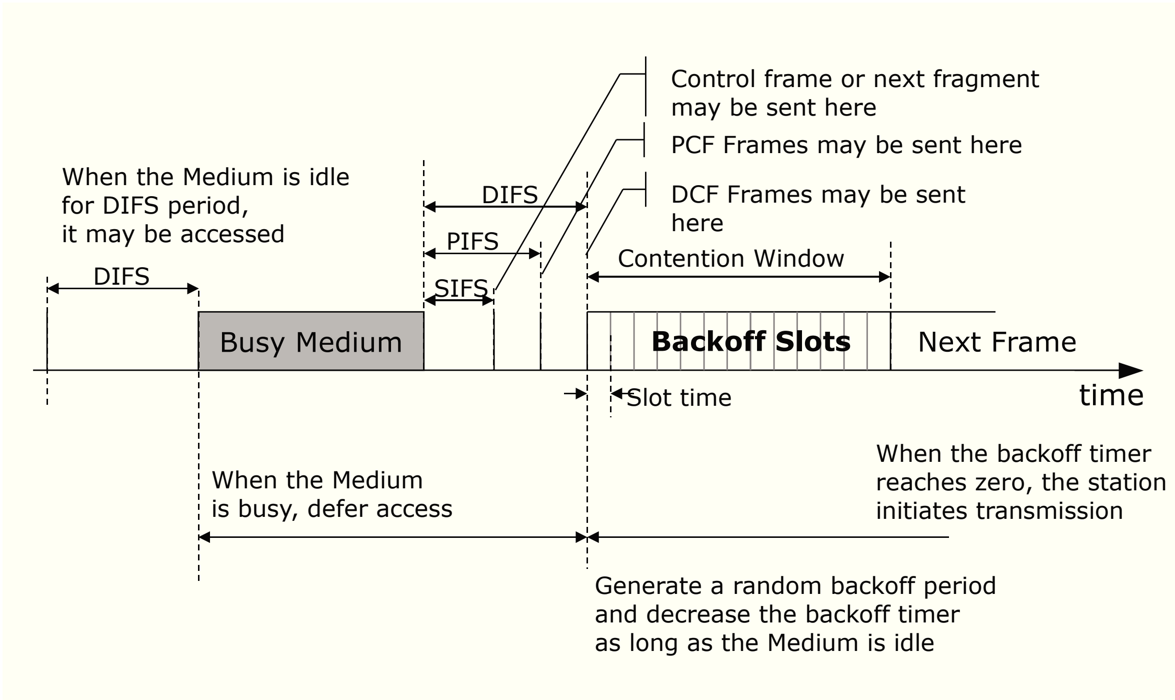


Figure 2.8: IEEE 802.11 channel access method: Distributed Coordination Function (DCF) [58]

(VCS) – is introduced, which are provided by the PHY and the MAC respectively. The PCS mechanism is based on the CCA function, described in Section 2.1.5.2. The VCS mechanism is often referred as the Network Allocation Vector (NAV). As mentioned earlier, the duration information of the frame is exploited to set the NAV, which is realized and implemented as a timer.

Interframe Spaces (IFS): The IFS is defined as the time interval between frames to provide the priority level for the channel access. By means of the PCS mechanism, a station can determine the idle duration equal to the IFS. Five kinds of IFS are mentioned in IEEE 802.11:

- Short IFS (SIFS)
- PCF IFS (PIFS)
- DCF IFS (DIFS)
- Arbitration IFS (AIFS)
- Extended IFS (EIFS).

The time durations of the IFSs depend on the PHY specification, however independent of a stations' PHY bit rate under the same specification. A list of SIFS durations is given in Table 2.3 and the model to calculate the durations for the PIFS and the DIFS out of the SIFS duration are given in equation 2.1. Figure 2.8 shows the relative durations of these IFSs.

Details of the DCF are given in the standard [63] which describes the rules to follow when a MAC layer Service Data Unit (MSDU) is arriving at the MAC layer from a higher layer. The basic rules are as follows:

- A station which desires to initiate a transmission, invokes the carrier sense mechanism (physical and virtual) to determine the idle/busy state of the channel.
- If the medium is sensed busy, the station must wait for the channel to become idle. It is termed as 'access deferral' according to the standard. In this case, the access is deferred until the medium is sensed idle without interruption for a period of time equal to DCF Interframe Space (DIFS) when the last frame detected on the medium was received correctly, or after the medium is sensed idle without interruption for a period of time equal to EIFS when the last frame detected on the medium was not received correctly.
- If the medium is sensed idle without interruption for a period of time equal to DIFS or EIFS according to the above condition, the station generates a random backoff period (which is quantified by the number of backoff slots[1]) for an additional deferral time before transmitting, unless the backoff timer already contains a nonzero value.
- If the medium is sensed busy at any time during a backoff slot, then the backoff procedure is suspended; that is, the backoff timer shall not decrement for that slot.
- The backoff procedure should resume when the medium is sensed idle for the duration of a DIFS period or EIFS period according to the above condition.
- If the channel remains idle for this additional random time, i.e. when the backoff timer reaches zero, the station initiates transmission.

One important additional feature is that all data frames are required to be acknowledged (using ACK frame) by the receiver, and the retransmission should be scheduled by the sender in case when no ACK is received.

[1]a unit of time, whose value is defined by the PHY characteristic parameter `aSlotTime`

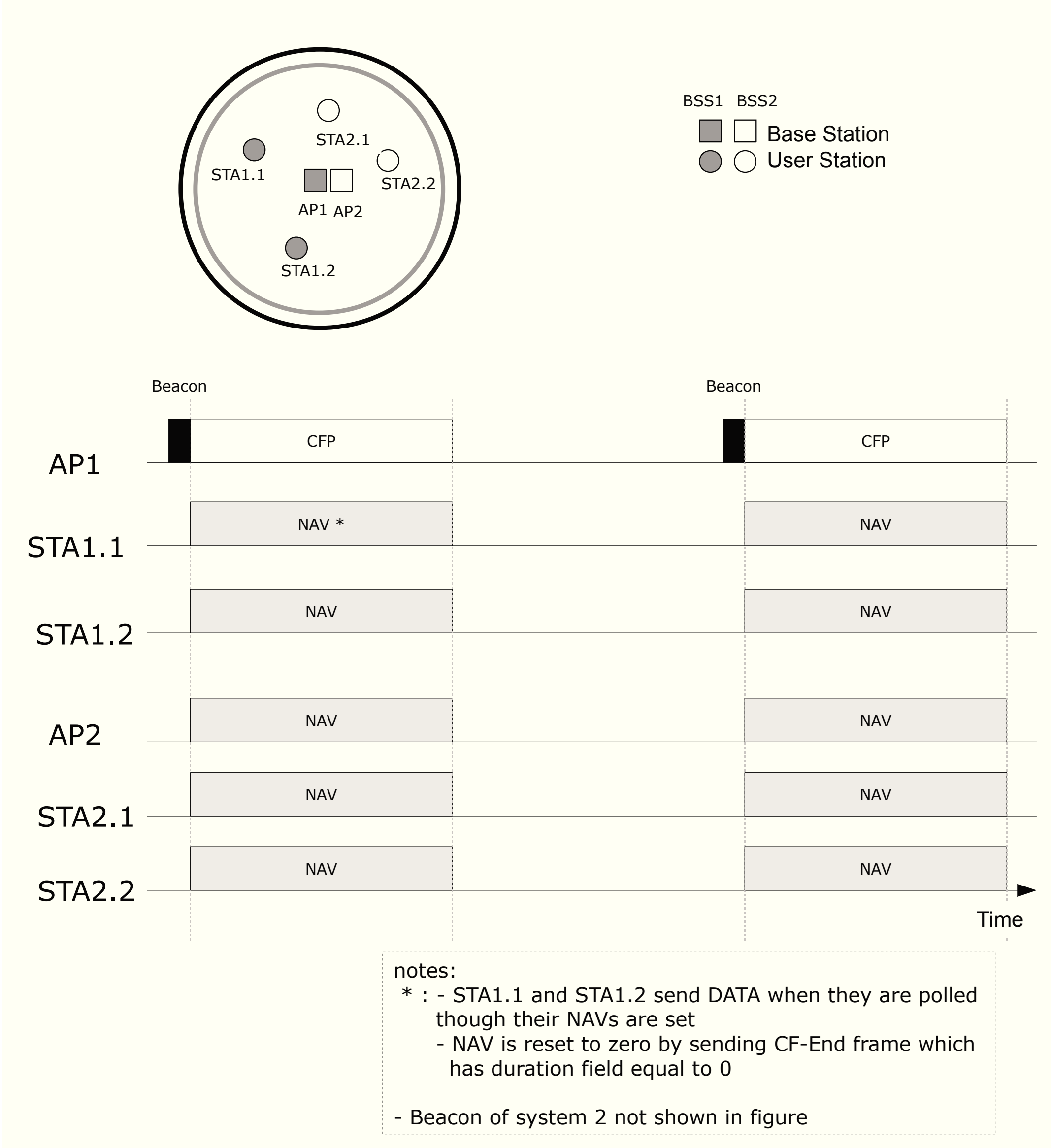


Figure 2.9: Timing diagram for channel access by collocated IEEE 802.11 systems using the PCF and the CFP concepts

2.1.4.4 Point Coordination Function

The PCF is a centrally controlled channel access scheme based on a polling mechanism. The PCF is an optional function and only working in infrastructure mode. When the WLAN system is set up to work in PCF, the channel access time is divided in periodic intervals called superframes. The PCF operates in the first part of the superframe, called the Contention Free Period (CFP). The DCF operates in the remaining part of the superframe called Contention Period (CP).

It has been shown in literature that the DCF and the PCF have limitations concerning the support of Quality of Service (QoS) [85]. This motivated the development of IEEE 802.11e to provide user level QoS. In IEEE 802.11e traffic flows are differentiated into categories like voice, video, best effort, and background and they are served according to their access priority. Wireless Multimedia Extension (WME) [17] based on IEEE 802.11e is the commercial version of WLANs with QoS support.

Its quite clear from the IEEE 802.11-2007 standard (p-274) that all stations, irrespective to which BSS they are associated, which can receive the Beacon frames containing the *CF Parameter Set* information element, set their NAV according to the `CFPMaxDuration` value. This is a useful rule which prevents any stations to take control of the channel during the CFP, even if the stations belong to other BSSs. At the end of each CFP, the Point Coordinator (PC) should send a CF-End frame according to the rule, which is basically helping all the stations, from any BSS, to reset the NAV. Figure 2.9 shows the frame exchange during PCF and setting of NAVs.

2.1.4.5 Hybrid Coordination Function

IEEE 802.11e [61] defines a coordination function called Hybrid Coordination Function (HCF) to provide the QoS support. The HCF includes two channel access mechanisms: the Enhanced Distributed Channel Access (EDCA) and the HCF Controlled Channel Access (HCCA). The EDCA is basically an enhancement to the DCF by introducing access categories and priorities. The HCCA is an enhancement to the PCF. Figure 2.10 gives an overview of the IEEE 802.11e superframe structure in the time domain. Each superframe starts with a Beacon frame. One main feature introduced in the HCF is the Transmission Opportunity (TXOP). A TXOP specifies the time duration when a station has the uninterrupted control over the medium and can transmit multiple consecutive frames with only SIFS spacing between an acknowledgement (ACK) and the next data frame. The TXOP is defined by a starting time and a specified maximum duration.

2.1.4.6 Enhanced Distributed Channel Access

The EDCA is mainly the enhancement of DCF, considering the traffic classes and introducing the traffic priority on the access methods by means of defining new parameters like AIFS[AC], CW[AC], CWmin[AC], etc. based on Access Category (AC). Another enhancement is done by means of introducing the EDCA Transmission Opportunity (*EDCA-TXOP*), which is the time span during which the TXOP holder can maintain uninterrupted

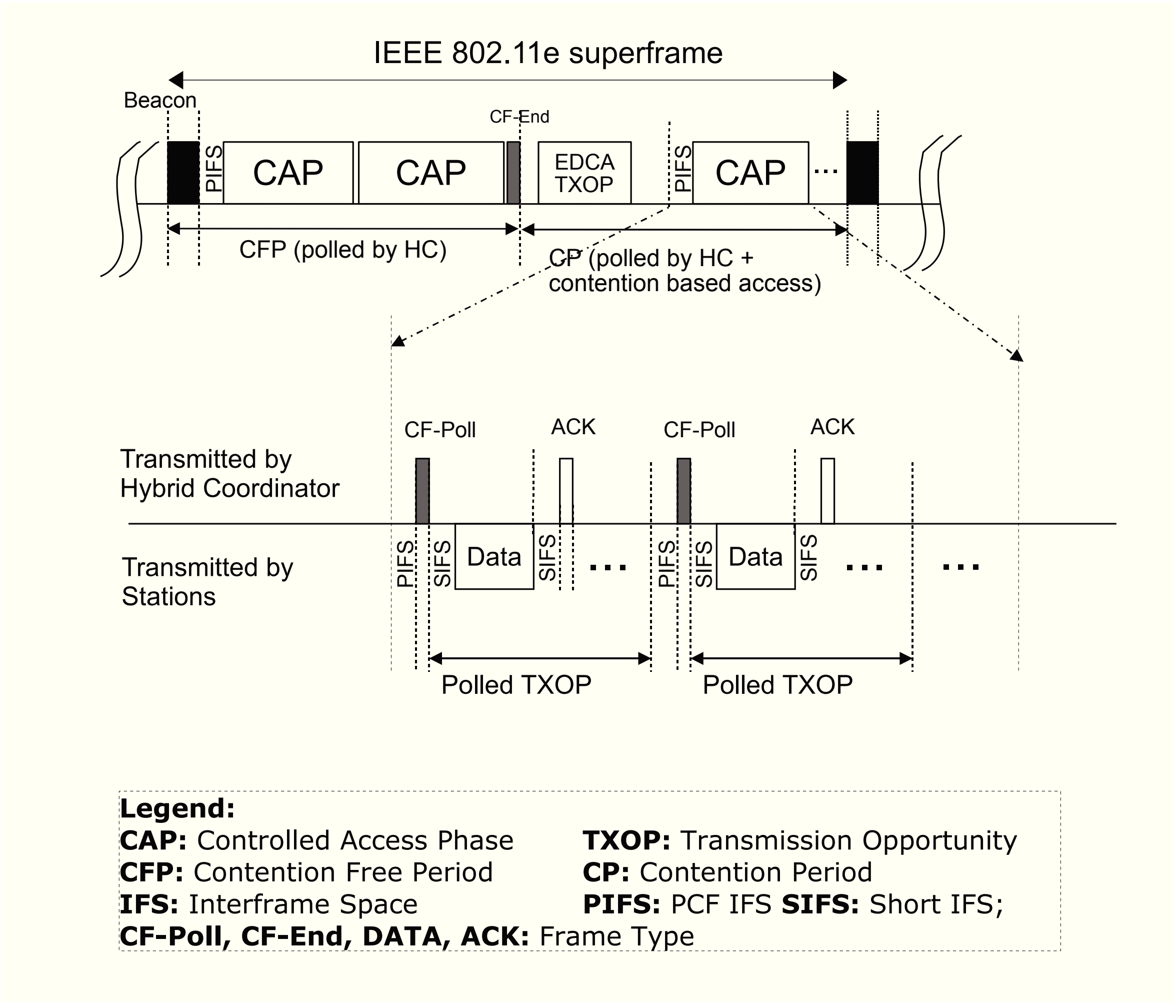


Figure 2.10: IEEE 802.11e superframe structure [99]

control over the medium and transmit multiple MSDUs inside the TXOP duration. The highest boundary for the duration of TXOP is determined by the TXOPlimit. Note that a TXOPlimit of 0 indicates a single MSDU exchange, which is similar to the DCF. This channel access method is not described in detail as it is not considered in this thesis.

2.1.4.7 HCF Controlled Channel Access

In HCCA the Hybrid Coordinator (HC), which is located in the AP, has the control over the channel. A station is granted a TXOP (often denoted as *polled TXOP*) by the HC. The polled station (in the uplink case) is informed about the allocated TXOP by a QoS CF-Poll frame. Other stations in the network set their Network Allocation Vector (NAV) according to the duration field of the QoS CF-Poll frame. Another special improvement in

Table 2.3: The physical characteristics of PHY techniques

PHY Protocol	Standard/ Amendment	Freq (GHz)	Channel spacing (MHz)	Slot time (μs)	SIFS duration (μs)
DSSS	802.11-1997	2.4	20	20	10
FHSS	802.11-1997	2.4	20	50	28
OFDM	802.11a	5	20 10 5	9 13 21	16 32 64
DSSS	802.11b	2.4	20	20	10
OFDM /DSSS	802.11g	2.4	20	long = 20 short = 9	10
MIMO OFDM	802.11n	2.4/5	20	9	16

the HCCA is the contention free burst, known as Controlled Access Phase (CAP), which is initiated during a Contention Period (CP) or during a Contention Free Period (CFP). Multiple consecutive polled TXOPs can be inserted inside a CAP period. The HC can start a CAP by sending a QoS CF-Poll or a data frame (in the case of uplink or downlink respectively) when the medium is idle for more than a PCF IFS (PIFS) period.

2.1.5 Physical Layer

Different PHY specifications are provided in the standard: Frequency-Hopping Spread Spectrum (FHSS) PHY specification (for the 2.4 GHz band), Direct Sequence Spread Spectrum (DSSS) PHY specification (for the 2.4 GHz band) and the Orthogonal Frequency Division Multiplexing (OFDM) PHY specification (for the 5 GHz band). The OFDM based PHY is considered in this thesis.

The physical characteristics like the SIFS duration (`aSIFSTime`) and the slot duration (`aSlotTime`) are determined according to the PHY techniques. Table 2.3 shows the values for different PHY specifications.

The MAC layer uses the above two parameters to define the IFS duration like the PIFS and the DIFS durations as follows.

$$\begin{aligned} PIFS &= aSIFSTime + aSlotTime \\ DIFS &= aSIFSTime + 2 * aSlotTime \end{aligned} \tag{2.1}$$

The impact of these PHY and MAC layer parameters on the pattern recognition based system type identification method is presented in Chapter 5.

2.1.5.1 Orthogonal Frequency Division Multiplexing

The OFDM technique is not a multiple access technique (misnomer), rather it is a modulation technique. It is a FDM like scheme which sends data over multiple carriers. To be precise and to the point, OFDM is a multicarrier modulation technique which divides the wideband/high-rate data stream to several narrowband/lower-rate substreams. Each of these substreams are then transmitted in parallel over different orthogonal sub-carriers, which are modulated with a conventional modulation method (e.g. phase-shift keying). By the parallel transmission, the desired total higher data rate is maintained, however with Inter-symbol Interference (ISI) free transmission [34]. The number of substreams is determined in a way that the symbol time on each substream becomes much greater than the delay spread of

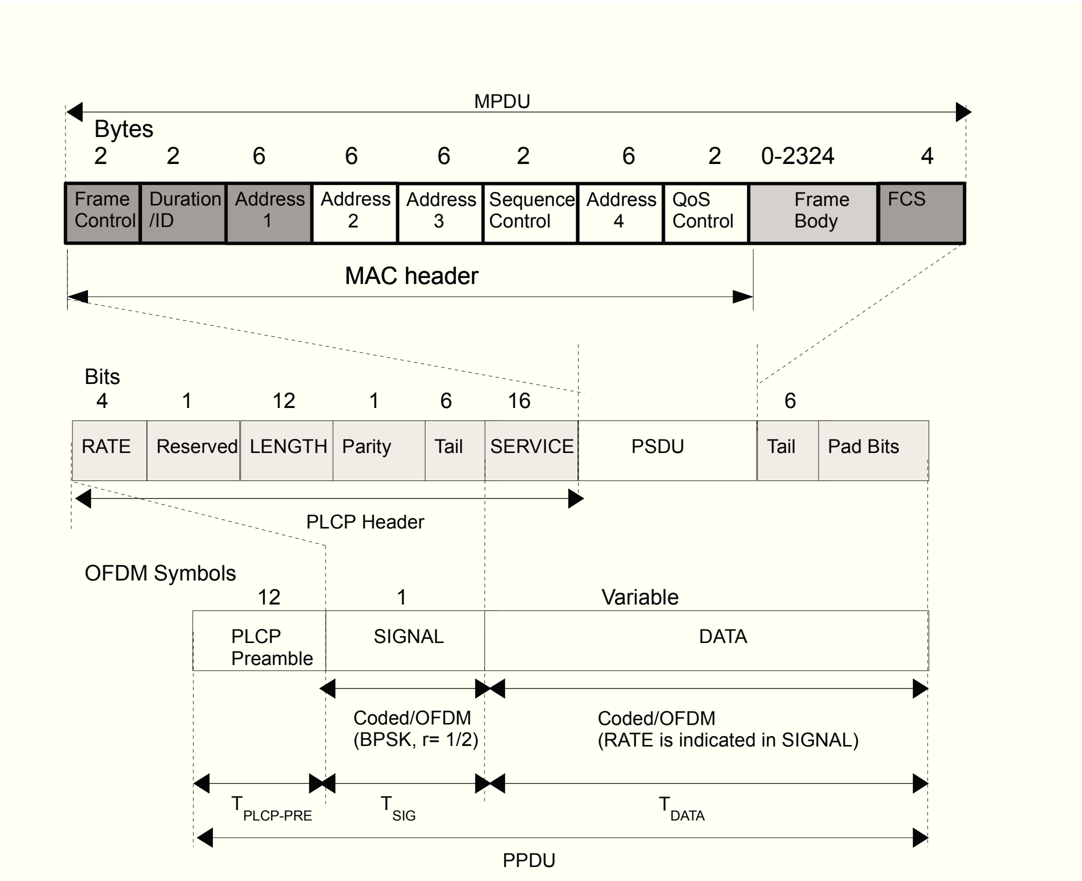


Figure 2.11: IEEE 802.11 PPDU frame format

that channel, in other words, that the sub-carrier bandwidth is lower than the coherent bandwidth of the channel so that the subcarrier experiences the flat-fading. It results in relatively low ISI which is then completely prevented by the concept of a cyclic prefix.

The OFDM based PHY provides the data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbits/s. The system uses 52 subcarriers that are modulated using Binary or Quadrature Phase Shift Keying (BPSK or QPSK) or using 16- or 64-Quadrature Amplitude Modulation (16-QAM or 64-QAM). Forward error correction coding is used with a coding rate of 1/2, 2/3, or 3/4.

Figure 2.11 shows the PPDU generated at the OFDM based PLCP sub-layer by adding the PLCP Preamble, PLCP header, tail bits and pad bits to the PSDU. Different fields in the PLCP header are shown in the figure.

2.1.5.2 Carrier Sense/Clear Channel Assessment Procedure

The Carrier Sense/Clear Channel Assessment (CS/CCA) procedure is one of the core functionalities which the IEEE 802.11 channel access mechanism depends on. It is performed at the PLCP sub-layer and sends the outcome to the MAC layer, according to the standard [63, 51]. The general purpose of the CCA procedure is to detect the condition of the medium whether it is *idle* or *busy* to accomplish two facts: (a) to detect a start of a frame that can be received and (b) to assess the medium as *clear* before starting a transmission. Different variants of CCA are available according to the PHY specification. From the perspective of the OFDM PHY specification, the detection procedure is based on the following criteria. The start of a valid OFDM signal (preamble detection) at the receiver level triggers the CCA to decide the channel busy if the received power level is equal to or greater than –82 dBm which is the *receiver minimum input sensitivity* at the lowest Modulation and Coding Scheme (MCS). This is considered as the CCA threshold. It is important to note that the CCA threshold depends on channel bandwidth/spacing. In the upper case, it is for the 20 MHz channel spacing. In case of missing the preamble (e.g, when the receiver can not decode the preamble), the CCA threshold is 20 dB above the receiver's minimum input sensitivity at the lowest MCS, which is in this case -62 dBm.

The advantage of the CCA algorithm is that it already activates the cognitive approach to prevent own transmissions in case of foreign nodes/systems. However, the drawback is that it can be easily exploited to make a denial of service (preventing to transmit) by creating a jamming signal by the attacker. Different solutions to this problem are proposed in related literature, however they are out of the scope of this thesis.

2.2 IEEE 802.16

IEEE 802.16 (aka WiMAX) is a wireless broadband access technology. Before going into details on IEEE 802.16, a short description on broadband and wireless broadband is provided as follows.

Broadband access technology is generally a term for a high-speed access technology which can provide a high rate of data transmission. The common two technologies providing the broadband access are Digital Subscriber Line (DSL) over twisted-pair telephone wires and cable modem over coaxial cable. To connect the users in the areas where the infrastructure is not available, broadband based on wireless technologies has evolved, called *wireless broadband*, which is expected to reduce the cost substantially compared to build the infrastructure.

IEEE 802.16 is firstly considered as the wireless broadband for the services like fixed-line broadband technology, sometimes called *fixed wireless broadband*. However, it is being extended to give service for nomadicity and mobility, sometimes called *mobile wireless broadband* [34]. Nomadicity gives the privilege to connect to the network from different locations via different base stations. Compared to fixed-line broadband like DSL, nomadicity already provides a significant benefit to the user where he in fact carries the access with him.The mobility feature completes the total flexibility and it helps the broadband industry to migrate from triple-play services (data, voice, video) to quadruple-play services (triple-play services, mobility) [93]. In this thesis, fixed and mobile (context of nomadicity) IEEE 802.16 wireless broadband is covered. The latter one is covered logically as the thesis handles the air interface only.

2.2.1 Architecture and Modes of Operation

The IEEE 802.16 standard defines a centrally controlled wireless communication protocol where the channel occupation of IEEE 802.16 systems is fully controlled by the scheduler in the Base Station (BS). Subscriber Stations (SSs) associate with the BS forming a cell. IEEE 802.16e only provides the air interface whereas the *WiMAX forum* has developed the end-to-end network reference model including IEEE 802.16e-2005 as the air interface, to provide a fundamental architecture for WiMAX deployment and to ensure the interoperability among different WIMAX operators and equipment. Figure 2.12 depicts an exemplary network architecture for IEEE 802.16 based systems based on the reference model provided in the IEEE 802.16e-2005 standard [62] and WiMAX Forum Network Architecture (2010) Specification [20]. The network elements which are inside the dashed circle in the

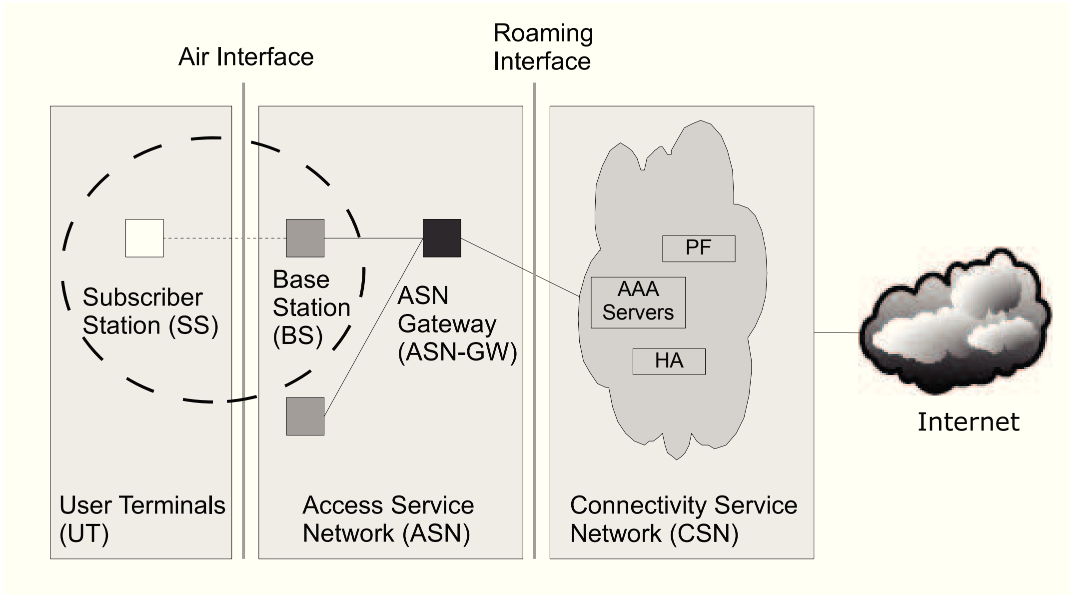


Figure 2.12: IEEE 802.16 network reference model [20]

figure are mainly considered in the framework of this thesis. The overall network is logically divided into three parts:

- **User Terminal (UT):** The end user's terminal to access the network. It could be a fixed, portable or mobile terminal.
- **Access Service Network (ASN):** It comprises network elements like one or more Base Stations (BS) and one or more ASN Gateways (ASN-GW), however each should be at least one. One BS to many ASN-GW is generally considered for providing options like load balancing or redundancy. According to [20], the base station is a logical entity which is compliant with the MAC and PHY specification of IEEE 802.16. It should incorporate the scheduling facility for downlink and uplink. The mapping between logical and physical implementations of the BS can be a one-to-one or multiple-to-one relationship.
- **Connectivity Service Network (CSN):** It provides IP connectivity and connectivity to the Internet. One ASN may be shared by more than one CSNs.

2.2.2 The 802.16 Standards and Amendments

The IEEE 802.16 Working Group established by the IEEE Standards Board in 1998, *aims to prepare formal specifications for the global deployment of broadband wireless metropolitan area networks (WirelessMAN, WMAN)*

[15]. The group's initial goal was to develop an air-interface standard considering the two aspects – the Physical (PHY) layer and the Media Access Control (MAC) layer – for Broadband Wireless Access (BWA) in line-of-sight (LOS) point-to-multipoint scenarios and for the operation in the 10-66 GHz band. The first approved standard came out in 2001. This is the same year when an industry group called the WiMAX Forum was formed to promote conformance and interoperability of the standard. From then the 802.16 family of standards which is officially called WirelessMAN, has got an industry given name *WiMAX* (Worldwide Interoperability for Microwave Access). The forum describes WiMAX as *a standard-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL* [19]. The mission of the forum is to promote and certify compatibility and interoperability of broadband wireless products.

Similar to the IEEE 802.11 standardization process, several working groups and task groups are created under IEEE 802.16 to enhance the operation of broadband wirelessMAN in several contexts and the final outcome of the task group is first published as amendments and later integrated in the main standard, similar procedure followed in IEEE. For example, IEEE 802.16-2004 consolidates 802.16-2001, 802.16a, 802.16c and 802.16d in 2004 and IEEE 802.16-2009 consolidates IEEE Standards 802.16-2004, 802.16e-2005 and 802.16-2004/Cor1-2005, 802.16f-2005, and 802.16g-2007 in 2009. A brief list of standards is given in Appendix A.1.

Up to now, IEEE 802.16d and IEEE 802.16e are the two major standards mostly adopted by the industries around the world. 802.16-2004 is sometimes referred to as *Fixed WiMAX*, since it has no support for mobility. 802.16e-2005, often abbreviated to 802.16e, is an amendment to 802.16-2004. It introduced support for mobility, among other things and is therefore also known as *Mobile WiMAX*. According to [21] showing the WiMAX deployments worldwide, sponsored by the WiMAX Forum, it is found that four out of six operators in Germany who deploy WiMAX have the profile matching with IEEE 802.16d and the other two with IEEE 802.16e.

This thesis is related with the standard: 802.16-2004, IEEE Std 802.16.2-2004, IEEE Std 802.16h-2010 where coexistence methods are discussed.

In the following the reference model is described according to the IEEE 802.16-2004 which includes IEEE 802.16d.

2.2.3 Reference Model

Figure 2.13 shows the reference model of IEEE 802.16 based system. The figure is depicted based on [60].

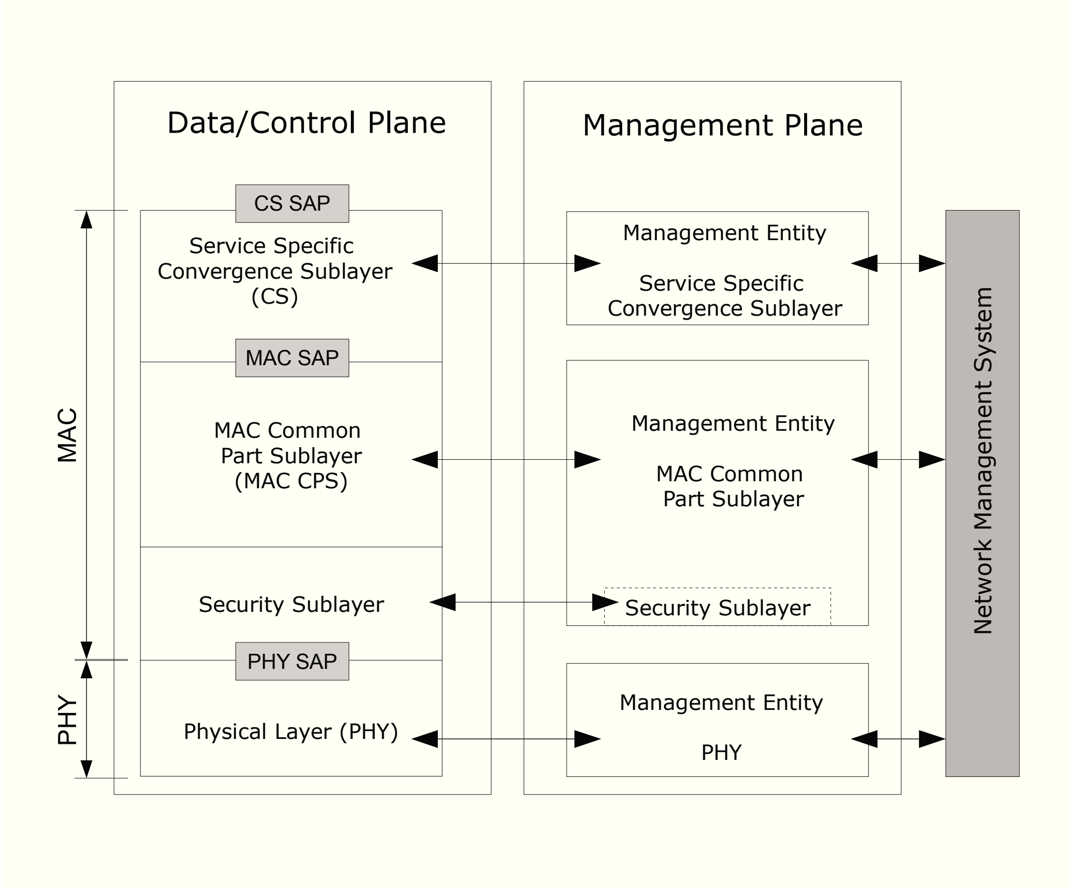


Figure 2.13: IEEE 802.16 reference model [60]

2.2.4 Medium Access Control

The IEEE 802.16 MAC comprises three sublayers which are discussed in the following subsections.

2.2.4.1 Service Specific Convergence Sublayer

The Convergence Sublayer (CS) is a kind of adaptation layer between network layer and MAC Common Part Sublayer (MAC CPS). One of the key tasks of the CS is to map network layer data into MAC Service Data Units (SDU). It is an address mapping as higher layer addresses are not visible to MAC and PHY layers. The process includes classification of network layer SDUs and then associates them to the appropriate MAC Service Flow ID (SFID) and Connection ID (CID). Note that IEEE 802.16 MAC is connection oriented and establishes a logical connection between the BS and the SS by means of a unidirectional CID, which can be seen as a dynamic and temporary layer 2 address between peer MAC/PHY entities to carry data and control plane traffic. The service flow is a unidirectional flow of MSDUs on a connection that is provided a particular QoS. The CS has to keep track of the mapping between network layer destination address and the SFID and another mapping of SFID and CID, which defines a QoS class of service flow associated with the connection.

According to the standard, multiple CS specifications can be provided for interfacing with several protocols. The internal format of the payload, which is very specific to the related CS, does not need to be understood by the MAC CPS. The packet based CS is considered in this thesis.

2.2.4.2 MAC Common Part Sublayer

The MAC CPS performs the core MAC functions such as medium access, radio resource allocation, scheduling, connection establishment and maintenance, all kinds of packet operations like fragmentation and concatenation of SDUs into MAC PDUs, QoS Control and ARQ. It receives data from various CSs, via the MAC SAP, and classified to particular MAC connections.

The IEEE 802.16-2004 standard supports four QoS scheduling types: Unsolicited Grant Service (UGS) for the Constant Bit Rate (CBR) service, Real-time Polling Service (rtPS) for the Variable Bit Rate (VBR) service, Non-real-time Polling Service (nrtPS) for non-real-time VBR, and Best Effort service (BE) for service with no rate or delay requirements. In the 802.16e standard, there is an additional service type called Extended Real-time Polling Service (ertPS) for Voice over IP (VoIP) service with silence suppression. These QoS classes are associated with certain predefined sets of QoS-related service flow parameters, and the MAC scheduler supports the appropriate data handling mechanisms for data transport according to each QoS class [44].

2.2.4.3 Security Sublayer

The security sublayer provides authentication, encryption and secure key exchange methods. These methods are not further discussed here, since security aspects are outside the focus of this thesis.

2.2.4.4 MAC Frame Structure

As discussed above, the SDUs coming from the higher layer into the MAC CPS are assembled to build the MAC PDU (MPDU). Similar to 802.11, the basic IEEE 802.16 MPDU consists of three fundamental components, however with different length:

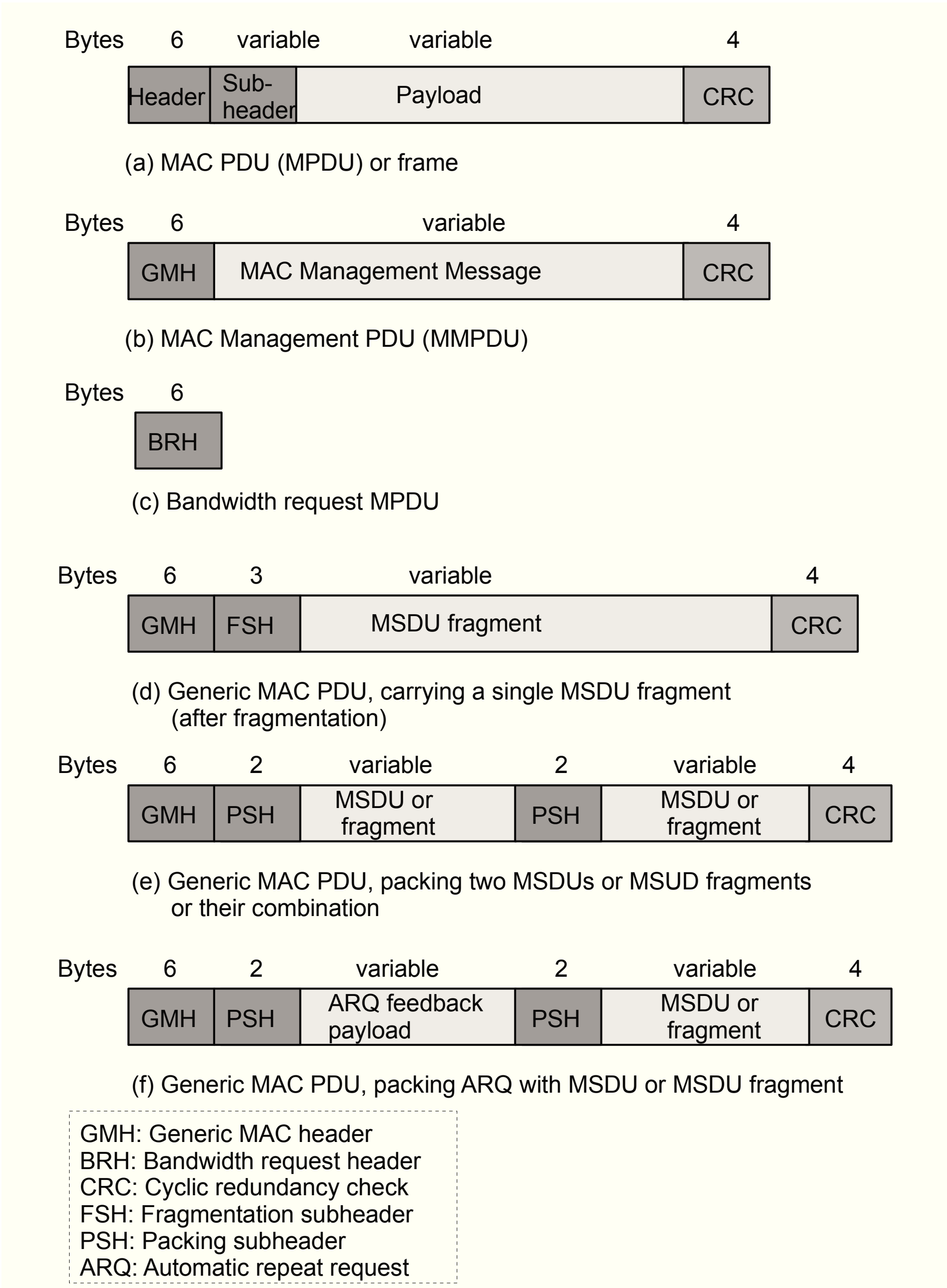


Figure 2.14: IEEE 802.16 MAC frames

- a 6-byte MAC header,
- a variable length payload, and
- an optional 4-byte CRC.

A single MPDU is always related to a single MAC connection. A MPDU is shown in Figure 2.14.(a). There is an option of inserting a subheader just after the header for some special MAC treatment, for example, in the following cases. Based on the length of the payload, multiple MSDUs can be concatenated or aggregated ('packing') on a single PDU, or a single MSDU can be fragmented on multiple MPDUs. The fragmentation subheader and packing subheader is used respectively.

There are two types of MPDUs available in IEEE 802.16.

1. **Generic MPDU:** Used to carry the data payload and MAC layer signaling information. A generic MPDU starts with a Generic MAC Header (GMH) whose different fields are listed and described in Appendix A.2. Various possible MPDU structures are discussed in the following. A MPDU carring a management message is shown in 2.14.(b). Figure 2.14.(d) depicts a MPDU carrying a MSDU fragment where the Frame Subheader (FSH) is inserted after the GMH. Figure 2.14.(e) depicts a MPDU carrying multiple MSDUs or MSDU fragments or their combination by packing them inserting Packing Subheaders (PSH) immediately before them. An ARQ feedback payload and a MSDU is shown in Figure 2.14.(f).
2. **Bandwidth request MPDU:** It is used by the SS to request for more bandwidth from the BS, for example when pending transmissions increase and eventually the MAC layer buffer size becomes saturated. This type of MPDU only contains the Bandwidth Request Header (BRH) whose different fields are listed and described in Table A.1, and no payload and CRC. A bandwidth request MPDU is shown in 2.14.(c).

Note that MAC message types like DL MAP and UL MAP, which are using broadcast connections, are neither fragmented nor packed. The DL MAP and UL MAP are used to inform the detailed DL and UL resource allocations respectively to all the SSs.

2.2.4.5 Automatic Repeat Request

The Automatic Repeat reQuest (ARQ) mechanism is an optional part of the IEEE 802.16 MAC protocol. If implemented, then the ARQ is enabled on per connection basis, which should be specified and negotiated during the connection setup. The additional effort is not put in this thesis to model the ARQ in its IEEE 802.16 model as the main goal is to handle spectrum sharing. However, the impact of the ARQ mechanism is not ignored. In the case of packet collisions in an uncoordinated coexisting scenario, the ARQ definitely increases the transmission reliability, however with the cost of packet delay. There is a tradeoff whether to enable the ARQ or not, based on parameters, like the traffic type, QoS requirement of the traffic, etc.

2.2.4.6 MAC Support of PHY

The Frequency Division Duplexing (FDD) and the Time Division Duplexing (TDD) techniques are supported by the MAC layer. From the perspective of this thesis, TDD is discussed in the following. In this case downlink (DL) and uplink (UL) transmissions are separated in time domain while using the same frequency, by traditional means of defining two respective subframes in a fixed TDD frame. Frame duration options are 2.5, 4, 5, 8, 10, 12.5 and 20 ms [60]. In 802.16 TDD, the resource allocation in DL and UL is adaptive and the split between them is a system parameter, which can be controlled thanks to the *physical slots*[2] (PS) feature (in IEEE 802.16 PHY specification), which supports the splitting concept. The frame structure from the point of TDD and specific PHY, OFDM is discussed below.

2.2.5 Physical Layer

Four different PHY specifications are included in the IEEE 802.16-2004 standard which can work with the specified MAC. They are:

1. WirelessMAN SC
2. WirelessMAN SCa
3. WirelessMAN OFDM
4. WirelessMAN OFDMA

Both WirelessMAN SC and WirelessMAN SCa is based on single carrier (SC) technology, however, WirelessMAN SC is designed for operation in the 10-66 GHz frequency band and WirelessMAN SCa is for non-line-of-sight operation in frequency band below 11 GHz. According to the PHY specification of the IEEE 802.16 system, it can also use the OFDM technique as well as the extension of OFDM for multiple access technology which is called Orthogonal Frequency Division Multiple Access (OFDMA). In the former one, a single user uses the all sub-carriers, which is also present in the IEEE 802.11a. It can be denoted as *single-user* OFDM. In the later one, multiple users can share the subcarriers. It provides an additional dimension for scheduling the different users only in different time slots (in time domain) but also in different subcarriers (in frequency domain), expecting to gain on multi-user diversity. In this thesis, only OFDM is considered.

[2] a unit of time, depending on the PHY specification, for allocation resource.

2.2.5.1 WirelessMAN OFDM

WirelessMAN OFDM is specified for non-line-of-sight (NLOS) operation at the frequencies between 2 to 11 GHz.

2.2.5.2 Frame Structure

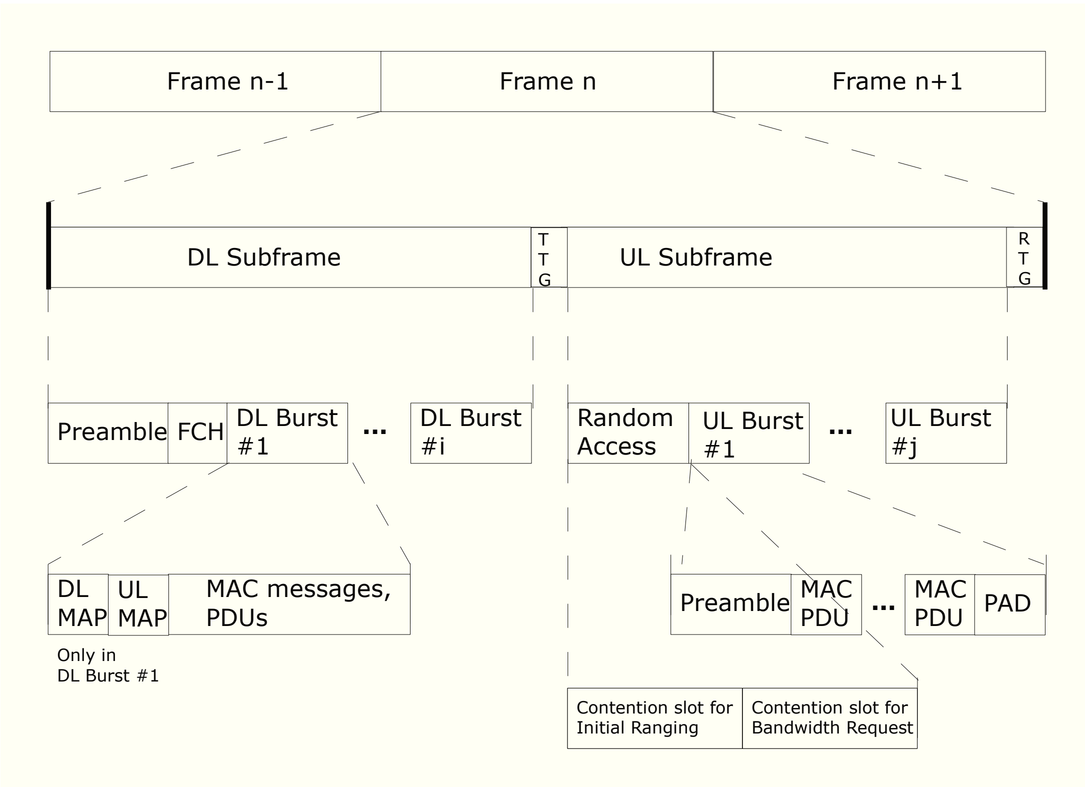


Figure 2.15: IEEE 802.16 Time Division Duplex (TDD) frame structure [60, 83, 88]

IEEE 802.16 supports FDD and TDD operation but TDD is mandatory for operation in unlicensed bands [84]. The IEEE 802.16 system follows a periodic MAC frame as shown in Figure 2.15. If TDD is used, each frame consists of a downlink (DL) and an uplink (UL) subframe. The Transmit Transition Gap (TTG) and the Receive Transition Gap (RTG) provide the required guard time for the transceiver to change from receive to transmit mode or the other way round.

Each frame, in this case also the downlink subframe, starts with a *preamble* followed by the *Frame Control Header* (FCH). The FCH is one OFDM symbol. Besides general information about the system, the FCH provides the first part of the socalled medium access pointer (MAP). The MAP is

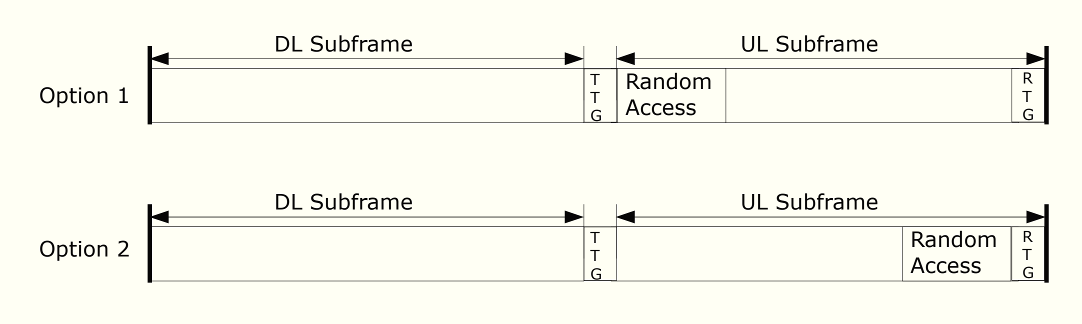


Figure 2.16: IEEE 802.16 Time Division Duplex (TDD) frame structure: two options

formed by the scheduler at the beginning of each frame deciding the exact structure of the current frame. It therefore contains the information describing which node should transmit or receive at which offset from frame start and which Modulation and Coding Scheme (MCS) should be used. As the FCH and the MAPs contain critical information that should reach all SSs, they are transmitted over a very reliable link, using MCS of BPSK rate 1/2. For the downlink, it inspects the queue and possible MCS for each subscriber station and grants it an appropriate share of the frame if possible. The DL MAP and UL MAP are transmitted in the first DL burst, followed by one or more *DL bursts* to transmit data from BS to SSs, both broadcast and unicast, in the forms shown in Figure 2.14. The allocation in each DL burst is corresponding to the Information Element (IE) of the DL MAP and each DL burst is transmitted in a particular MCS independent of other bursts. Bursts have a short preamble (one OFDM symbol) for synchronizing the SSs.

The uplink subframe comprises the following parts: *Initial ranging* is the contention based period which is used for initial access of the SSs into the network. *Bandwidth request contention slot* is used for sending bandwidth requests (traffic demands) by the SSs. For the uplink, the scheduler relies on information from the SSs to estimate their demands. Both these slots are also known as Random Access (RA) phase. The rest of the uplink subframe is filled with one or more *UL bursts* from different users. Each UL burst starts with a short preamble which is followed by UL resource allocations, where the SS is expected to transmit data, in the forms shown in Figure 2.14. The allocation in each UL burst is corresponding to the Information Element (IE) of the UL MAP and each UL burst is transmitted to the particular SS with a particular MCS assigned by the BS on a frame by frame basis, independent of other bursts [86].

Figure 2.16 illustrates two example structures of the frame where in the first example, the RA phase is followed by UL bursts whereas in the second example, it is the other way around. Note that the IEEE 802.16 frame structure is quite flexible to build.

The scheduling algorithm is not defined by the standard. It is common to fill the subframes by Protocol Data Units (PDUs) in ascending time order. Idle periods occur at the end of the downlink and uplink subframe if they are not fully utilized.

2.3 Channel Model

The performance of the wireless communication fundamentally depends on the radio channel, which is error-prone. The transmission path between the transmitter and the receiver is varied, from a small scale to a large scale, due to a number of reasons, which provides the random characteristic to the radio channel. The modeling of the radio channel is thus historically a difficult part of system design [91], where simplification is considered based on system design objectives. Basically, propagation models are studied to evaluate the radio channel in the system design. Three mutually independent and multiplicative propagation phenomena: *large scale pathloss*, *shadowing* and *multipath fading* are considered in the propagation model.

The pathloss is caused by the general physical phenomenon of signal attenuation resulting in gradual decrease of the received power at the receiver with the distance between the transmitter and the receiver, It is also the inverse-square proportional to the operational frequency.

The shadowing or shadow fading is caused by large nearby obstacles resulting in severe power loss due to diffraction. Shadowing is often denoted as *slow fading*. These two phenomena, the pathloss and the shadowing are also often known as *large scale fading* which is considered in the large scale propagation model.

The multipath fading is caused by the propagation of the signal over multipath due to several reflecting and scattering objects, resulting in variation of received signal strength over very small duration. It is often denoted as *fast fading* and also known as *small scale fading* which is considered in the small scale propagation model.

2.3.1 Propagation Model

The **generic model for received power**, P_R at the receiver due to *each transmission* is as follows:

$$\begin{array}{ll} P_R = \frac{P_T G_T G_R}{L_{path} L_T L_R} & \text{in Watt} \\ P_R = P_T + G_T + G_R - L_{path} - L_T - L_R & \text{in dB} \end{array} \tag{2.2}$$

where, P_T is the transmitted signal power, G_T and G_R are the antenna gains at the transmitter and the receiver, L_T and L_R are the system loss factors not due to propagation, rather due to transmission line attenuation, filter losses and antenna losses in the communication system in the transmitter and receiver side respectively. L_{path} is the overall propagation loss factor, which can be formulated as follows:

$$\begin{array}{ll} L_{path} = L_{PL} * L_{Sh} * L_{FF} & \\ L_{path} = L_{PL} + L_{Sh} + L_{FF} & \text{in dB} \end{array} \tag{2.3}$$

where, L_{PL} is the loss factor due to large scale pathloss, L_{Sh} is the loss factor due to shadowing and L_{FF} is the loss factor due to multipath fast fading.

Assuming a value of $L_{T/R} = 1$, means no losses due to system hardware and a value of $G_{T/R} = 1$, Equation 2.2 becomes

$$\begin{array}{ll} P_R = \frac{P_T}{L_{PL} L_{Sh} L_{FF}} & \text{in Watt} \\ P_R = P_T - L_{PL} - L_{Sh} - L_{FF} & \text{in dB.} \end{array} \tag{2.4}$$

Assuming that there is no loss due to shadowing and multipath, making $L_{Sh} = 1$ and $L_{FF} = 1$, Equation 2.2 becomes

$$P_R = \frac{P_T G_T G_R}{L_{PL} L_T L_R} \qquad \text{in Watt.} \tag{2.5}$$

Equation 2.5 is a different version of **Friis free space pathloss equation**, which is given as below

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 d^2 L} \text{ where, } \lambda = \frac{c}{f}. \tag{2.6}$$

Here, λ is the wavelength in meters, d is the distance between the transmitter and the receiver in meters, c is the light speed in meters/s, f is the carrier frequency in Hertz and $L = L_T * L_R$.

By assuming G_T, G_R and L equal to 1, the received power is given by

$$P_R = P_T \left(\frac{c}{4\pi f d} \right)^2. \tag{2.7}$$

So the pathloss L_{PL} is

$$L_{PL} = \frac{P_T}{P_R} = \left(\frac{4\pi f d}{c}\right)^2. \tag{2.8}$$

Considering d in km and f in MHz, the free space pathloss is

$$\begin{aligned} L_{PL} &= \left(\tfrac{4\pi f 10^6 d 10^3}{3.10^8}\right)^2 \\ &= \left(\tfrac{40\pi f d}{3}\right)^2, \end{aligned} \tag{2.9}$$

which can be written in dB as follows

$$\begin{aligned} L_{PL}(dB) &= 20log_{10}\left(\tfrac{40\pi}{3}\right) + 20log_{10}f + 20log_{10}d \\ &= 32.44 + 20log_{10}f + 20log_{10}d. \end{aligned} \tag{2.10}$$

It is clearly seen that for $d = 0$, Equation 2.6 does not hold. Hence, the propagation model applied a received power reference point, known as *close-in distance*, d_0 such that it lies in the far-field region, i.e, $d_0 > d_f$, where d_f is the the far-field distance [91]. Then the received power at any distance $d > d_0 > d_f$, $P_R(d)$ is calculated from $P_R(d_0)$ as follows

$$P_R(d) = P_R(d_0)\left(\tfrac{d_0}{d}\right)^2. \tag{2.11}$$

The practical pathloss estimation like **log-distance pathloss model** is discussed in the following.

$$L_{PL}(dB) = L_{PL}(d_0) + 10\gamma log_{10}\left(\tfrac{d}{d_0}\right) \tag{2.12}$$

where, $L_{PL}(d_0)$ is the free space path loss at close-in reference distance, d_0, γ is the path loss exponent which describes how fast the path loss increases with distance. Pathloss at $d_0 = 1m$ according to Equation 2.10 is

$$\begin{aligned} L_{PL}(d_0 = 1) &= 32.44 + 20log_{10}f + 20log_{10}(10^{-3}) \\ &= -27.56 + 20log_{10}f. \end{aligned} \tag{2.13}$$

Hence, the pathloss at any distance d according to Equation is

$$L_{PL}(dB) \quad = \quad -27.56 + 20log_{10}f + 10\gamma log_{10}d. \tag{2.14}$$

This is the **one-slope log-distance pathloss model**, which is considered in the framework of the thesis with γ equal to 3.5, representing the residential/indoor scenario. Figure B.3 in the Appendix shows the pathloss against distance.

The shadowing and the multipath are not considered in the simulation, that is why their models are not discussed here.

In general the received power is calculated using the propagation model stated above considering all the gain and the loss factors. If several concurrent transmissions are active, received power levels of to the intended signal and the unintended signal (interference) are calculated using the propagation model. Then the Signal to Interference plus Noise Ratio (SINR) is calculated for each intended transmission.

2.3.2 Signal to Interference plus Noise Ratio and Error Model

The SINR value is treated as the decision value whether a packet transmission is successful or not based on the error model.

When several concurrent transmissions are ongoing, which is most likely the case in the uncoordinated coexisting scenarios, the reception power of the intended signal is interfered by the interference power. This phenomenon has a great impact on the received power which is modeled by the SINR. The SINR is calculated for each link as follows. For simplicity, stationary conditions are considered, i.e. time dependency is not considered in the following.

Let the set of concurrent transmitting nodes is $\{n_{tx} : tx \in T\}$. If node $n_j, j \notin T$ receives intended packets from intended transmitting node $n_i, i \in T$, the SINR at node n_j is

$$SINR_{i,j} = \frac{P_{i,j}}{N + \sum_{k \in T, k \neq i} P_{k,j}} \tag{2.15}$$

where, $P_{i,j}$ is the received power of the intended signal, $P_{k,j}$ is the interference (received power of the unintended signal) and N is the background noise including thermal noise. The time-weighted average (TWA) SINR is considered in the simulation, discussed in Appendix B.3.

An error model, which is a link-to-system level interface, is implemented in the simulation based on a SINR to packet error mapping, taken into account the Modulation and Coding Scheme (MCS) as well as the packet length.

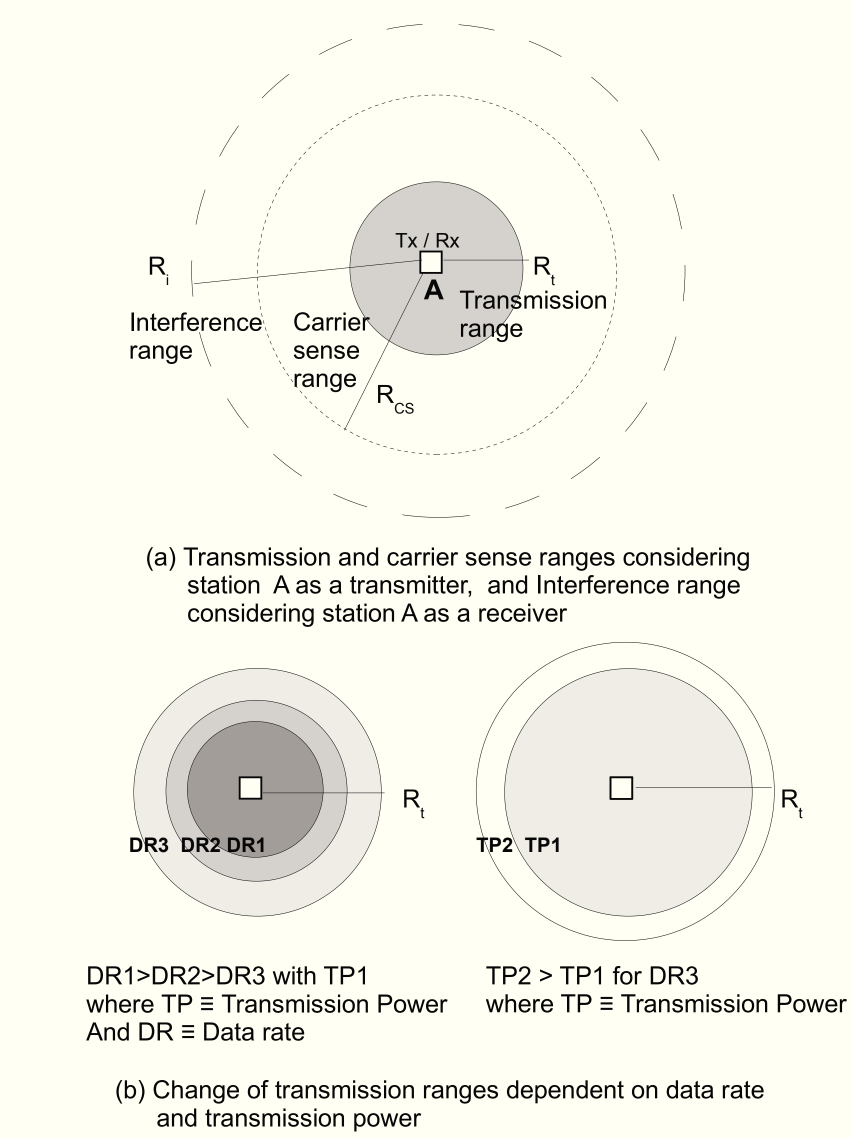


Figure 2.17: Wireless ranges: transmission, carrier sense and interference ranges

2.4 Wireless Ranges

When studying wireless networks, the influence of a wireless node on the RF environment around it is an important issue, which is realized by the physical wireless ranges. Figure 2.17.(a) shows three different kinds of wireless ranges from the context of a station located in the center which are discussed as follows.

Transmission range or data rate range: From the transmitter's point of view, the receiver (destination) up to this range can demodulate data packets from the transmitter, provided that no concurrent transmissions from other stations are ongoing. In other words, the received power up to this range is above the minimum receiver sensitivity level. This range depends on the transmission power and the supported data rate, which basically depends on the underlying Modulation and Coding Scheme (MCS). Figure 2.17.(b) shows the transmission ranges for the above two parameters in case of an omnidirectional antennea, where the radius R_t is generally considered as the transmission range. The higher the data rate, the lower the transmission range as shown in the left diagram. The higher the transmit power, the higher the transmission range which is shown in the right diagram.

Carrier sense range: From the transmitter's point of view, a station up to this range may not be able to demodulate data packets from the transmitter due to low RF receiving power, however, its carrier signal is strong enough to be sensed, provided that no concurrent transmissions from other stations are ongoing. This range depends on the carrier sense (CS) threshold, which does not vary with the data rate being used. The carrier sense range is observed in the IEEE 802.11 based networks, where the CS/CCA threshold is considered (Section 2.1.5.2). For the wireless networks where the carrier sensing method is not deployed like in the legacy IEEE 802.16, the carrier sense range is not relevant.

Interference range: When a transmission is ongoing between stations in their transmission ranges, any other transmission from a third station (interferer) in the interference range of the receiving station can corrupt the data packets destined to the receiving station. The interference range of a receiver cannot be precisely estimated [104]. In Figure 2.17.(a) the interfering station can be located anywhere inside the inference range of R_i, considering the receiving station is located in the center. Assuming a fixed distance between the transmitter and the receiver and a fixed transmit power level, the interference range is correlated with the power of the interferer and the propagation path condition from the interferer to the receiver. If the potential interfering station follows carrier sensing (like in the IEEE 802.11 system), then interference is avoided if the potential interfering station is inside the carrier sense range of the transmitter. However, the 'access deferral', mentioned in Section 2.1.4.3, due to carrier sensing results in increased delay and jitter in transmitting packets, which are often considered as different forms of interference.

CHAPTER 3

SPECTRUM SHARING

Radio spectrum is the primary resource for wireless communication. So, its regulation is an important task, from which the spectrum licensing concept was evolved in the last century. However, with mature technologies and with their continuous improvements in different aspects in the modern world, it becomes apparent that tight licensing might no longer be required for all wireless services. That is the reason which originates the concept of using the unlicensed bands for wireless communication. In an unlicensed band, several wireless technologies can operate in coexistence. Tremendous success in such a coexistence of technologies in unlicensed bands stimulates the concept of open spectrum: Dynamic spectrum sharing among collocated wireless systems is one of the requirements for open spectrum. Hence, spectrum sharing has already become a hot topic in the wireless area to deal with, and several groups, from academia, industry and standardization, are devoting their efforts to this topic. Different enabling techniques are identified for spectrum sharing. In this chapter, the above points are discussed in detail to have a comprehensive overview.

The structure of this chapter is as follows. Section 3.1 gives the introduction of the radio spectrum and how wireless communication is consuming the available radio spectrum. The importance of radio spectrum sharing is introduced in Section 3.2, followed by descriptions of the current state of the art and standardization initiatives towards spectrum sharing in Section 3.3 and the enabling techniques in this respect in Section 3.4. The chapter is summarized in Section 3.5.

3.1 Spectrum Bands

Electromagnetic (EM) radiation is classified by wavelength into EM waves, which are then classified into different regions of the electromagnetic spectrum shown in Figure 3.1. Almost the full range of spectrum bands is shown to give an overview based on [101]. In the EM spectrum, the range from 3 kHz to 300 GHz is very often called radio wave spectrum. The radio spectrum, in short spectrum, is the most important and fundamental resource for wireless communication.

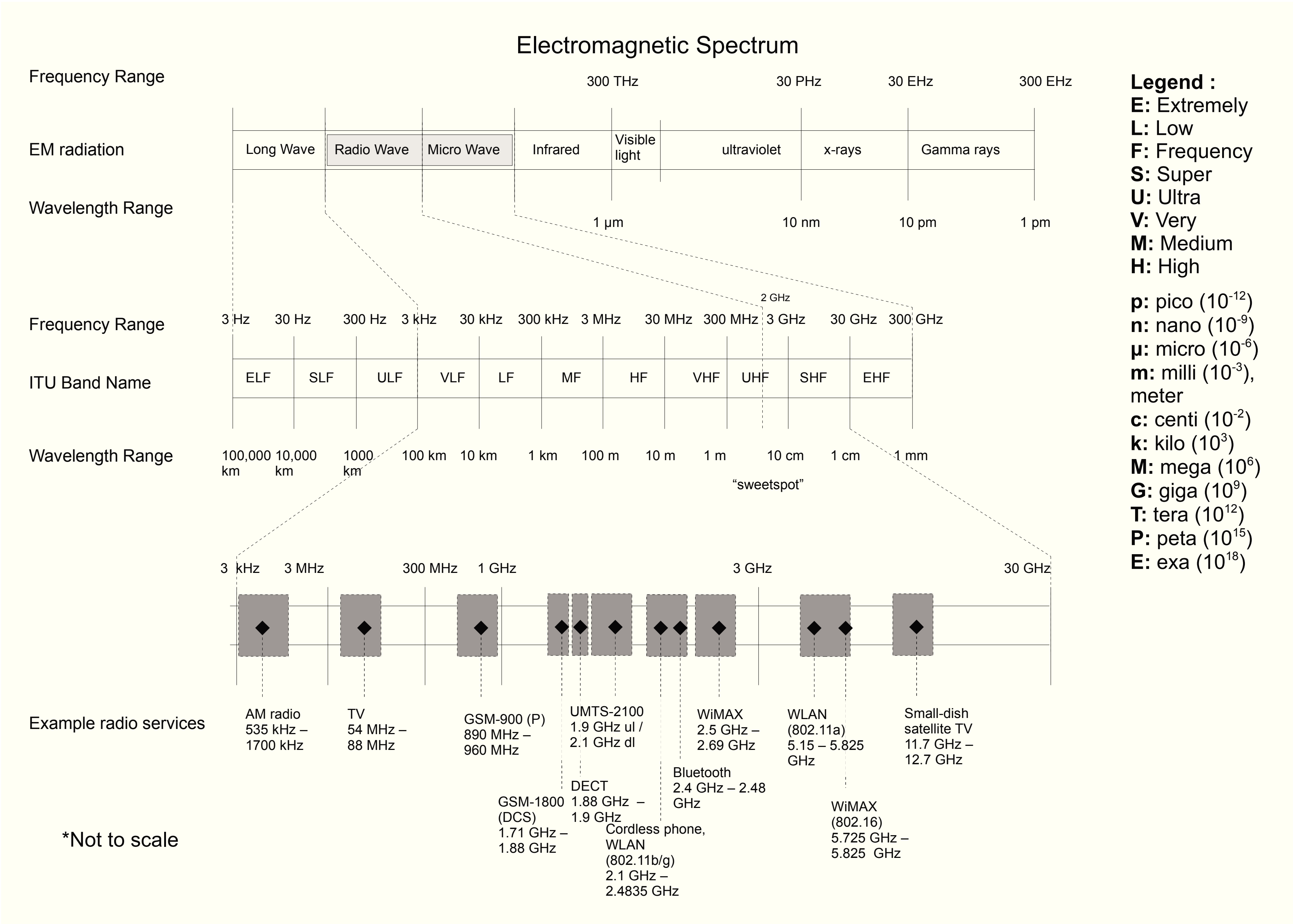


Figure 3.1: Electromagnetic spectrum bands [101]

Almost all new wireless technologies use radio wave spectrum for communication. In the figure, several examples of radio based services are shown with their predefined spectrum allocations. For instance, television broadcasting uses the 54-88 MHz band for channel 2 to 6, Wireless Local Area Networks (WLAN) operate in the 2.4 and 5 GHz band. Sometimes, one band is not fixed for a particular service, which is generally the case for unlicensed bands, like the 2.4 GHz ISM band, which is used by several services, like WLAN and Bluetooth, even can be used by WiMAX.

The regulatory authorities in different countries around the globe, for example, the Federal Communications Commission (FCC) in the United States of America and the Federal Network Agency (known as 'Bundesnetzagentur') in Germany, are responsible for managing and licensing the spectrum for commercial and non-commercial usage inside the country. In licensing the spectrum, they classify the services, e.g., public safety, television broadcast and radio, commercial mobile service, military service, etc., allocate specific spectrum bands for these services, and also specify transmission parameters, e.g., transmit power, transmit spectrum mask, etc.

In the process of spectrum licensing, the radio spectrum is categorized into licensed and unlicensed bands.

3.1.1 Licensed Bands

Licensed bands are only allowed to be used exclusively by the license holders after paying a licensing fee to have this right. This exclusive right provides the protection from being interfered by other systems/services from other entities on these bands. This ensures the license holder to design and provide the services on these bands by utilizing the spectrum efficiently from its perspective and have the advantage to maximize the reliability. For example, the cellular networks industry and service providers invested hundreds of millions of dollars to operate in the 900 MHz band and the 2.1 GHz band (aka GSM-900 and UMTS-2100 respectively, shown in Figure 3.1). The wireless industry launched commercial products for WiMAX in licensed bands (i.e., 2.3 GHz, 2.5 GHz, and 3.5 GHz). However, as an end effect, the consumers, the end users, are billed to pay for using these bands following the business model.

3.1.2 Unlicensed Bands

On the contrary, unlicensed or license-exempt bands are not restricted for use by only one entity through a spectrum licensing approach. They are allowed to be used free of cost by any person or entity to provide/build a license free network at any time for either private or public purposes including commercial high speed Internet service, however, without infringing the rules for the equipment or its use. These bands have pre-defined technical rules for both the hardware and deployment methods of the radio to mitigate interference, like transmission with low spectral density, so that the interference level is kept at a minimum when there are other users in the area [16].

A group of unlicensed bands is known as Industrial, Scientific and Medical (ISM) bands, which were originally reserved internationally for the use of RF energy for industrial, scientific and medical purposes and which can be used by anybody without a license in most countries. Currently, the ISM band is being used by many different technologies and services. According to [4], the FCC Rules, which are known as Part 15.247 opened up the ISM bands for wireless LANs and mobile communications in 1985. Later in 1997, the FCC Rules, which are known as Part 15.407, opened up additional bands in the 5 GHz range, known as the Unlicensed National Information Infrastructure (U-NII). The 2.4 GHz (2.4-2.4835 GHz) ISM band is used by systems like IEEE 802.11b/g based WLAN, microwave ovens, Bluetooth, and cordless phones.

The 5 GHz (5.15-5.825 GHz) ISM band is used by IEEE 802.11a, and HIPERLAN/2 based WLAN. This band is also known as the UNII band, and has 4 sub-bands, UNII1 (5.150-5.250 GHz), UNII2 (5.250-5.350 GHz), UNII2 extended band by ETSI (5.470-5.725 GHz) and UNII3 (5.725-5.825 GHz) [3]. UNII3 has been authorized to deliver enough power for last mile delivery, which already attracts WiMAX operators and providers to deploy their networks in 5.8 GHz spectrum.

3.1.3 Open Spectrum

The process of licensing and regulations was started at the beginning of the last century, when the whole radio industry and technology was immature. At that time, radio receivers complied with only one signal at a time and the sensitivity of the receiver was quite low, so that the receiver cannot differentiate the received signal if the power is not significantly higher than the noise level and/or power from any other signal that is near the same frequency. So the main problem was not the interference, rather the available technology at that time. Analog circuits are one example of such a short coming, where even guard bands are required. However, due to the above reasons, the idea of regulation was triggered by the industry to ensure that each carrier frequency is allocated for each user or entity in the same geographical area. This exclusive concept of spectrum and interference lasted for such a long time, that still the regulatory 'command and control' model is in people's mind to protect one entity from interference of others, though the technology is quite mature now. By today's technological improvement in different areas, like low-priced integrated circuits (microchips) consisting of millions of transistors, new modulation and coding techniques, powerful digital signal processing methods, transmitters and receivers have the capability to differentiate their own signal from other signals. These tremendous improvements open the door for new concepts and technologies to share spectrum in multiple dimensions, like frequency, time, space and coding, rather than sticking to the traditional concept of particular frequency channels, resulting in creating a huge amount of new capacity [24, 72]. These dimensions are described in detail in Section 6.1.

Open spectrum is a set of new concepts and radio technologies that would help to dynamically manage the spectrum access (and, thus spectrum sharing), with the context of opening up more of the spectrum for unlicensed use. Open spectrum initiative is driven by Open Spectrum Alliance. It is believed that open spectrum will create a revolution in the communication industry, just like open standards and open software did in the networking and computing industry [24]. This would create a significant new capacity within existing spectrum, where new users can co-exist with legacy spectrum users. The story behind this new concept is the tremendous success of the IEEE 802.11 standard and technology, which creates a multi-billion industry by its innovative methods of operation in the unlicensed band, where many other users from other technologies co-exist. Due to the same reason, the heads of FCC have even showed interest about the importance of unlicensed spectrum and remarked that it would play a key role in stimulating innovation. Commercially successful xG Technology's xMax mobile VoIP and broadband technology [22], which operated in the unlicensed bands, represents a good example of such innovation. It is also able to give an encouraging business model in unlicensed band where innovation and business meet each other.

3.2 Towards Spectrum Sharing

There are basically two issues the wireless industry has to deal with:

1. It is quite apparent from the above section that the actual problem is not mainly due to limited spectrum, but rather artificial scarcity due to poor utilization resulting from the spectrum use policy provided by current methods of spectrum regulation.
2. According to a survey and recommendation by the Wireless World

> Research Forum (WWRF) [1] in [103], 7 trillion wireless devices will be serving 7 billion users by 2017, which actually means 1000 wireless devices per person. This is quite a big number, however, from the understanding of the author, the vast majority of these devices will be short-range wireless communication systems.

To meet this fast-growing demand for wireless communications with the limited radio spectrum, on the one hand, promising new steps have to be taken in the regulatory command and control method by means of opening up more spectrum for unlicensed use, and on the other hand, efficient and intelligent spectrum sharing methods amongst multiple services and radio networks are needed to be developed. In the first case, regulatory bodies have to take steps, whereas manufacturers, vendors, and service providers can fuel and promote the process with their innovations in the second case.

In the next section, different initiatives for new ideas and concept towards spectrum sharing are presented.

3.3 The Drivers to Dynamic Spectrum Sharing

In this section, several initiatives and initiators are described as the drivers to spectrum sharing as they show some promising and valuable examples towards dynamic spectrum sharing. State of the art as well as the standardization process in this context is described in the following.

3.3.1 State of the Art

Dynamic spectrum access and spectrum sharing is currently a huge concern for researchers from the field of communication technology. Two research projects in this respect are discussed below.

3.3.1.1 DARPA–XG

The Defense Advanced Research Projects Agency (DARPA) neXt Generation (XG) communication program presents an intelligent spectrum access technology to the public.[1] XG denotes the opportunistic spectrum access technology and develops the opportunistic use of wasted spectrum both in space and time in such a way that interference to the primary (incumbent) user will be reduced. For example, this can be an adaptive radio technique to use an unoccupied TV-band. XG program published Requests for Comments

[1] It should be made clear at this point, that xG Technology mentioned before has no connection with DARPA XG.

(RFCs) describing the vision, system architecture and policy architecture in [27, 25, 28].

The DARPA documents include the terms 'policy' and 'protocol' which are of major importance throughout all considerations. Policy means behavioral rules how a system should react to varying conditions inside the frequency spectrum which it is using. A policy can be, for example, a rule such as 'if a TV signal is sensed on the current frequency, then the transmission range must not be higher than 20 meters'. It is then up to the station how it actually implements this policy by using a protocol. In the above policy example, the station might check if it is possible to reduce the transmitter power to a level which meets the above criteria but is still sufficiently high to continue the communication with the partner station. Another option might be to switch to another frequency channel for which the policy given above does not apply. It can be seen that the policy is an abstraction of the actual protocol: the policy describes a goal, but not how to achieve it, which is performed by the protocol.

Another important term, 'spectrum' is highlighted in the XG context, which means any resource which is used or can be modified when performing a wireless communication; thus, it means not only frequency but also transmitter power, modulation scheme, channel bandwidth, channel allocation in the time domain, etc.

In traditional radio systems operating policies are hard or soft coded with protocols and any change in policies would require re-design, re-implementat- ion and re-accreditation. However, according to XG, a radio could be made policy agile by decoupling the policies from behaviors, behaviors from protocols and protocols from their implementations and these policies could be changed dynamically. To change the policies, the radio part should have the capability to read and interpret the spectrum policies (published by a spectrum authority) which are encoded in a machine interpretable form and can be loaded into the XG radio using smart media or over the Internet.

3.3.1.2 E3

The End-to-End Efficiency (E3) project is a Large Scale Integrated Project (IP) of the 7th Framework Programme of the European Commission. The main aim of the project is to facilitate the efficient introduction of the concept of cognitive wireless systems in the Beyond 3G (B3G) wireless world, where heterogeneous wireless system infrastructures are considered. Some of the results of the project are: the market assessment and the business models, the overall E3 Functional System Architecture, cognitive dynamic spectrum management, Cognitive Pilot Channel (CPC) concept, spectrum sensing methods. E3 provides contributions to the standardization work like ETSI, IEEE and influences the regulations area, like providing contributions to CEPT (European Conference of Postal and Telecommunications Administrations) and ITU (International Telecommunication Union).

3.3.2 The Standards

Successful studies and innovations in the field of dynamic spectrum access, sharing, cognitive radio, software defined radio have triggered the standardization initiatives. Some of them are listed below.

3.3.2.1 IEEE Standards Coordinating Committee 41

SCC41 [9] is working in the areas: dynamic spectrum access, cognitive radio, interference management, coordination of wireless systems, advanced spectrum management, and policy languages for next generation radio systems. It is giving its potential to develop standards related to Dynamic Spectrum Access (DSA) and Cognitive Radio (CR), focusing on the capacity enhancement and improved utilization of spectrum. In 2005, the IEEE 1900 Standards Committee was established with the objective of developing supporting standards for dealing with new technologies and techniques being developed for next generation radio and advanced spectrum management. In 2007, the IEEE 1900 Committee ceased and the work of the IEEE 1900.x Working Groups (WGs) continued under SCC41. The IEEE SCC41 is particularly interested in ideas that could be implemented in commercial products in the near to medium term, which is targeted as 2 to 3 years, according to the IEEE SCC41 Chair [11]. The working domains of the IEEE 1900.x WGs are briefly discussed in Appendix A.4.

3.3.2.2 ITU-R Working Party 1B

International Telecommunication Union (ITU) is the agency of the United Nations for information and communication technology (ICT). Managing the international radio-frequency spectrum and satellite orbit resources is at the heart of the work of the ITU Radiocommunication Sector (ITU-R). Study Group 1 (SG 1) of the ITU-R is responsible for spectrum management principles and techniques, general principles of spectrum sharing, spectrum monitoring, long-term strategies for spectrum utilization, economic approaches to national spectrum management. Working Party 1B (WP 1B) [13] is created under SG 1 to develop the definitions of software defined radio and cognitive radio systems, to identify potential regulatory issues associated with SDR and CR Systems, and to innovate related concepts such as the Cognition supporting Pilot Channel. Working Party 1C (WP 1C) is responsible for issues on spectrum monitoring.

3.3.2.3 ETSI - Reconfigurable Radio Systems

The European Telecommunications Standards Institute (ETSI) produces globally-applicable standards for Information and Communication Technologies. The ETSI Board decided to create a Technical Committee for Reconfigurable Radio Systems (RRS) in January 2008 with the aim of studying the feasibility of standardization activities related to RRS, a generic concept based on technologies such as Software Defined Radio (SDR) and Cognitive Radio (CR) [6]. There is great interest in cognitive radio technologies in Europe similar to the rest of the world. Based on the outcomes of feasibility, the ETSI Board will then decide on a possible continuation into actual standardization activities. Four working groups are structured under TC RRS.

3.4 Enabling Techniques towards Cognitive Dynamic Spectrum Sharing

The following methods and concepts are identified as enabling techniques for dynamic spectrum sharing.

- **Spectrum Sensing and Measurement Method:** Spectrum Sensing and Measurement Methods are considered as the enabler techniques for spectrum sharing, because by these methods, the knowledge about the wireless environment can be obtained. Further processing and management of this gained knowledge is needed to detect the presence of other wireless systems and to perform estimation of relevant parameters. In the framework of this thesis, sensing methods are developed including the detection of signals from other systems followed by system identification techniques and estimation of traffic demand. In Chapter 5 those methods are described in detail.
- **Software Defined Radio:** A Software Defined Radio (SDR) is a radio system in which operating parameters like transmission frequency, modulation type, and maximum radiated power can be reconfigured without making any hardware changes, which was previously not possible in traditional radio or adjusted manually. Enhancements in SDR

technology have the potential to facilitate dynamic spectrum sharing. Chapter 6 is related to this topic.

- **Adaptive Method:** An adaptive method is defined as a method where operating parameters are updated or reconfigured during the operating time of the system, where the method is invoked. Facilitating the method with continuously updating the parameters based on a specific strategy would increase the performance. The contribution from the author in this direction is provided in Chapters 6, 8 and 9.
- **Cooperative Communication Method:** During the spectrum sharing, a cooperation between the systems is expected to increase the overall performance. The benefits of cooperative communication in wireless networks are provided in [48]. The generic method developed in this thesis is originated by keeping the idea of cooperation between the systems. The hypothesis considered in the generic method is: *Regular channel occupation by one system in the time domain, can support other systems to detect and reliably predict spectrum opportunities (idle periods) and utilize idle periods efficiently, resulting in fair sharing as well as a better accumulated performance.*
- **Policy based Adaptation Method:** Like in the DARPA XG concept, the usage of policy regulated methods to reconfigure the system parameters is considered as an enabling technique. The application of policy in multi-layer and in multi-scale, would help the service providers and operators (intra and inter level) to update the spectrum sharing policy whenever required in a flexible way.

3.5 Conclusion

In this chapter, electromagnetic spectrum bands (3 Hz - 300 EHz) are shown with an emphasis on the radio spectrum band (3 kHz - 30 GHz). Operational spectrum bands for selected wireless technologies are illustrated in Figure 3.1 showing the unlicensed bands where operation of different technologies is overlapping. It is already proven that there is a great opportunity to innovate techniques on these overlapping bands and exemplary business models are already available. This leads the open spectrum and the spectrum sharing concepts to become a field of interest to the wireless community. The work of some of those groups are presented in this chapter, ending with promising related supportive methods towards spectrum sharing.

CHAPTER 4

COEXISTENCE SCENARIOS

The future coexistence scenarios from the perspective of wireless networks and a systematic analysis of such scenarios for academic research are the foci of this chapter. The integration of wireless communication in consumer electronic devices is increasing, and the acceptance of those devices in day to day human lives is increasing as well, which results in a situation where different wireless networks/systems are coexisting, where underlying technologies also differ like IEEE 802.11 or IEEE 802.16. An analysis of such a scenario, denoted as a Metropolitan Scenario, is shown, which inspires to develop a scenario matrix to describe and to study the overall scenario part by part. Example scenarios are defined and it is shown for those parts how to map them to the real world.

The structure of this chapter is as follows. The chapter begins by highlighting several new application scenarios in medium to long range wireless communication in Section 4.1. Section 4.2 introduces a future wireless networks deployment scenario with the consideration of those applications. The scenario matrix is described in Section 4.3. Two specific coexistence scenarios located in apartment and office buildings are characterized in Section 4.4. The related work considering the coexistence and interference analysis is given in Section 4.5, followed by the evaluation methodology considered in this thesis in Section 4.6. Section 4.7 summarizes the chapter.

4.1 The Future of Wireless Connectivity

Day by day more values are added in the consumer electronic devices by enabling wireless network connectivity. There are plenty of devices and services available based on wireless communication. Some few examples are as follows.

- Having the IEEE 802.11 based wireless LAN interface in laptops and notebooks, users are now enjoying the mobility, which eventually make them more flexible. Users do not have to sit/stay in a static location to be able to connect to the Internet via wired links.

- Including IEEE 802.11/Wi-Fi in digital cameras allows users to send photos directly to social networking sites more easily and quickly.
- Printing wirelessly has also become common by means of IEEE 802.11 enabled printers.
- The concept of Wireless Display (WiDi) is an innovation which is being introduced to users to view and share content on the big screen at home wirelessly from their PC hard disks or any other active storage devices connected to the home network, or even from different location via the router connected to the Internet.
- IEEE 802.11 based High Fidelity (HiFi) systems add a new dimension in home entertainment by having audio content as streaming or file transfer.

These are a few examples in medium range wireless communication. On the other hand, the applications and the benefits of the long range wireless communication based on IEEE 802.16/WiMAX are as high as the medium range.

- Many application scenarios including Wireless Local Loop (WLL) and 'Wireless DSL' have already been studied. Though Wireless DSL (WDSL) is a misnomer because DSL technically requires copper wires, the term became popular, meaning high speed Internet connection over the radio signals rather than wires. The IEEE 802.16 technology, developed for Broadband Wireless Access (BWA) fits perfectly to provide a solution like WDSL in the area where the infrastructure network is not yet present. On the other hand, the IEEE 802.16 base station connected to the backbone (Internet or PSTN), could easily provide the last mile solution (as WLL) to subscriber equipment without the need for an expensive and extensive wireline solution, shown in the next section.
- In [54] application scenarios like environment monitoring, fire prevention, tele-medicine and tele-hospitalization running on top of the mobile WiMAX are described with corresponding end-to-end architectures.
- The application of WiMAX technology in the education sector is described in [18] as briefly discussed in the following. On the one side, implementing a district-wide wireless broadband internet access network utilizing the WiMAX technology will bridge the digital divide in most schools not only in developing countries but also in developed countries, on the other side, it will help the students by giving access

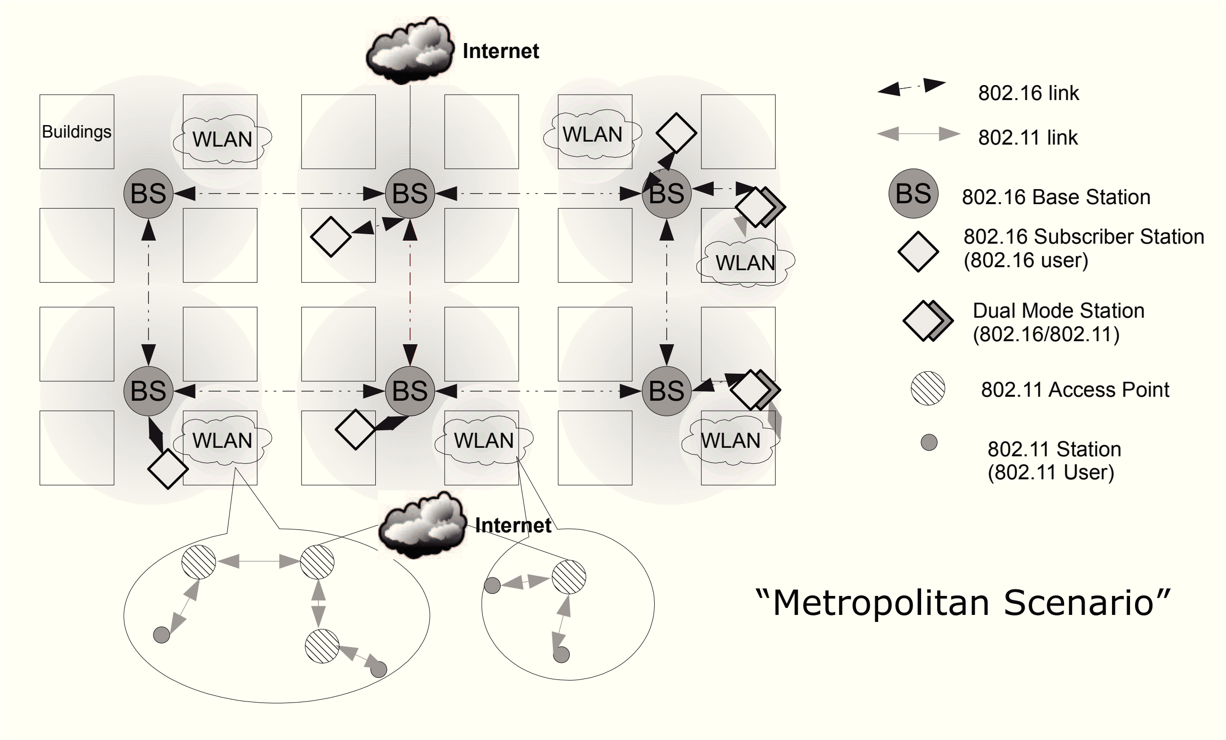


Figure 4.1: Possible future metropolitan scenario

to vast academic contents in the Internet.

- The smart grid companies are going to use the WiMAX technology in their electricity networks to monitor smart-meters in homes and to monitor the power outage in their energy distribution. [5, 10] are two examples in this context, where additional applications like power distribution automation and power station monitoring are also planned to be integrated by using WiMAX solutions.

The density of wireless based devices is increasing tremendously due to all of the above application scenarios. A prediction by the Wireless World Research Forum on the number of wireless devices is given in section 3.2.

4.2 Metropolitan Scenario Analysis

Considering all these present and future application scenarios, a possible future deployment scenario is depicted in Figure 4.1, which is denoted as *Metropolitan Scenario* by the author in [78]. In the figure, two different types of wireless technology are considered as shown: IEEE 802.11 and IEEE 802.16. The squares in the figure are representing buildings. In the scenario, on the one hand, IEEE 802.16 Base Stations (BSs) are providing services

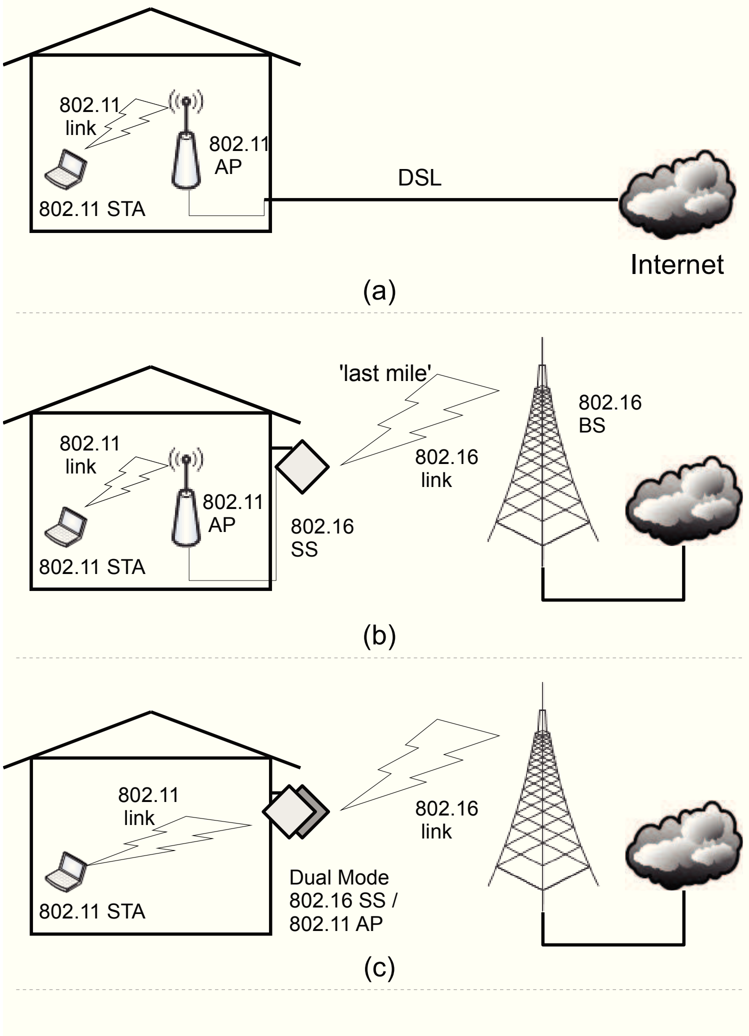


Figure 4.2: Different deployment scenarios of IEEE 802.11 and IEEE 802.16 based networks: IEEE 802.11 network connected to the Internet via
(a) Wired DSL
(b) Wireless IEEE 802.16 based link
(c) Dual-mode station, bridging IEEE 802.11 and 802.16 networks

to local Subscriber Stations (SSs), and on the other hand, they are in some cases acting as relay stations. In some cases, a SS provides services to the IEEE 802.11 based WLAN. For IEEE 802.11 networks, two types of network are possible: ad-hoc or infrastructure mode. Connecting to the gateway to the Internet two options are possible: gateway router connected to the wired backbone (DSL) or the wireless backbone (e.g., IEEE 802.16 network).

In Figure 4.2, the 'Metropolitan Scenario' is broken down into smaller parts showing different possible selected combinations, keeping in mind that other combinations are possible as well, for example, IEEE 802.11 ad hoc networks, standalone IEEE 802.16 link are not considered here. the Standalone IEEE 802.16 link means the connection between the IEEE 802.16 SS chipset enabled user devices and IEEE 802.16 BS. In the figure, (a) and (b) show more clearly the two cases where an IEEE 802.11 based network is connected to the Internet via DSL and a last mile connection provided by an IEEE 802.16 based network respectively. For the second case, The IEEE 802.11 Access Point (AP) is connected to the IEEE 802.16 SS by Ethernet wire. In this case, AP and SS are considered as single mode stations as they can only receive and understand messages from their own protocols. From this point, a concept of another possibility is evolved considering the dual-mode stations shown in Figure 4.2.(c), which can be denoted as 'SS/AP', acting as IEEE 802.16 SS and IEEE 802.11 AP. Dual mode stations are

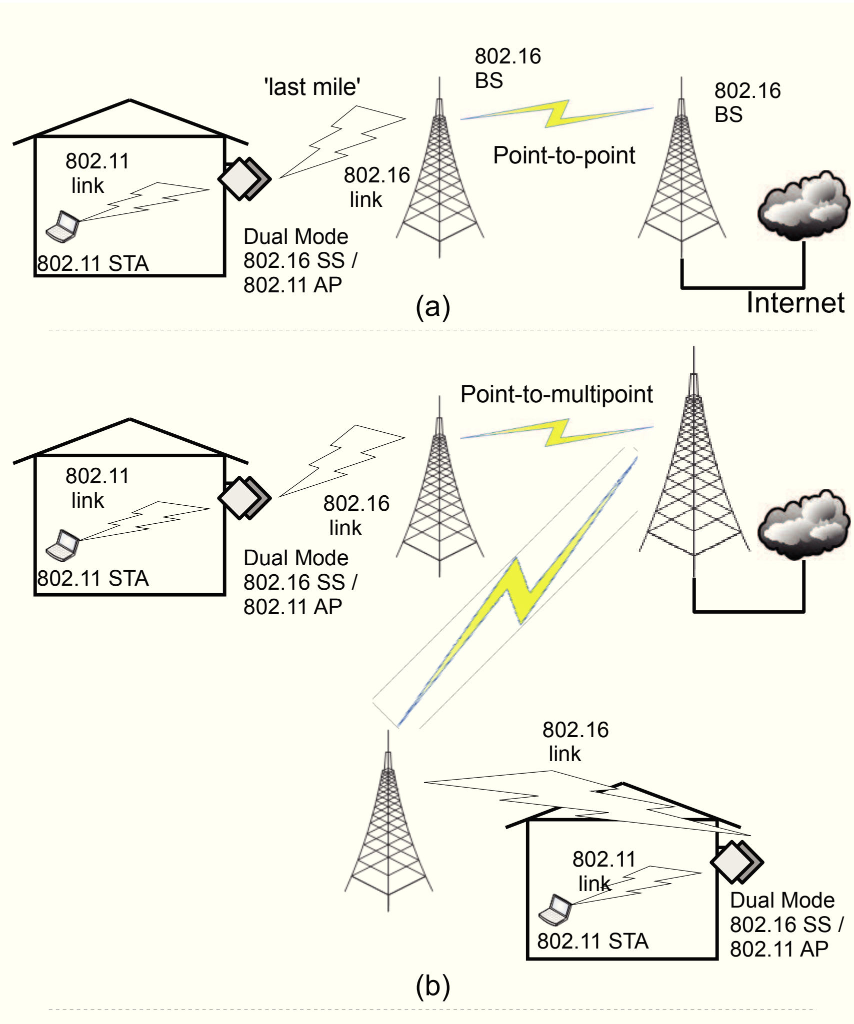


Figure 4.3: (a) Point-to-point (b) point-to-multipoint IEEE 802.16 backhaul connections

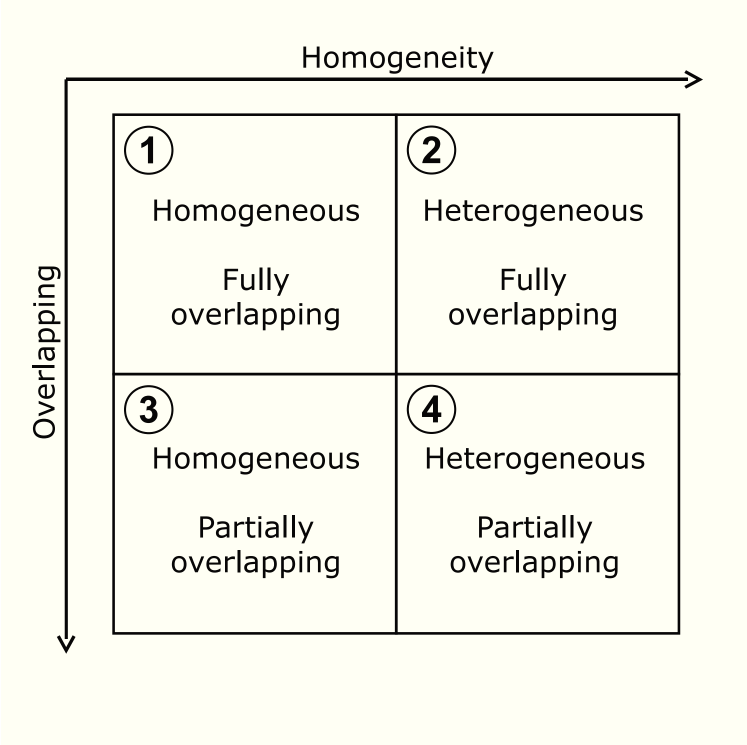


Figure 4.4: Scenario matrix [84]

able to participate in both the IEEE 802.16 and the IEEE 802.11 network; they can receive and understand messages from the both protocols and are allowed to transmit either specific control messages only or all kinds of messages, including data frames, to both networks. In the rest of the document all the stations considered are single mode stations having a single interface unless specified differently.

The relay enhanced IEEE 802.16 WiMAX backbone networks can increase the coverage area as already shown in Figure 4.1. The relays could amplify or decode the signal. Relays could have point-to-point or point-to-multipoint wireless connections to build the backbone as shown in Figure 4.3(a) and Figure 4.3(b). Principally the same concept of a relay network could also be possible in the case of IEEE 802.11 based networks as shown in the figure, however the coverage area is expected to be smaller than in the case of IEEE 802.16 based networks.

From a research point of view, the whole scenario as shown in Figure 4.1 is quite a challenge to be investigated. Therefore, an idea of developing a scenario matrix is done as the first step to study the overall scenario on a case by case basis, which is described in the following.

4.3 Scenario Matrix

A matrix describing the key research directions considering the coexistence scenarios and the properties of the scenarios is shown in Figure 4.4. The dimensions of the matrix are homogeneity and degree of overlapping of coexistent systems. Homogeneity addresses the scenario deployments to contain systems of the same technology and standard, for example only IEEE 802.11 or only IEEE 802.16 systems (in case of coexistence of homogeneous systems), or to contain systems according to different standards (where heterogeneous systems have to coexist). The major two technologies considered in the scenario matrix are described below.

- **IEEE 802.11 WLAN**: Medium access techniques follow carrier sensing which is discussed in Section 2.1.4. In the case of legacy IEEE 802.11, the Distributed Coordination Function (DCF) is applied by the stations in the networks. However, in the extended case with IEEE 802.11e, a centrally controlled channel access mechanism is also provided as an option. Data transmission in the case of IEEE 802.11 is bidirectional, i.e., an Automatic Repeat Request (ARQ) concept is standardized and required to be implemented in the MAC layer irrespective of any ARQ implementation on a higher layer, e.g., in the transport layer. Generally each packet is acknowledged by sending an ACK packet from the receiver after a Short Interframe Space (SIFS). In some cases, a block ACK concept could also be used to reduce overhead.
- **IEEE 802.16 WiMAX**: Carrier sensing is not the part of the IEEE 802.16 standard like in IEEE 802.11. However, in the IEEE 802.16h standard [68], a carrier sensing concept is introduced. The IEEE 802.16 stations follow the centrally controlled channel access mechanism where the BS acts as the central coordinator. Details of IEEE 802.16 medium channel access are given in Section 2.2.4. Here, the uplink and downlink are split and dynamically adjusted.

Overlapping refers to the degree that systems overlap each other with respect to their coverage area.

- **Fully overlapping**: In a fully overlapping scenario, any simultaneous transmission by any node of one system causes interference to the nodes in the other system, so that transmitted data might not be received successfully. This scenario has the advantage that all nodes of the systems can observe the state of the common radio channel, i.e., the base station or the access point has the full knowledge of the

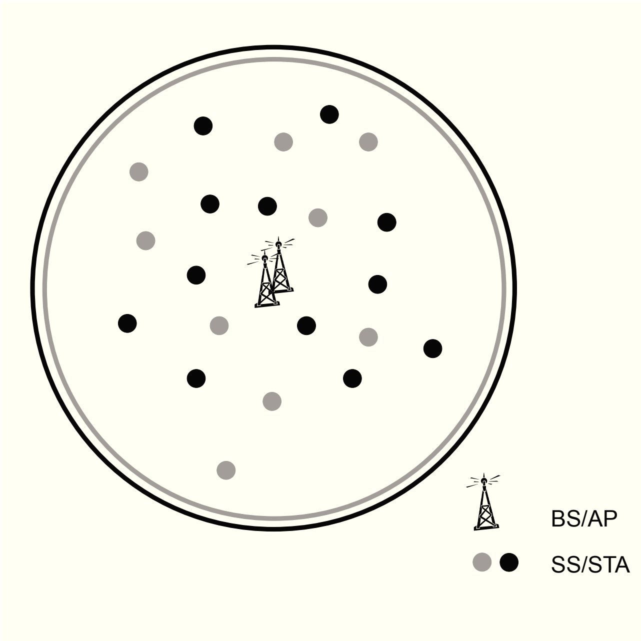


Figure 4.5: Fully overlapping scenario

wireless environment. However, spatial reuse might not be possible in such a scenario. In the case of fully overlapping WLANs scenario, all the stations are inside the carrier sense ranges (see Section 2.4) of each other.

- **Partially overlapping**: In a partially overlapping scenario, nodes of the systems involved can only have partial knowledge about their radio environment, i.e., the base station or the access point does not have the full knowledge of the wireless environment. In this case, not all stations interfere with each other. They may benefit from the fact that radio links far distant from each other can operate simultaneously with low mutual interference. Spatial reuse could be possible, for example, spatial reuse TDMA (STDMA) [40].

When two systems have two different coverage ranges, e.g., in the case of a heterogeneous coexisting scenario consisting of IEEE 802.16 and IEEE 802.11 based systems, the consideration of overlapping differs from the perspective of systems. For example, generally IEEE 802.16 has a large coverage area and an IEEE 802.11 based system has a smaller coverage area. In the case where the smaller area is completely located inside the larger one, the IEEE 802.11 system is considered to be inside a fully overlapping scenario, whereas the IEEE 802.16 system is considered to be inside a partially overlapping scenario. Figure 9.26 illustrates such a case in Section 9.5.

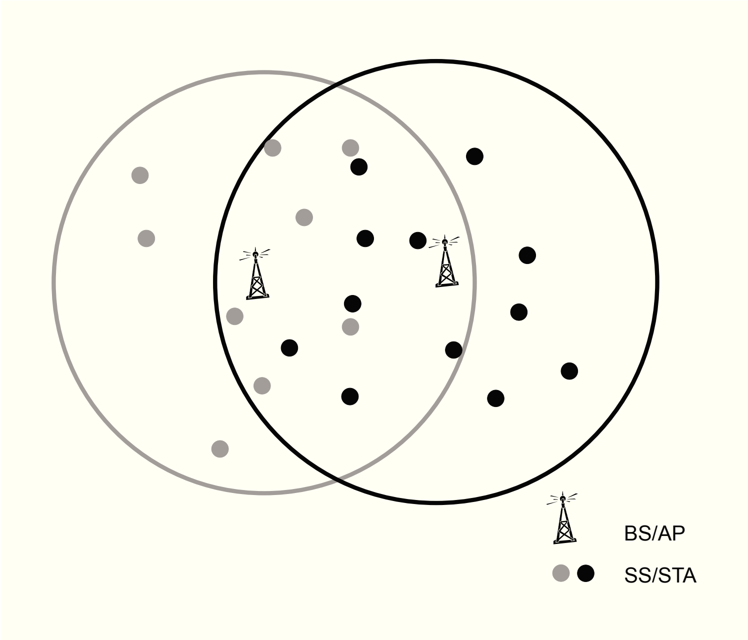


Figure 4.6: Partially overlapping scenario

The matrix can be extended to another dimension considering the existence of relays in the networks, however, this is not considered in the framework of this thesis.

4.4 Mapping to the Real World

In the context of wireless facilities in a building, in the best cases it could be assumed that the setup of wireless local area networks in the building is done centrally. This includes frequency planning of the base stations to cover the full (office/apartment) building to maximize the performance. However, this is not the case in reality. Every company in a building has its own wireless network setup. In such a case, the networks are generally uncoordinated from the context of frequency planning. In the case of an apartment building, a centrally controlled wireless facility is rather challenging as the inhabitants of the building have their own freedom of choice to select the operators. This makes the concept of centralized control of frequency planning complex and in most cases not feasible in practice.

The two real world scenarios from the context of wireless environments are identified as 'apartment' and 'office' scenarios as described in the following.

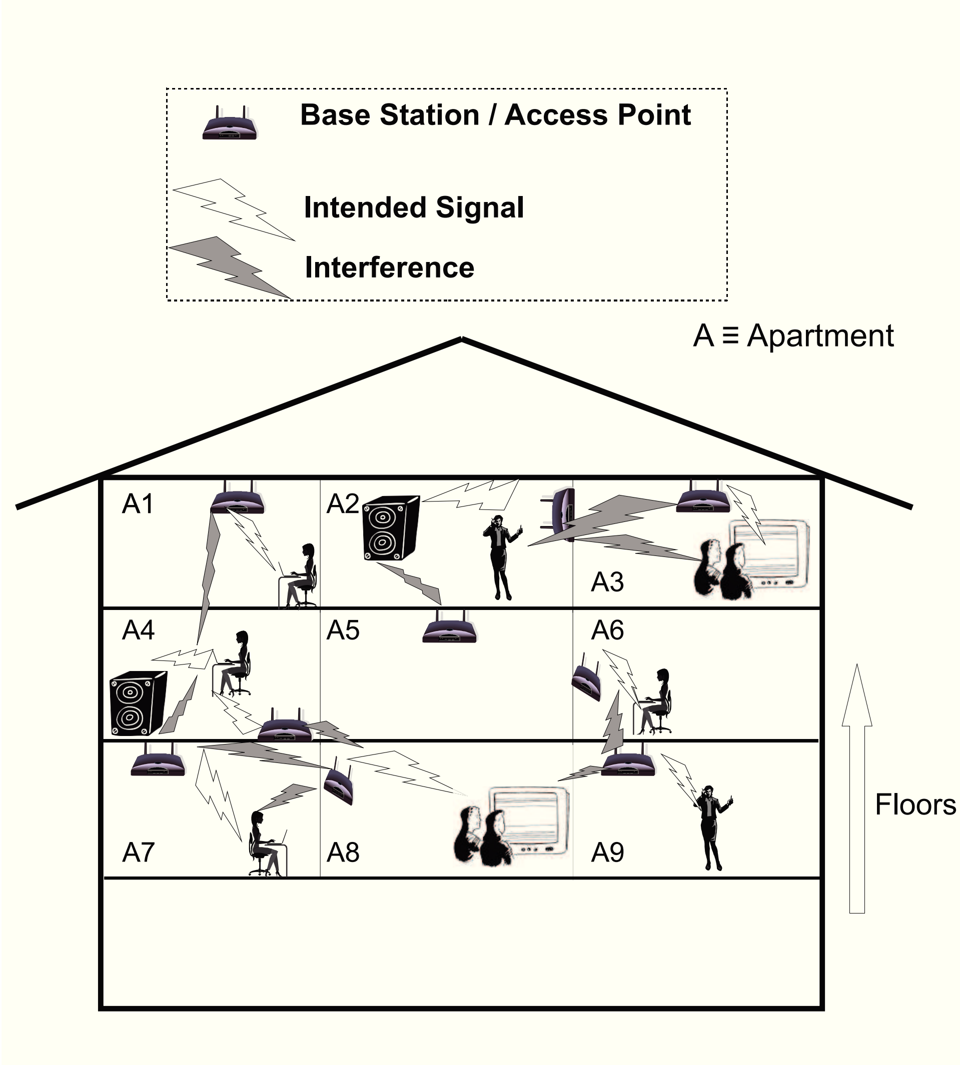


Figure 4.7: Example apartment scenario

4.4.1 Apartment Scenario

Figure 4.7 shows a scenario, which is located in an apartment building, which consists of many apartments in a dense urban area. Some features of this scenario are as follows.

- The number of user terminals under the same IEEE 802.11 access point (AP) are less compared to the office scenario.
- The density of IEEE 802.11 access points is higher, as each neighbor probably has his own AP to connect to the Internet.
- The density of consumer products, like wireless screen/display (e.g. WiDi), video and audio streaming over wireless medium, etc. using the IEEE 802.11 based technology is higher.

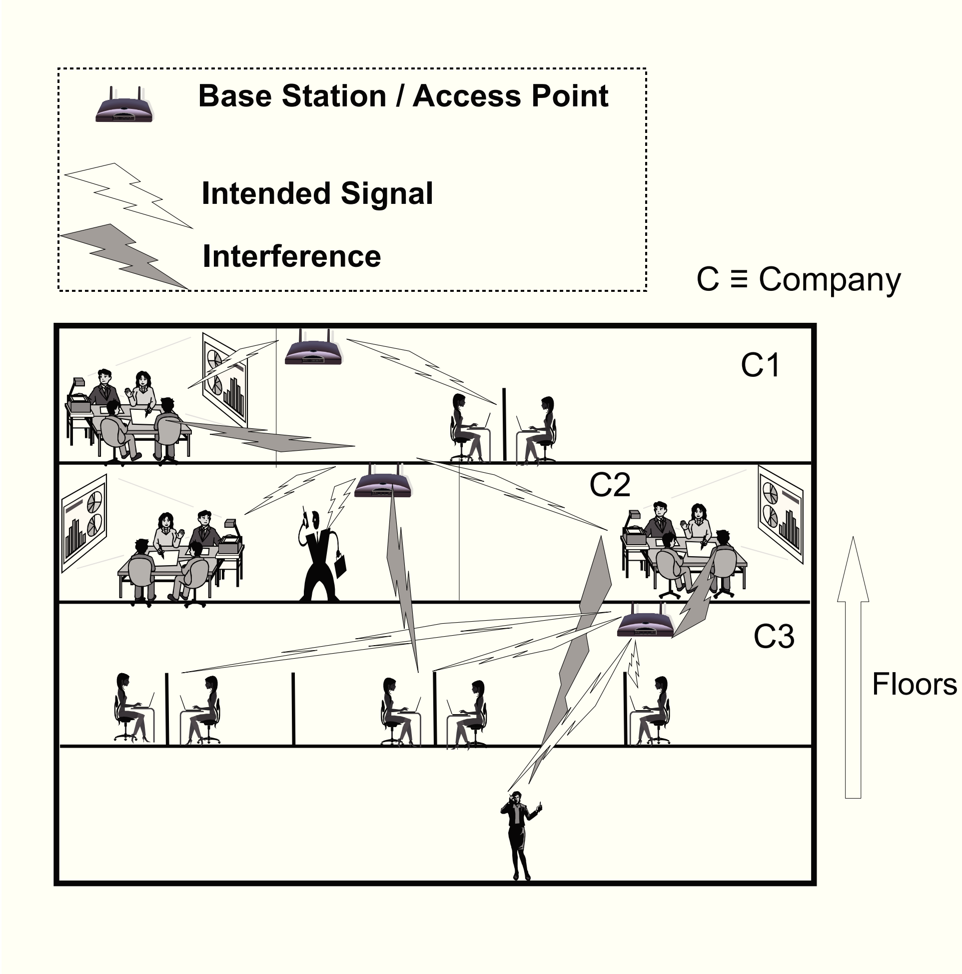


Figure 4.8: Example office scenario

4.4.2 Office Scenario

Figure 4.8 shows a scenario which is located in an office building. In such a scenario, several individual offices are located in the same building; on the one hand, in different floors and on the other hand, in different blocks in the same floor. Some features of this scenario are as follows.

- The number of user terminals under the same access points is higher compared to the apartment scenario.
- The density of IEEE 802.11 access points is lower, assuming that APs are managed internally at least in the same company.
- The number of users using real-time applications like VoIP calls, messaging, video conferencing is higher.

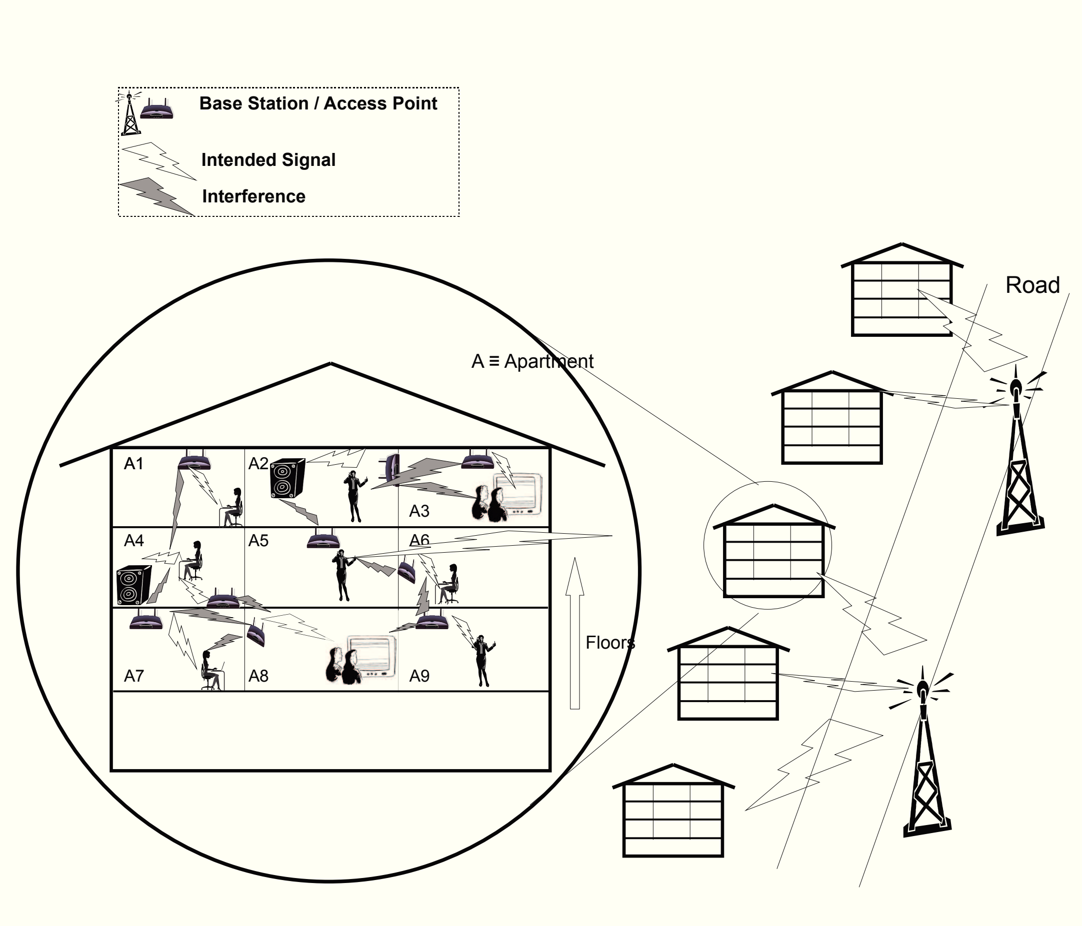


Figure 4.9: Example apartment scenario with the heterogeneous coexisting networks

In both scenarios, a possibility of several users using the IEEE 802.16 wireless technology for voice and data communication exists. Figure 4.9 shows an example of heterogeneous coexisting networks in the locality of an urban residential area where both IEEE 802.11 and IEEE 802.16 based wireless networks are in operation.

In all of the above coexisting scenarios, interference among systems is quite a dominant physical phenomenon. Interference analysis methods are provided in the next section as reference.

4.5 Coexistence/Interference Analysis Methods

Standardization groups like the International Telecommunication Union (ITU) and IEEE published several documents to define types of interference and to give a structural framework to analyze the interference. A brief description is provided below.

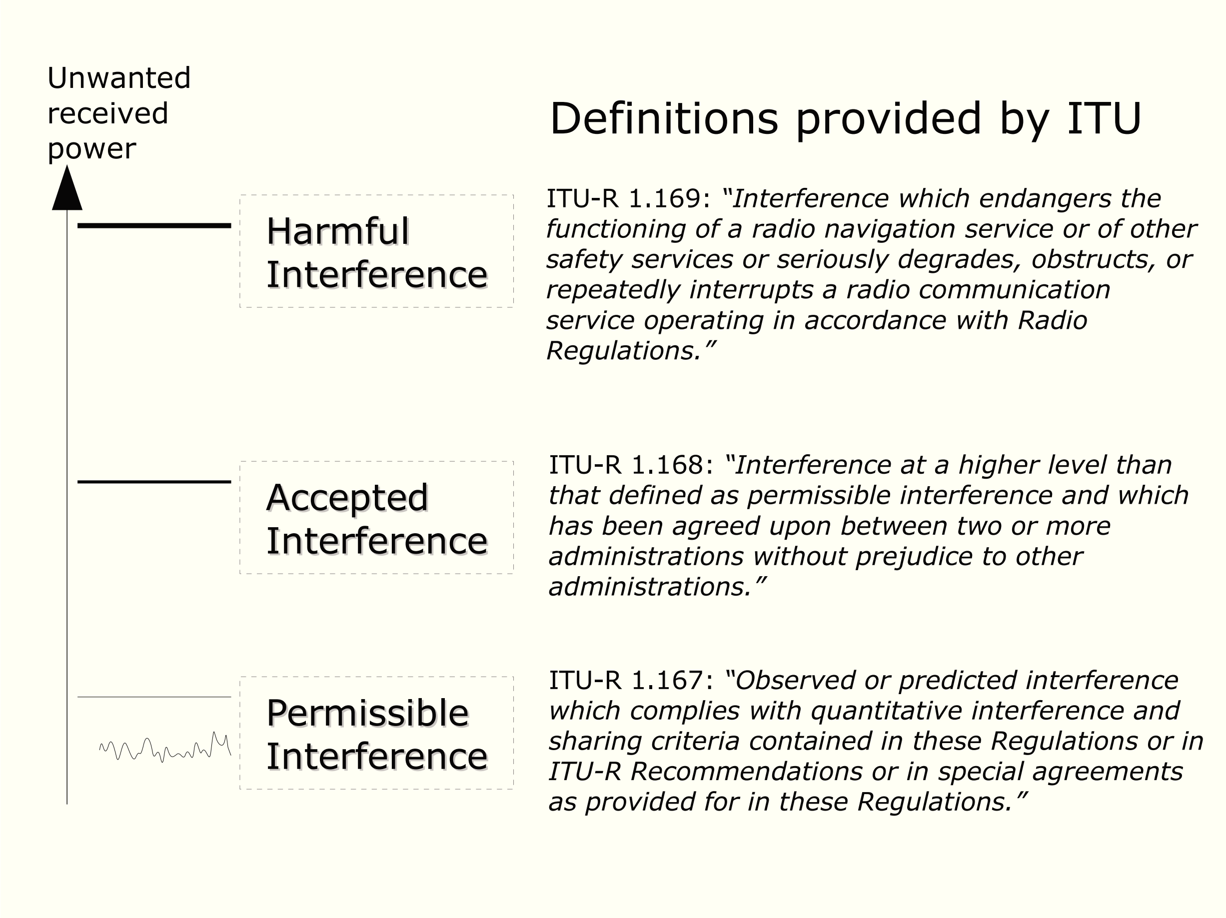


Figure 4.10: Comparative interference levels and their definitions according to the ITU Radio Regulations - Provisions 1.167 to 1.169

4.5.1 ITU-R

The ITU defines interference in their International Radio Regulations (IRRs) and corresponding ITU-Recommendations (ITU-Rs). The terms interference, permissible interference, harmful interference and accepted interference are defined respectively in the provisions ITU-R 1.166, ITU-R 1.167, ITU-R 1.168, and ITU-R 1.169 [26]. ITU-R 1.166 defines interference as follows:

The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.

The comparative unwanted energy levels and the definitions of the above mentioned interferences according to the ITU-R are shown in Figure 4.10. The levels of interference that are acceptable under conditions of static spectrum assignment are provided in the IRRs. In the coordination of frequency assignments between systems and their administrations, these recommendations are followed.

On the other hand, the IEEE Standards Coordinating Committee 41 (SCC- 41) intends to extend recommendations on interference analysis in the case of dynamic spectrum assignment considering 'traffic or other local conditions, among a number of radio systems, coexisting in a common spectrum assignment' [64].

4.5.2 SCC41

General technical guidelines are provided in the the draft IEEE 1900.2-2008 [69] as recommended practice to analyze the coexistence or, alternatively, the interference between radio systems, operating in the same spectrum assignment or between different spectrum assignments. This recommended practice provides a structure and describes a method for analyzing the interference between radio services under a variety of coexistence scenarios so that the analyst can consider all relevant issues in a systematic and scientific way. The motivation behind the recommended practice is to make the comparison of different analyses easier. That means, when different analyses utilize a common structure and method of analysis, the identification of the reasons for similarities or differences in conclusions are assumed to be fast. This helps to go to the next step of the critical elements, where more data or further analysis may either confirm results or aid in the understanding of differing conclusions.

According to the IEEE 1900.2-2008 draft, the interference analysis should count all the effects of the unwanted energy from the bottom physical layer to the topmost application layer if the impact of that energy is quantifiable. Three terms are highlighted in this draft: 'measurement event', 'interference event', and 'harmful interference'. Interference is defined by the characteristics, which are reformulated into variables that are treated as measurement events. The characteristics are used to determine the level where the interference has its impact. Some of the characteristic variables listed in the standard are as follows.

- Carrier-to-Interference ratio (C/I) and Carrier-to-Interference plus Noise ratio (C/I + N) (sometimes referred to as Desired to Undesired ratio (D/U))

- Bit loss
- Packet loss
- Packet latency
- User data loss
- Link loss or device impact
- System throughput
- Equipment resource utilization, e.g., battery, processor, or memory utilization

For example, in a coexistence scenario between systems, the interference can be characterized by different levels, like the degradation of the carrier-to-interference plus noise ratio in the PHY layer or the degradation of packet delay and throughput due to several retransmission efforts in the MAC layer. The packet loss in the MAC layer could be lower than the endangered threshold when ARQ is enabled.

A measurement event in which a quantifiable performance degradation is observed on the recipient device or system or for the user of a recipient device or system (System A) due to transmission by a source device or system (System B), is considered as an interference event. Interference events are therefore a subset of the measurement events. Harmful interference is the level at which the analysis determines that interference events have created unacceptable interference. The level is defined in terms of interference events per time unit and/or users or systems that cause an unacceptable degradation of the recipient system's performance.

4.6 Coexistence Evaluation Method

In the framework of this work, to evaluate coexistence supporting algorithms stochastic event driven simulation is considered extensively including related particular mathematical calculations.

The reference scenarios as apartment and office scenarios for evaluation are defined including the number of coexisting systems, number and position of nodes, underlying technology standards, and used applications. Traffic model parameters are defined for applications.

For every reference scenario, performance results for both technologies in (a) a clean environment (without interference) (b) a coexistence environment (with the interference effect) without spectrum sharing are obtained and evaluated. Performance results with (c) a spectrum sharing method are compared against (b). The following key performance indicators / key performance metrics are identified for evaluation which are related to the interference characteristics variables described in section 4.5.2.

4.6.1 Key Performance Indicators

In the following, Quality of Service (QoS) measures are considered as the KPIs.

- **Throughput**: The performance metric throughput used in this thesis is defined as follows. It is the number of useful data bits successfully received (excluding the retransmissions) divided by the time it took to transmit them over the medium. The individual as well as aggregated throughput for the systems are evaluated, where aggregated throughput is calculated by summing the individual. Generally, the throughput with respect to the MAC layer is considered unless stated otherwise. The achieved throughput, normalized by the physical bit rate of the channel, is often considered as the channel utilization.
- **Packet Delay**: Delay is also known as Latency. Delay is technically the amount of time it takes a packet to be transmitted from source to destination. The delay definition is layer dependent, in the sense that from which layer the packet transmission starting time is considered. The definition of the delay considered in this thesis is as follows. The time it takes to transmit a packet from the time it is passed to the MAC layer until it is successfully received at the destination. It generally accounts for queuing, channel access, propagation, transmission and retransmission delays as discussed in Chapter 2. The queuing and channel access delays are highlighted during the performance evaluation and in the rest of the thesis, retransmission delay will be calculated inside access delay, unless stated otherwise.
- **Delay-jitter**: Delay-jitter is technically the measure of the variability of the delay on time. In the framework of this thesis, the standard deviation of the delay is defined as delay-jitter [75].
- **Packet loss ratio**: From the technical point of view, it is the ratio between the number of lost packets to the total number of packets generated. Packet loss considered in this thesis, in broader sense, is due to two reasons: packet drop in the buffers and packet loss during the transmission via the channel. Generally there are several buffers located in several layers in the transmitter and the receiver where a packet could be dropped if the consequent process is not ready to accept the packet and eventually the buffer becomes full. During the

transmission, packet loss is caused by several factors, like channel congestion, lower signal-to-noise ratio, collisions due to random channel access, etc. In this thesis, packet loss ratio thus is evaluated in two sub-ratios: buffer loss ratio and Cyclic Redundancy Check (CRC) loss ratio.

4.7 Conclusion

A broad overview on the future coexisting scenarios considering two different wireless technologies is given in this chapter. Spectrum sharing methods developed under the framework of this thesis are tailored to the scenarios, like the apartment and the office scenario, which are described here. Performance evaluation metrics and its methodology followed in this thesis are discussed.

CHAPTER 5

SPECTRUM SENSING AND MEASUREMENT METHODS

Nothing exists until it is measured.[1] In this chapter, the sensing and the estimation methods to obtain the knowledge about the wireless environment are proposed, which are considered as the enabling techniques for spectrum sharing, as already mentioned in Section 3.4. Under the framework of this thesis, a RSS-based (Received Signal Strength based) detection method is exploited for measuring the channel occupation. RSS means Received Signal Strength. A comprehensive study on the characteristics of channel occupation by the IEEE 802.11 and the IEEE 802.16 wireless systems is provided. The simulation models are used in this respect applying a wide range of scenarios. Based on the analysis, a pattern recognition based algorithm is developed for system identification. The statistical knowledge based estimation methods are developed and introduced for traffic demand estimation which eventually help to share the resource efficiently in the coexistence environment.

The structure of this chapter is as follows. The related work is presented in Section 5.1. Section 5.2 describes the spectrum sensing architecture, followed by a detailed description of spectrum occupation measurement in Section 5.3. Analyses on spectrum occupation measurement results (collected from simulation test scenarios) is provided in in Section 5.4. Traffic demand estimation methods are described in Section 5.5. Section 5.6 introduces the buffer sensing architecture for estimating one's own traffic demand. A solution space for spectrum sensing strategy is given in Section 5.7. The chapter is summarized in Section 5.8.

5.1 State of the art

In [106] spectrum opportunity detection in frequency and time domain is described with a particular emphasis on the optimal exploitation of measurement history. It is anticipated that the observed history gives a statistical knowledge about the dynamics of time-varying spectrum occupation.

[1] Niels Bohr (1885-1962).

An adaptive spectrum sensing approach has been shown in [46], where spectrum sensing parameters, like sweep bandwidth, sweep time, etc., are adjusted according to the features of the channel of interest. Sweep bandwidth is the amount of frequency span scanned/swept by the measurement instrument and the sweep time is the total amount of time required to scan/sweep the complete sweep bandwidth. The approach also shows a scheduling of spectrum sensing methods, which includes when to set the front end to sense, transmit or idle mode for each spectrum channel and time slots. In [46], a Markov model is investigated to show the channel occupancy as well.

In [52], the measurements of channel occupation in a real scenario with a vector signal analyzer in the 2.4 GHz ISM band are described and the gathered data are processed to find the idle and busy periods of the channel. In that case detection performance depends on the sampling rate: the higher the sampling rate, the faster the RSS changes can be identified. In this respect, two different sensing strategies are considered, depending on whether the sensing station knows the other system type or not. Energy-based detection is used when the transmission standard of the other system is not known. Feature-based detection is used when the other system type (e.g., WLAN) is known. A simplified semi-Markov model is proposed having two states, transmit/busy state and idle state. To fully specify the semi-Markov model, the sojourn times in each state are characterized. A generalized Pareto distribution is shown as a good fit for the sojourn time in idle state for varying packet rates.

The scientific work in [52] has been extended in [53] in the following way: a statistical analysis of the gathered data is done to show a good fit with the empirical distribution. In this paper, a hyper-Erlang distribution is shown as a good fit curve which is a tradeoff between modeling accuracy and tractability of the model. In [53], VoIP and FTP-based traffic are considered.

5.1.1 IEEE 802.11k: An Example

In the scientific community and industry, there is a significant concern in the field of radio resource measurement and its enhancement for the next generation wireless networks. Following this consequence, the IEEE 802.11 standardization board created a task group TGk, which has published an amendment called IEEE 802.11k-2008 [66]. In the scope of this amendment, different measurement techniques are defined, which could be implemented by the radio systems to acquire the knowledge about the radio environment, which as an end effect will assist to improve performance and reliability of the wireless networks. The effort of this work is a promising step towards one of the key enabling technologies, spectrum sensing for cognitive radio and dynamic spectrum sharing. This measurement technique provides the following: the types of measurement information to be measured, the corresponding measurement request and report methods and the frame format for measurement requests and reports through which information exchange among the stations can be performed.

5.2 Spectrum Sensing Architecture

As mentioned above, sensing the spectrum to obtain knowledge about the wireless environment is considered as an enabling technique towards cognitive spectrum sharing [95, 84]. Two of the sub-requirements of the sensing are the identification of the collocated system's type and the estimation of required bandwidth by the collocated system. For further reference, they are denoted as System Type Identification (STI) and Traffic Demand Estimation (TDE). If the type of a coexisting system is known, spectrum sharing can be improved for example as follows. If the collocated system is known to be an IEEE 802.11 system, this knowledge can be exploited to protect radio resources to be used for the own system, e.g. by transmitting a busy signal by the Access Point (AP) to temporarily inhibit the channel access for the other system.

One of the techniques for STI is the observation of the current channel occupation pattern. Two different scenarios are feasible for sensing and detection; they can be differentiated by the degree of complexity which is provided in each participating station: a single mode and dual mode station. In the frame of this work, the single mode stations are considered, where it is assumed that the stations in each network/system are only able to receive, understand and transmit frames that are structured according to their own Medium Access Control (MAC) and Physical (PHY) layer. Therefore, it is impossible for them to decode the messages exchanged in the coexisting network, which makes the detection quite a challenging task. A station can only identify an occupied channel as it receives 'noise' during the transmissions of the coexisting system, sometimes noted as foreign protocol. On the other hand, dual mode stations can decode the messages exchanged in the coexisting system. It is believed by the author that in the case of dual mode stations, the detection methods would be more trivial as the other system can be overheard, and therefore this case is not covered in this thesis.

The block diagram of the spectrum sensing method, developed in the framework of this work, is shown in Figure 5.1. The blocks are described briefly as follows, and are later described in detail.

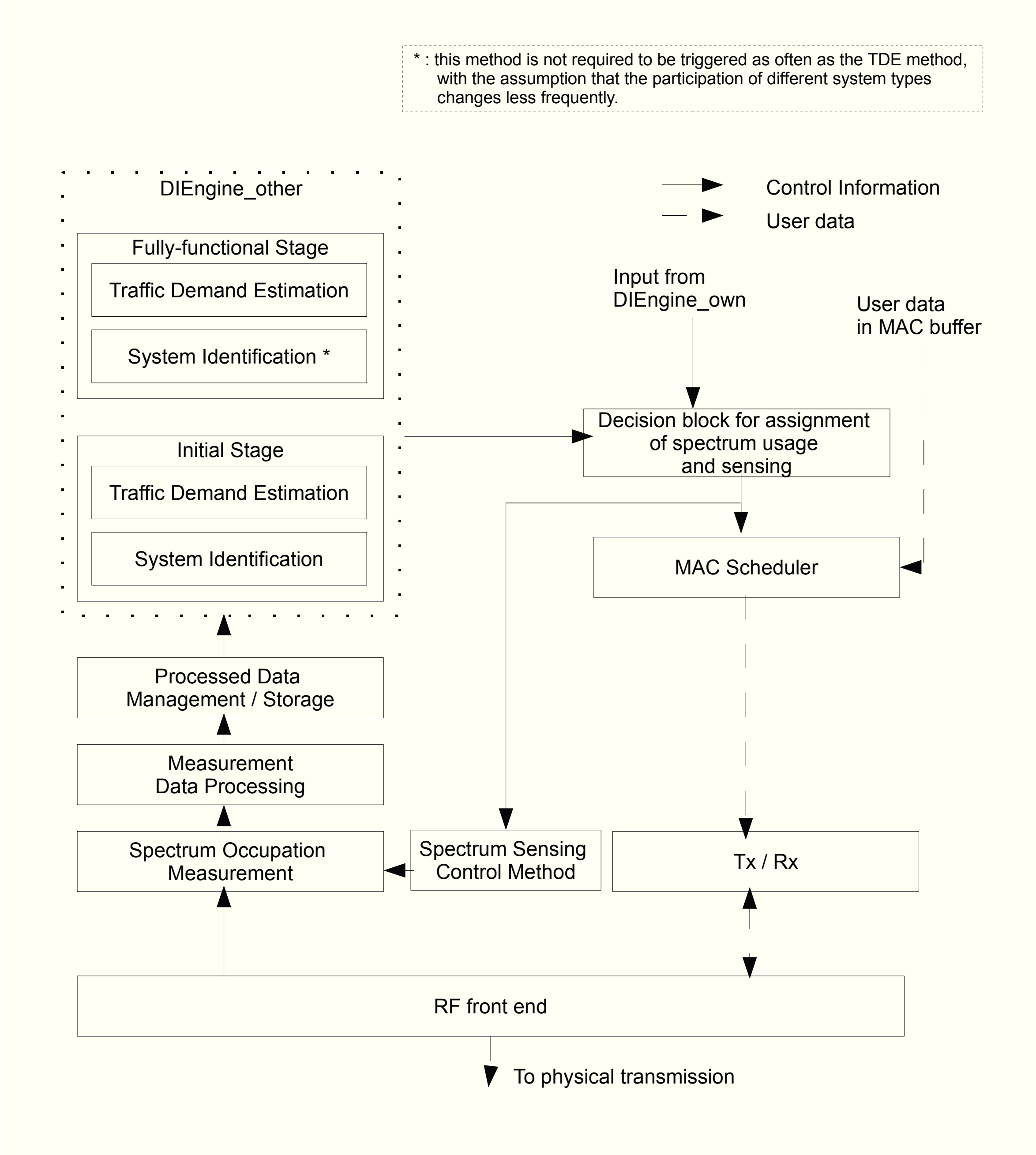


Figure 5.1: Functional block diagram of spectrum sensing methods (channel measurement, system identification and traffic demand estimation)

- **Spectrum Occupation Measurement**: Received radio frequency (RF) power, generally known as Received Signal Strength (RSS) is decided to be a parameter to be measured, whose consequent values give a clear idea about the channel condition. **RF front end** receiver part of the radio facilitates the purpose of this functional block.

- **Measurement Data Processing**: This block is responsible to calculate the idle and busy period durations and to provide a binary trace of start of busy periods based on the measured RSS values. The channel occupation ratio per unit time is also determined in this block for Traffic Demand Estimation (TDE).

- **Processed Data Management**: In the scope of this block, the required raw and processed data are stored for next steps.

- **Detection, Identification and Estimation Engine (DIEngine)**: Processed information is analyzed in order to characterize the spectrum occupation for STI and TDE. Two stages have been considered for this process. The initial stage starts just after the system is deployed and goes up to when the system is in the fully-functional stage. In the initial stage, STI and TDE model parameters are estimated according to the measurement values and when the estimation of those parameters reach a certain confidence level, the fully-functional stage is started. In the fully-functional stage, the own system does not need to be quieted for a long time and an advanced sensing strategy (mentioned in Section 5.7) can be implemented for short-term estimation. In this stage, the system identification method is marked with a star (*) sign, indicating that this method is not required to be triggered as often like the TDE method, with the assumption that the participation of different system types changes less frequently.

- **Decision Block for Assignment**: The outcome of STI and TDE is fed into this block which has the responsibility to allocate the resources for the own system and keep free space for the other system. This block also gets input from DIEngine_own shown in the figure. The DIEngine_own is a separate block shown in Figure 5.31. The user data scheduling in **MAC Scheduler** is done based on resource allocation. This block is also responsible to schedule and couple sensing time duration with user data scheduling when required.

- **Spectrum Sensing Control Method**: This block is provided in the architectural blocks to model the sensing strategies, for example, whether the sensing will be done in a periodic manner, and if so, how long should be the sensing time interval, sensing duration and so on.

5.3 Acquisition of Spectrum Occupation

Unless stated otherwise, single mode stations are considered in the following. It means, a station acquires information about the spectrum occupation by measuring dynamically and changing RSS values due to transmissions of the other system. In this case, the received RF power is treated as 'noise' by the station. Generally, spectrum occupation can be measured along frequency, time and space dimensions. However, the time dimension is considered in the following, unless stated differently.

5.3.1 Spectrum Occupation Measurement

During measurement and processing, the received RF power is considered as a parameter, nevertheless, care should be given on how it is defined, modeled and implemented. According to [105], it is defined as the Received Signal Strength (RSS) of a received frame measured at the receiver's front end antenna. In the case of this thesis, RSS measurements per frame are considered in the simulation, where the RSS consists of signals from other stations and interference. Details of RSS measurement are not shown here. During the measurement period when the own system is silent, the RSS consists of the signal power of the other system/s (which are treated as noise). RSS depends on the transmission powers, the distance between the transmitter's and receiver's antennas and the channel conditions due to multi-path fading. The latter is not considered in the following unless stated otherwise.

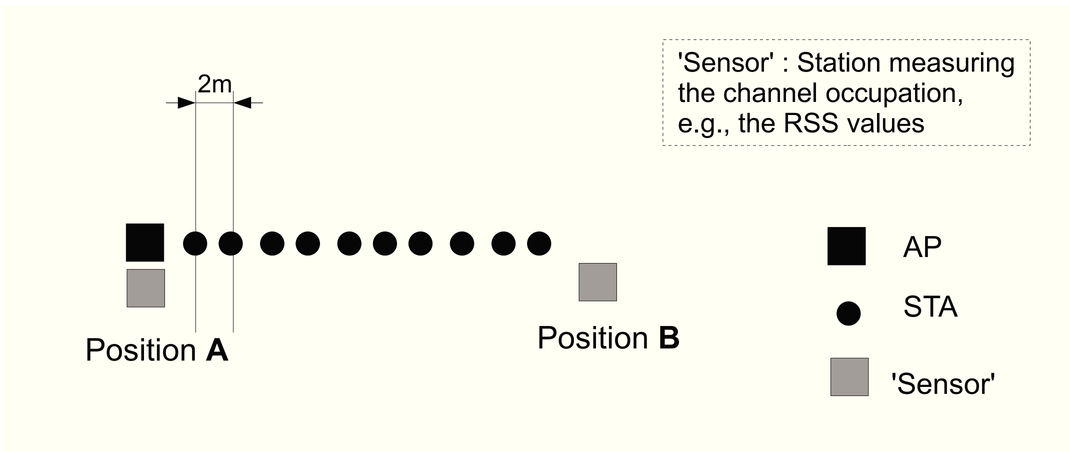


Figure 5.2: A testing scenario with 10 WLAN stations

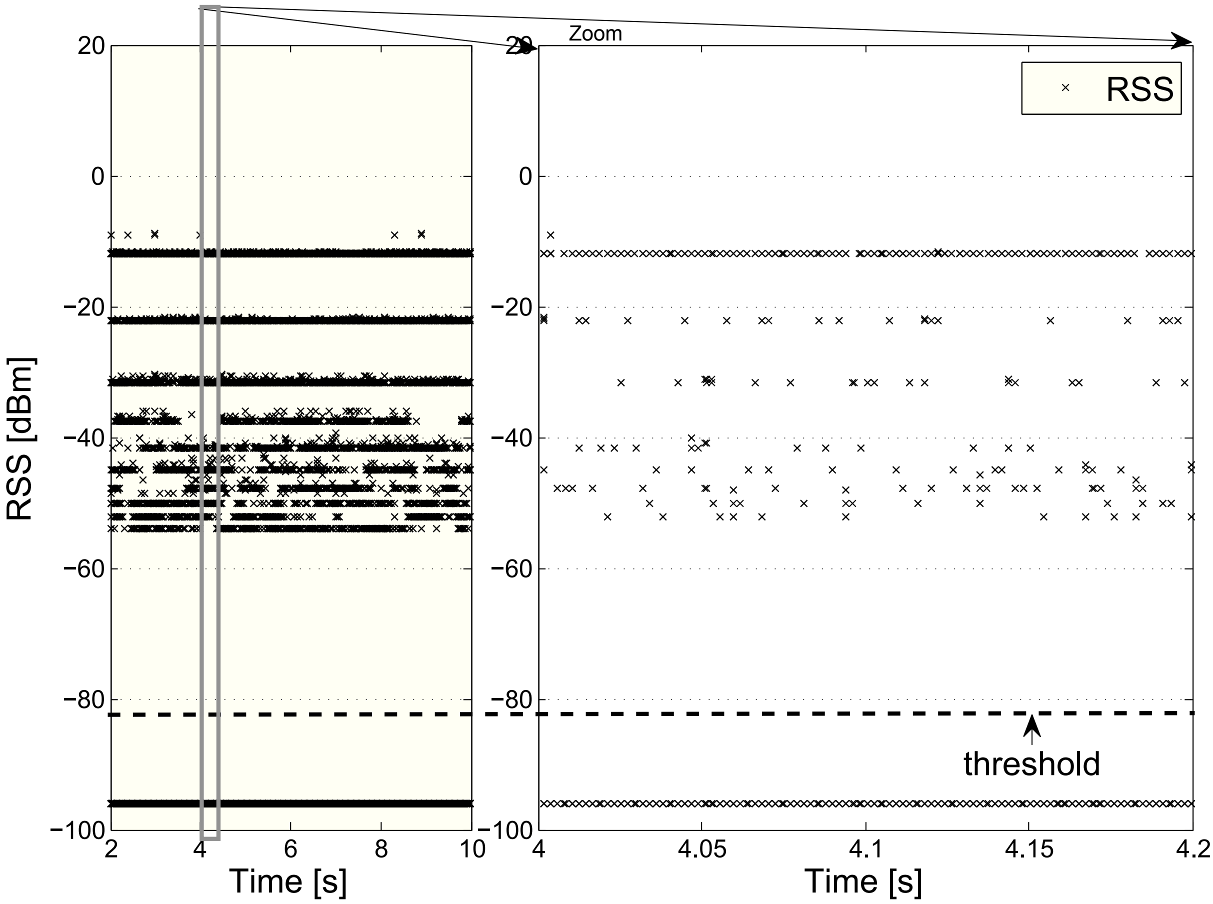


Figure 5.3: Measured RSS values against model time in the scenario: shown in Figure 5.2

A series of RSS measurement values can be represented as a vector $\mathbf{R}$:

$$\mathbf{R} = [R(t_j)], \tag{5.1}$$

where, $R(t_j)$ is a RSS measurement sample at time instance t_j, $j = 1,.....N_t$, and N_t is the number of time instances inside the measurement period.

An example of measured RSS values is shown in Figure 5.3 for a testing scenario as shown in Figure 5.2. In the scenario, 10 IEEE 802.11 stations are aligned in x-direction in such a way that they are apart from other stations by 2 meters. Uplink traffic, i.e., stations are sending packets to the AP, is considered in the scenario. The station which measures the RSS values is defined as 'sensor' in the figure. In the scenario, the 'sensor' station is almost collocated with the AP at position A and the transmission power of all stations is kept equal. Figure 5.3 shows the measured RSS values over simulation time. The measured RSS values are distributed over different regions (from –55 dBm to –10 dBm) during the transmission. The reason is that the various stations are located at different distances from the sensor. However, most of the RSS values are above the threshold of –82 dBm. The significance of the threshold is discussed in later sections. Those measured RSS values, which are equal to –95 dBm, are due to the absence of signal and considered as noise floor.

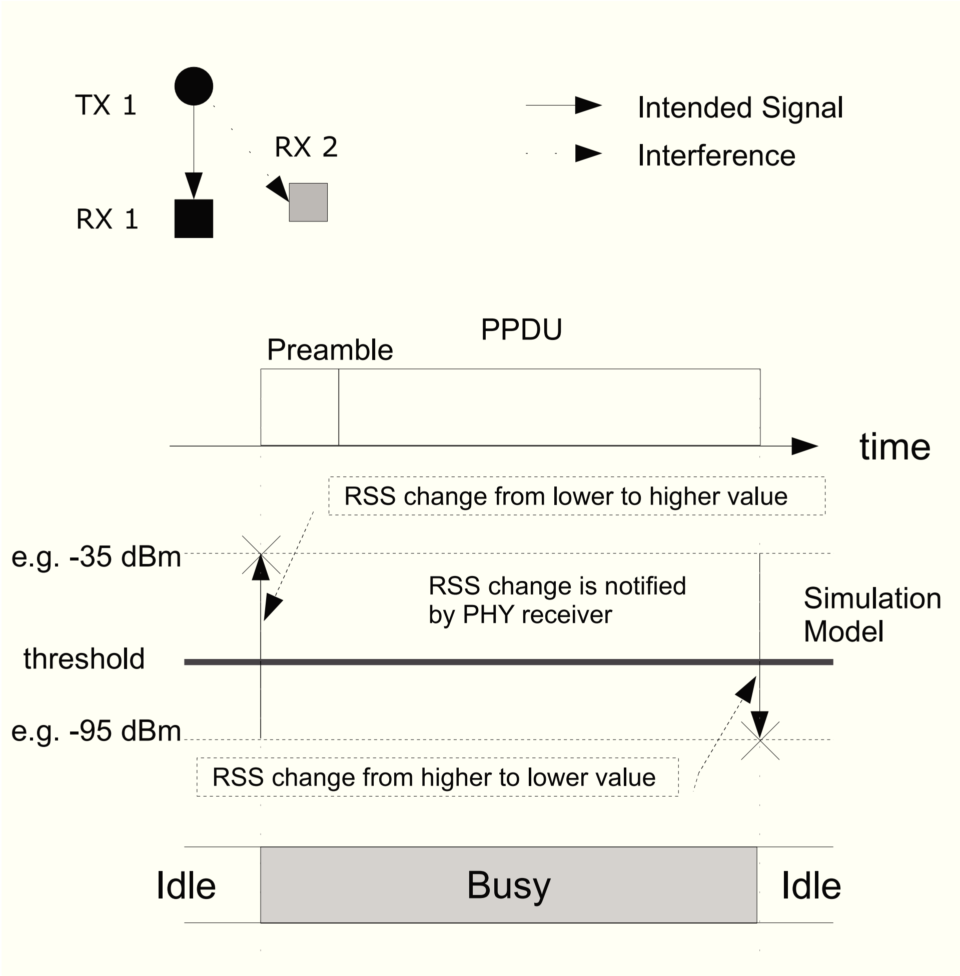


Figure 5.4: RSS Model to determine channel state

5.3.2 Spectrum Occupancy Detection (Measurement Data Processing)

After having the RSS measurement data, the next step is to detect whether the channel is occupied or not based on the RSS measurement values.

5.3.2.1 RSS-based Detection

In the simulation model given in this work, any change in the RSS is notified just in time, e.g., at the start and the stop of transmission, which is possible in practice by extending the sensing during the receiving mode in microsecond scale i.e., sampling rate of 10^6 samples/s. It could be considered as a perfect sensing in this case.

In this circumstance, the spectrum occupancy of a specified channel can be modeled as a two state random variable denoted as S, where 'channel occupied' or 'signal present' is considered as 'busy period' and 'channel available' or 'signal absent' is considered as 'idle period'. A measurement sample $R(t_j)$ is classified as the start of busy period (represented by '1') or the start of idle period (represented as '0') based on a decision threshold as mentioned by:

$$R_c(t_j) = \begin{cases} 1 \text{ (occupied)}, & \text{if } R(t_j) \geq \gamma_{th} \\ 0 \text{ (free)} & \text{if } R(t_j) < \gamma_{th} \end{cases}, \quad R(t_j) \in \mathbf{R} \tag{5.2}$$

where $R_c(t_j)$ represents the channel occupancy states at time instance t_j and is an element of a vector of classified measurements denoted as R_c and γ_{th} is a decision threshold.

The following example scenario can give a better understanding of the detection method. In Figure 5.4, it is assumed that Tx-1 is sending a packet to Rx-1, however Rx-2 hears the ongoing transmission as interference. The start and end of the transmission are notified by the receiver model and the RSS value is changed at the same time. Generally when there is no signal, the RSS value is equal to the noise level (e.g. –95 dBm). At the start of transmission the RSS value is changed. If the RSS value is above the predefined threshold (e.g. –82 dBm), the channel is considered to be busy and the time instance is considered as the end of the idle period and the start of the busy period. For further analysis, this time instance, when a transition from state '0' to state '1' happens is denoted as $T_j(R_c(t_j) = 1, R_c(t_{j-1}) = 0)$, in short $T_j(1, 0)$. The RSS value can be changed due to the end of a packet transmission (shown in the figure) or due to the start or end of another transmission (not shown in the figure). However, the bottom line is that if the RSS value goes below the threshold, the channel is considered as idle and the time instance is considered as the end of the busy period and the start of the idle period. This time instance can be denoted as $T_{j+1}(R_c(t_{j+1}) = 0, R_c(t_j) = 1)$, in short $T_{j+1}(0, 1)$, meaning that a transition from state '1' to state '0' happens.

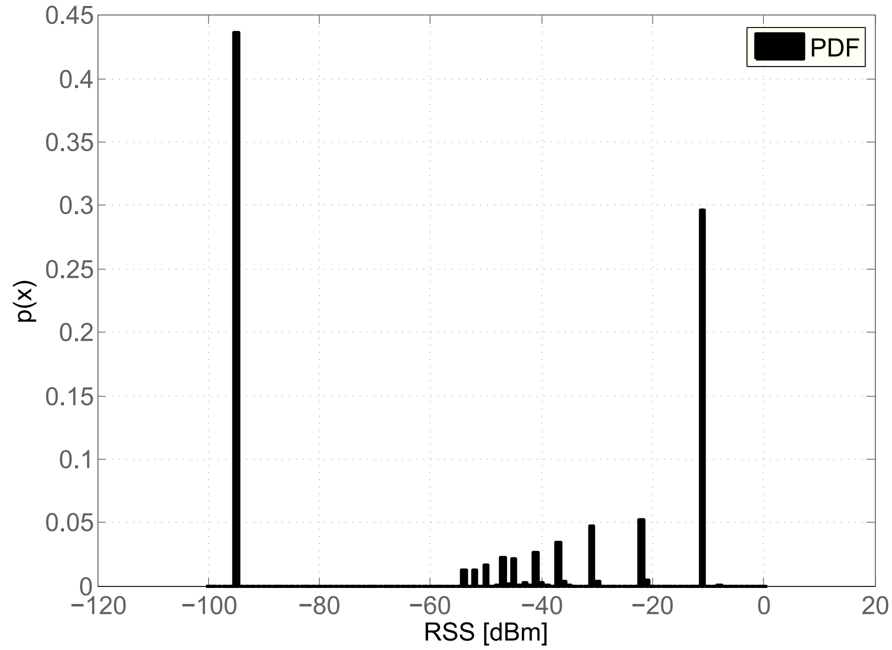


Figure 5.5: PDF of RSS values in the scenario shown in figure 5.2

The probability density function (PDF) for the measured RSSs values, shown in Figure 5.3, is depicted in Figure 5.5. It is a significant characteristic of this PDF that the levels of RSS values are different due to the different location of the stations. The probability of –95 dBm is represented by the state when the channel goes idle after each transmission ends. The RSS values of –10 dBm (approx.) represent the transmissions nearest to the sensor. As the AP has to acknowledge (ACK packets) all data packets, the probability of –10 dBm is higher than the rest of the RSSs values, which represent the data packets sent from various distances. One of the reasons for different probabilities observed in the PDF are the different locations of the stations.

If the sensor is located at position B, the RSS values are different than in position A as shown in Figure 5.6. It also justifies that in this orientation the AP of the other system is far away from the sensor. However, the bottom line is that, in both cases the RSS values due to transmissions are above the threshold.

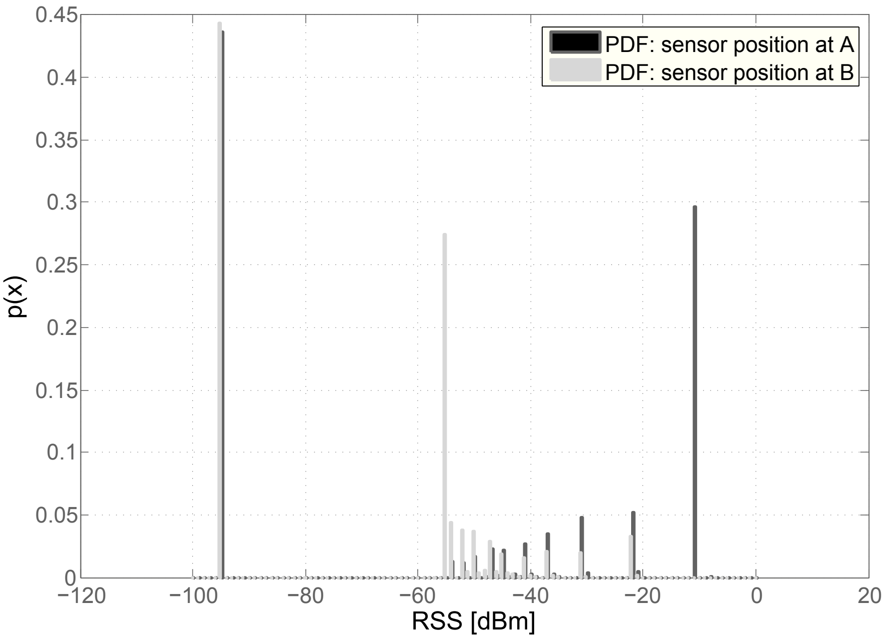


Figure 5.6: PDFs of RSS values for different sensor positions in a scenario shown in figure 5.2

5.3.2.2 Determining Idle and Busy Period Durations

Once the start and end of the busy period and the idle period are determined, then the durations themselves are calculated as follows.

$$\begin{aligned} IP(t_j) &= T_j(1{,}0) - T_{j-1}(0{,}1) \\ BP(t_{j+1}) &= T_{j+1}(0{,}1) - T_j(1{,}0) \end{aligned} \tag{5.3}$$

where $IP(t_j)$ and $BP(t_{j+1})$ are respectively the idle and busy period duration in time instance t_j and t_{j+1}. Note that in the rest of the thesis, the elapsed time duration of the idle or busy period is denoted as 'idle or busy period duration' or simply 'idle or busy duration'.

The simulation model of determining the idle and busy period durations is shown in Figure 5.7. Like in Figure 5.4, the IEEE 802.11 transmission is considered in this figure, where an ACK packet is followed by a DATA packet. Between the packets there is an Interframe Space (IFS), called Short IFS (SIFS), which is discussed in detail in Section 2.1.4.3. The SIFS duration is dependent on the PHY standard. For example, the IEEE 802.11a OFDM based PHY standard for 20 GHz channel spacing requires SIFS of 16 μs. A

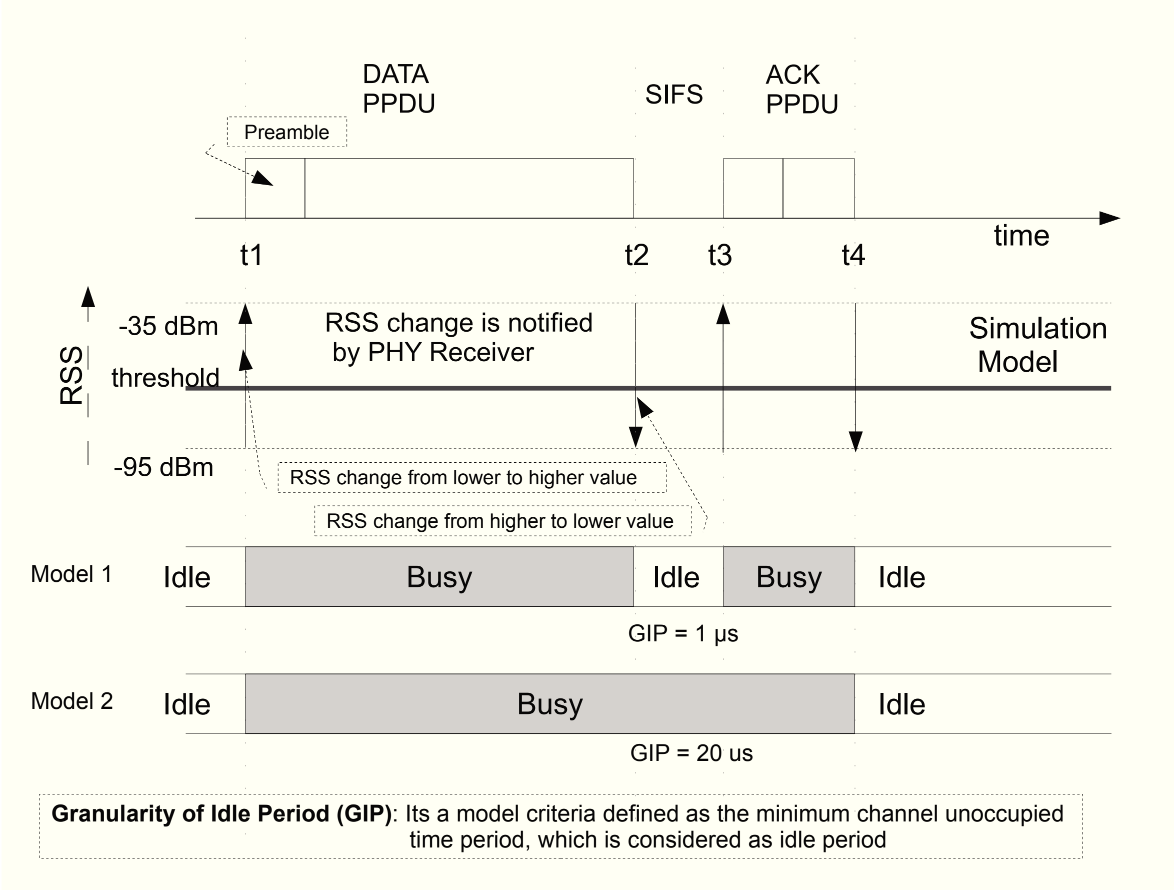


Figure 5.7: RSS Model to determine the idle and the busy period durations

table of PHY characteristics for different PHYs is given in Section 2.1. Based on the RSS measurement values, the busy period durations are calculated as $(t_2 - t_1)$ and $(t_4 - t_3)$ and idle period duration as $(t_3 - t_2)$. The granularity of measured values for the idle period is model dependent, for example, smaller idle periods (e.g. less than or equal to $16\,\mu$s) could be included inside the busy period measurement as shown at the bottom of the figure (Model 2). In this context, Granularity of Idle Period (GIP) is defined, which is the minimum channel unoccupied time period considered as idle period duration.

5.3.2.3 Determining the Autocorrelation Coefficient of the Start of Busy Periods

The autocorrelation function (ACF) is formally defined as a statistical tool whose purpose is to identify the repeating patterns in the time series. In other words, it helps to determine the presence of periodicity or patterns in

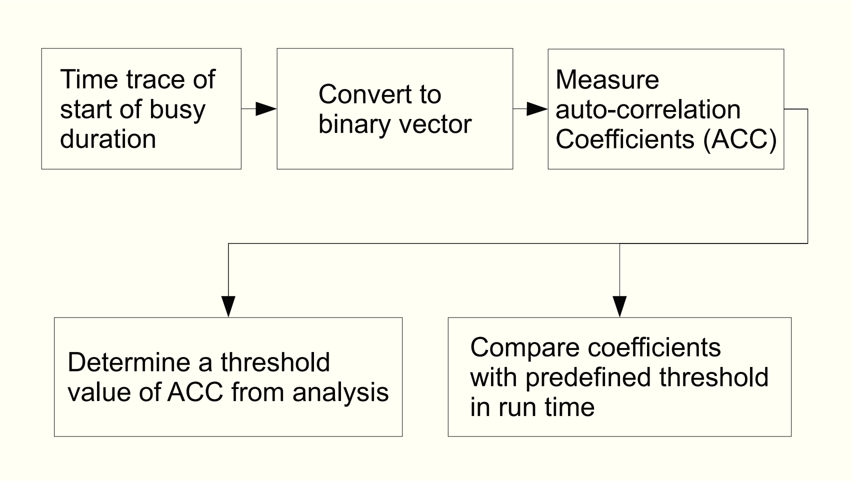


Figure 5.8: Block diagram of ACF calculation

the series of data values, observed and collected against time. Equi-distant time steps are assumed to be used for the observations to get meaningful results. The ACF is a series of autocorrelation coefficients (ACC) for consecutive *lags* in a specified range of lags (e.g., 1 through 100). The ACC measures the correlation between observations of the same variable at a certain distant apart, which is denoted as *lag*. The ACC at lag q is calculated as follows:

$$r_q = \frac{\sum_{t=1}^{N}(x_t-\bar{x})(x_{t+q}-\bar{x})}{\sum_{t=1}^{N}(x_t-\bar{x})^2} \quad \text{where } \bar{x} = \frac{1}{N}\sum_{t=1}^{N} x_t. \tag{5.4}$$

Here, N is the total number of observed data samples, x_t is the observed data sample at time instance t, $\bar{x}$ is the mean value of all data samples. The ACC is generally the covariance divided by the variance.

If the error (due to any unavoidable reason, like measurement error, etc.) is not too large, periodicity can be visually identified in the series as a pattern that repeats every q elements.

Figure 5.8 shows the processing steps of the method to determine the ACC of the start of busy period which is used, for example, to identify the IEEE 802.16 systems. At the beginning, the timing information corresponding to the starts of the busy periods are measured. To create a binary sequence vector out of the timing information sequence, a slot duration is defined. The slot duration represents the granularity of converting the timing sequence to a binary sequence. For example, if the slot duration is defined as 1 ms and the collected busy period start time sequence is like a = [1, 6, 11] ms, then the binary sequence would be b = [10000100001]. The binary sequence vector is used as an input to the autocorrelation coefficient model in Equation 5.4 to determine the ACCs.

During this process, two steps are done. In the first step, an analysis is done to measure the value of ACC for different configurations of system parameters and ACC parameters and determine the threshold value to identify the system type. This is done for the ideal case as details provided in section 5.4.2. In the second step, during runtime ACCs would be calculated for different situations and those would be compared against the predefined threshold so that a decision could be taken.

5.4 Analysis of Idle/Busy Pattern in Channel Occupation

In the previous section the sensing parameters which help to detect and identify a system, like the RSS, the idle and the busy period durations, and the start of busy periods are mentioned and a detailed description is given on how to measure those parameters. In this section, based on those sensing parameters and measurement methods, applied to a simulation, the channel occupation trace is analyzed from the perspective of repeated idle and busy period duration patterns.

5.4.1 Analysis of 802.11 Channel Occupation

In section 2.1.4, general channel access mechanisms for IEEE 802.11 stations are provided which describe how the airtime is shared on the one hand, among the stations, and on the other hand, among different packet types (like, DATA, ACK, etc.) from the perspective of a station.

In this section, five different cases during the IEEE 802.11 channel access are highlighted as those are captured during the measurement period and shown in Figure 5.9 for further discussion. Note that DCF based channel access method is considered in the analysis, where the RTS/CTS method, fragmentation of DATA packets are excluded. Moreover, IEEE 802.11e HCF based channel access method is also not considered in the analysis unless stated otherwise. A scenario consisting of a small number of stations is considered for showing the principle of operation. In this figure, for data processing, an idle period duration of more than or equal to $1\,\mu$s is considered as an identical idle period duration, i.e., Granularity of Idle Period (GIP) is equal to $1\,\mu$s. In each case, the top figure shows the channel access by the stations and the bottom figure shows the idle and the busy period duration measured by the sensor. The cases are discussed in the following.

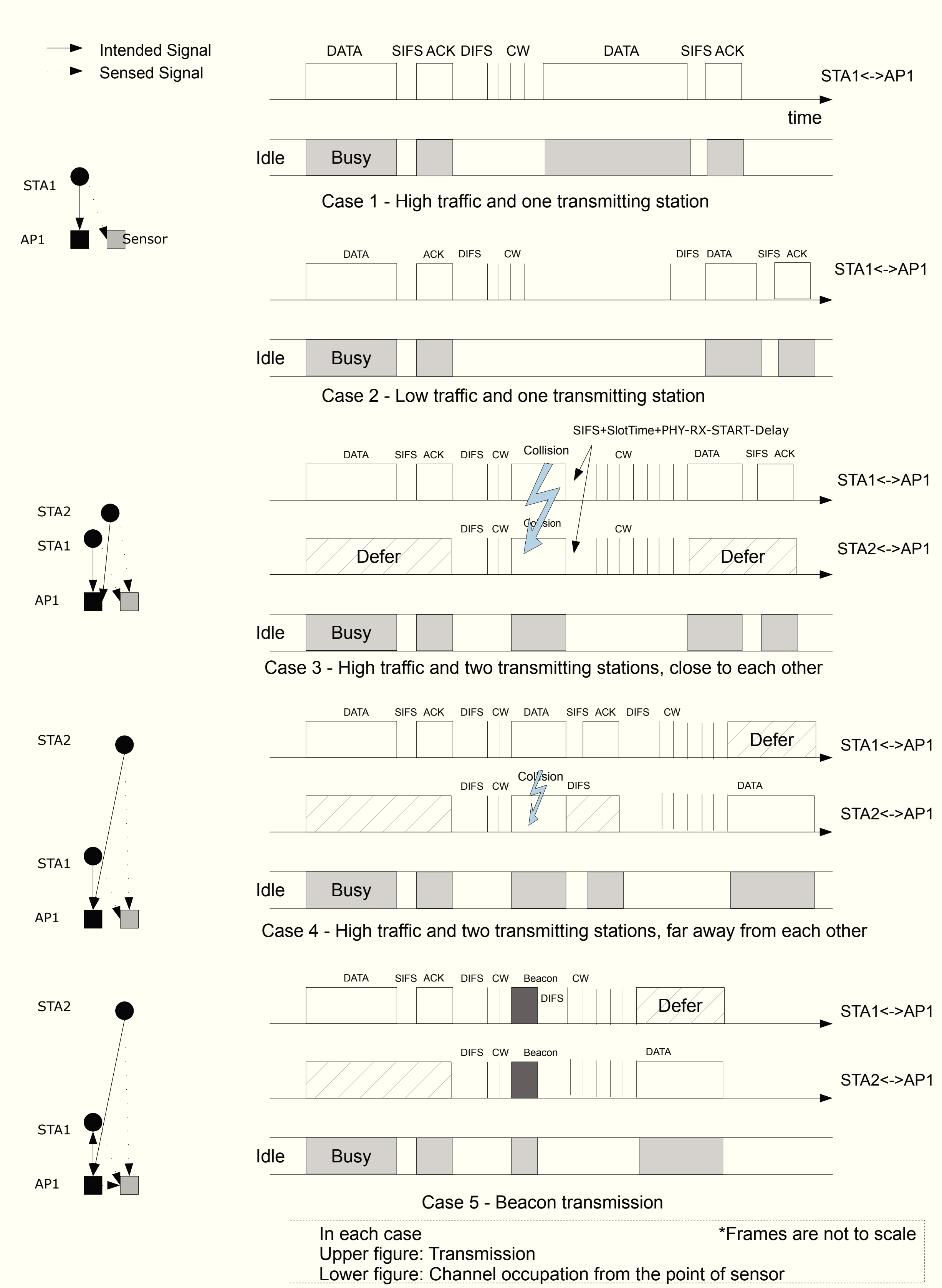


Figure 5.9: Five different cases observed during the IEEE 802.11 channel occupation measurement

- **Case 1 - High traffic and one transmitting station**: In this case, ongoing transmissions between a station and an access point under the condition of heavy load are considered. Busy periods are due to DATA and ACK transmissions and idle periods are due to SIFSs and channel access time like DIFS and contention slots.
- **Case 2 - Low traffic and one transmitting station**: In this case, longer idle period durations are observed due to low traffic.
- **Case 3 - High traffic and two transmitting stations, close to each other**: Here, ongoing transmissions between two stations and an access point under the condition of heavy load are considered. This case occurs when more than one station is going to transmit in the same time which results in a collision. This is due to an end of the contention period at the same point of time. In such a case, the sensor station senses the collision duration as a busy period duration. But unlike in previous cases, there is no subsequent busy period duration equal to the ACK duration. Due to collision, the station will wait for an `ACKTimeout` interval, with a value equal to (`aSIFSTime` + `aSlotTime` + `aPHY-RX-START-Delay`) at the end of the last transmission. This ACKTimeout interval value is observed as an idle period duration by the sensor. The value of `aPHY-RX-START-Delay` is 25 μs in case of the OFDM based physical layer and considering 20 MHz channel spacing. This value is a PHY parameter which is different for different PHY specifications.
- **Case 4 - High traffic and two transmitting stations, far away from each other**: The configured scenario is similar as in case 3, except that STA2 is at such a distance from STA1 that, when both stations are transmitting in the same time to AP1, the Signal to Noise plus Interference Ratio (SINR) for a packet from STA2 is much lower than that of STA1. As the packet error rate (PER) and corresponding CRC calculation in the receiver (AP) side mainly depend on the SINR values, it is likely that the receiver (AP) responds to the DATA packet from STA1 but not to the STA2 (as CRC is invalid) by sending an ACK packet. Unlike case 3, in this case, the sensor senses a subsequent busy period duration equal to the ACK duration after the DATA packet.
- **Case 5 - Beacon transmission**: Busy period due to Beacon packet is observed.

Various expected characteristics of IEEE 802.11 channel occupation are as follows:

- The probability of busy period durations equal to the beacon transmission duration depends on the traffic load. In the case of saturated traffic load, the number of busy periods due to other than Beacon packets is much higher and the number of busy durations equal to beacon transmission durations is comparatively very low. But for low traffic, the number of busy durations equal to beacon transmission durations would be significantly higher.
- If there is no collision like in case 1 and case 2 or collisions like in case 4, then it is expected that the probability of idle period durations equal to SIFS duration and the probability of busy period durations equal to ACK transmission duration would be equal and it would be almost 50 % for higher load.
- If there is no collision like case 1 and case 2 or collisions like in case 4, then it is expected that the probability of busy period durations equal to the ACK duration and equal to the DATA transmission duration would be almost the same and it would be almost 50 % for higher load.
- In the case of saturated traffic load, the rest of the idle periods other than those equal to the SIFS duration are generally equal to DIFS plus contention slot durations.

In the ideal case with no collision, the relations as provided in Equation 5.5 can be formalized, considering the following notations.

- BP is the busy period duration,
- IP is the idle period duration,
- BI is the beacon interval,
- N_{BP} is the total number of busy period durations measured during D_{meas},
- D_{meas} is the total measurement duration,
- $N_B = N(BP = Beacon)$ is the number of busy period durations equal to beacon transmission duration,
- $P_B = P(BP = Beacon)$, $P_D = P(BP = DATA)$ and $P_A = P(BP = ACK)$ are the probabilities that the busy periods equal to beacon, DATA and ACK transmission durations respectively,
- $P_S = P(IP = SIFS)$ is the probability that the idle period equals to the SIFS durations.

$$\begin{aligned}
&P_B = \tfrac{N_B}{N_{BP}}\\
&N_B = \lfloor \tfrac{D_{meas}}{\text{BI}} \rfloor\\
&P_D = P_A = 0.5 \cdot (1 - P_B)\\
&P_S = P_A.
\end{aligned} \tag{5.5}$$

In case of collisions due to a higher number of contending stations and higher traffic load, above equations are extended to the following form with the assumptions, provided in the Appendix C.1.

$$\begin{aligned}
&P_D^* = \tfrac{1}{1+P_s}\\
&P_A^* = P_S^* = \tfrac{P_s}{1+P_s}
\end{aligned} \tag{5.6}$$

where, P_s is the probability that a transmission occurring on the channel is successful, shown in [38] and calculated in section 2.1. P_D^* and P_S^* are the respective probabilities considering the collisions in the channel. A detailed derivation is provided in the Appendix C.1.

During the measurement, at a particular time instance t_k, the probabilities of idle period durations equal to the SIFS duration and busy period durations equal to the ACK duration are calculated as follows:

$$\begin{aligned}
&P_S(t_k) = \tfrac{1}{N_I(t_k)} \textstyle\sum_{j=1}^{k} (IP(t_j) = SIFS)\\
&P_A(t_k) = \tfrac{1}{N_B(t_k)} \textstyle\sum_{j=1}^{k} (BP(t_j) = ACK).
\end{aligned} \tag{5.7}$$

The corresponding transition probability from SIFS to ACK can be computed as:

$$\begin{aligned}
&P_{S \to A}(t_k) =\\
&\tfrac{1}{N_I(t_k)+N_B(t_k)} \textstyle\sum_{j=1}^{k} (BP(t_{j+1}) = ACK, IP(t_j) = SIFS).
\end{aligned} \tag{5.8}$$

For the rest of the analysis where simulation models are being used for investigation, the system parameters of the IEEE 802.11 stations are configured according to Table 8.1.

Figure 5.10 shows the PDFs of idle and busy period durations for the parameter configuration as stated at the top of the figure. In this case, the saturated traffic load is considered and the granularity of idle period (GIP) duration measurement is 1 μs. The top part of the figure shows the PDF of idle periods. The main observations are as follows:

- The probability of idle period durations equal to 16 μs, which is a SIFS duration, is higher than other idle period durations. In the IEEE

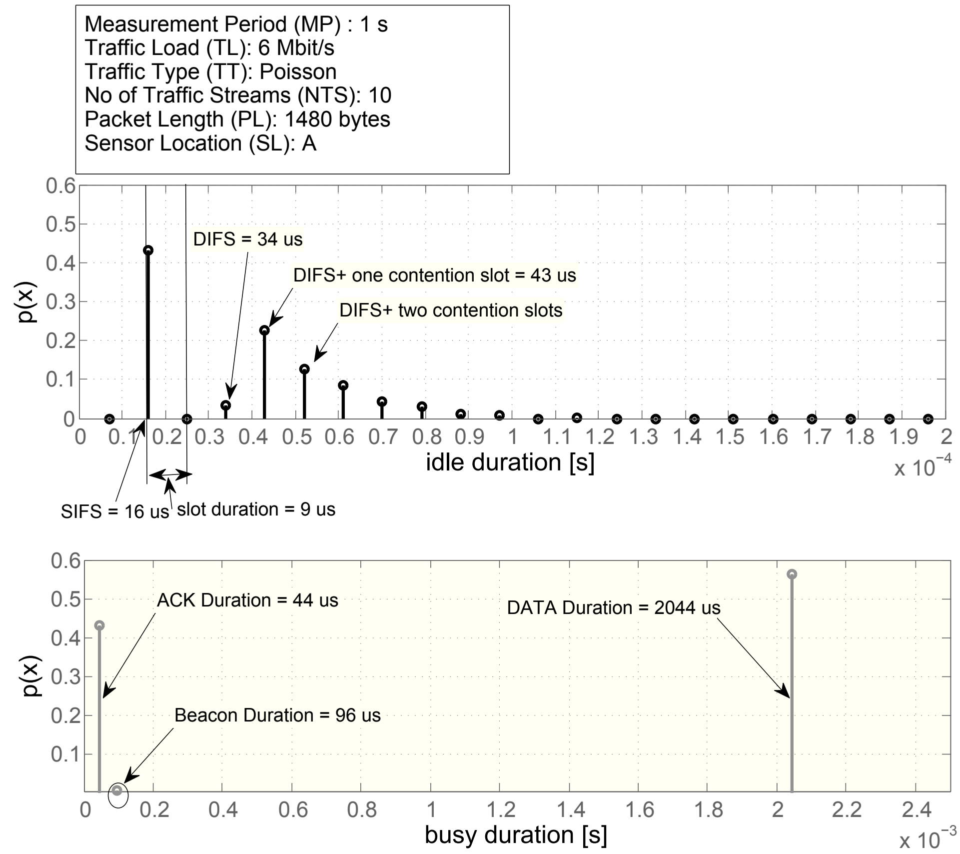


Figure 5.10: The PDFs of idle and busy period durations

802.11 channel access, there is a SIFS between DATA and ACK packets. As discussed earlier, if there were no collisions, then the probability would be expected to be 50 %. But in this case, due to several stations with saturated traffic load, there are collisions which results in the probability of idle period durations equal to SIFS duration less than 50 % but above 40 %.

- The probability of idle period durations equal to DIFS plus slot durations is exponentially decreasing. This is expected in the case of saturated traffic as the stations have always a packet in the MAC queue to send and they follow the exponential backoff algorithm for channel access.

The bottom part of Figure 5.10 shows the PDF of busy periods. The main observations are as follows:

- The probability of busy period durations equal to 44 μs, which is an ACK transmission duration, is high. In the IEEE 802.11 channel access, there is an ACK packet just after a DATA packet. As shown in case 3, when there are collisions of DATA packets, ACK packets are not sent according to the MAC access method. This is the reason why the probability of busy period durations equal to ACK is lower than the probability of busy period durations equal to DATA transmission durations in case of collisions happened in the network during the measurement duration.

- The probability of busy period durations equal to the beacon transmission duration is very low.

For the rest of the analysis, PDFs of idle and busy period durations are investigated from the simulation results for the following parameter space:

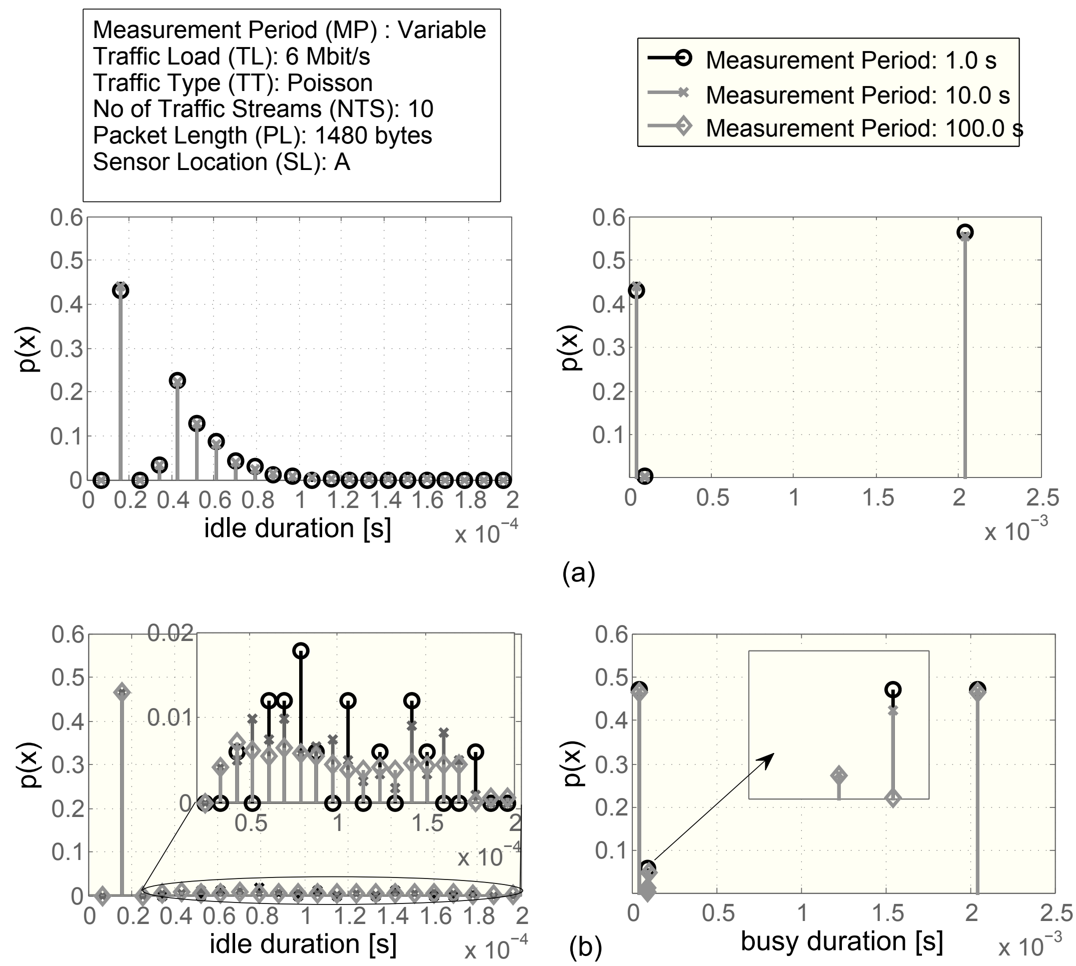


Figure 5.11: The PDFs of idle and busy period durations for different measurement periods, for (a) saturated and (b) low traffic load

- Measurement period
- Packet length
- Traffic load
- Traffic type
- No of traffic streams
- Sensor location
- Stations positions.

Measurement period: Figure 5.11 shows the PDFs of idle and busy period durations for different measurement durations, where the other parameters are configured as stated on top of the figure. Figure (a) and (b) are for saturated and low traffic load respectively. In the case of saturated traffic load, PDFs are similar even though the measurement duration is increased. In the case of low traffic load (i.e. 0.08 Mbps in each stream), equations in 5.5 match the probability of busy period durations equal to 44 μs and the probability of idle period durations equal to 16 μs quite well as the number of collisions are very low. The probability of busy period durations equal to a beacon transmission duration (96 μs) is almost 5 %. With increasing the measurement duration, the following fact becomes visible. The probability of idle period durations equal to DIFS plus slot durations is exponentially decreasing and this is one of the characteristics of IEEE 802.11 DCF channel access method where exponentially increasing random backoff is used.

Traffic load and traffic type: The PDFs of idle and busy period durations for low and saturated traffic load with constant bit rate (CBR) and Poisson traffic type are shown in Figure 5.12, where other parameters are configured as stated on top of the figure. Significant differences are not found in the PDFs due to different traffic types. Due to less collisions in the low traffic case, the probability of duration equal to SIFS and ACK is slightly higher than in the case of saturated traffic.

Traffic load and the number of traffic streams: Figure 5.13 shows the PDFs of idle and busy period durations when the number of stations varies in the scenario, with low and saturated traffic load.

At saturated traffic and single station, Equation 5.5 perfectly matches the results as there are no collisions. In this case, idle period durations are uniformly distributed between DIFS and DIFS + contention window (CW), which is expected. For a higher number of stations, effects of case 3 and 4 are seen in the probability distribution.

In the case of low traffic and a single station, due to the lack of samples (i.e., not fulfilling the law of large numbers from the perspective of statistical

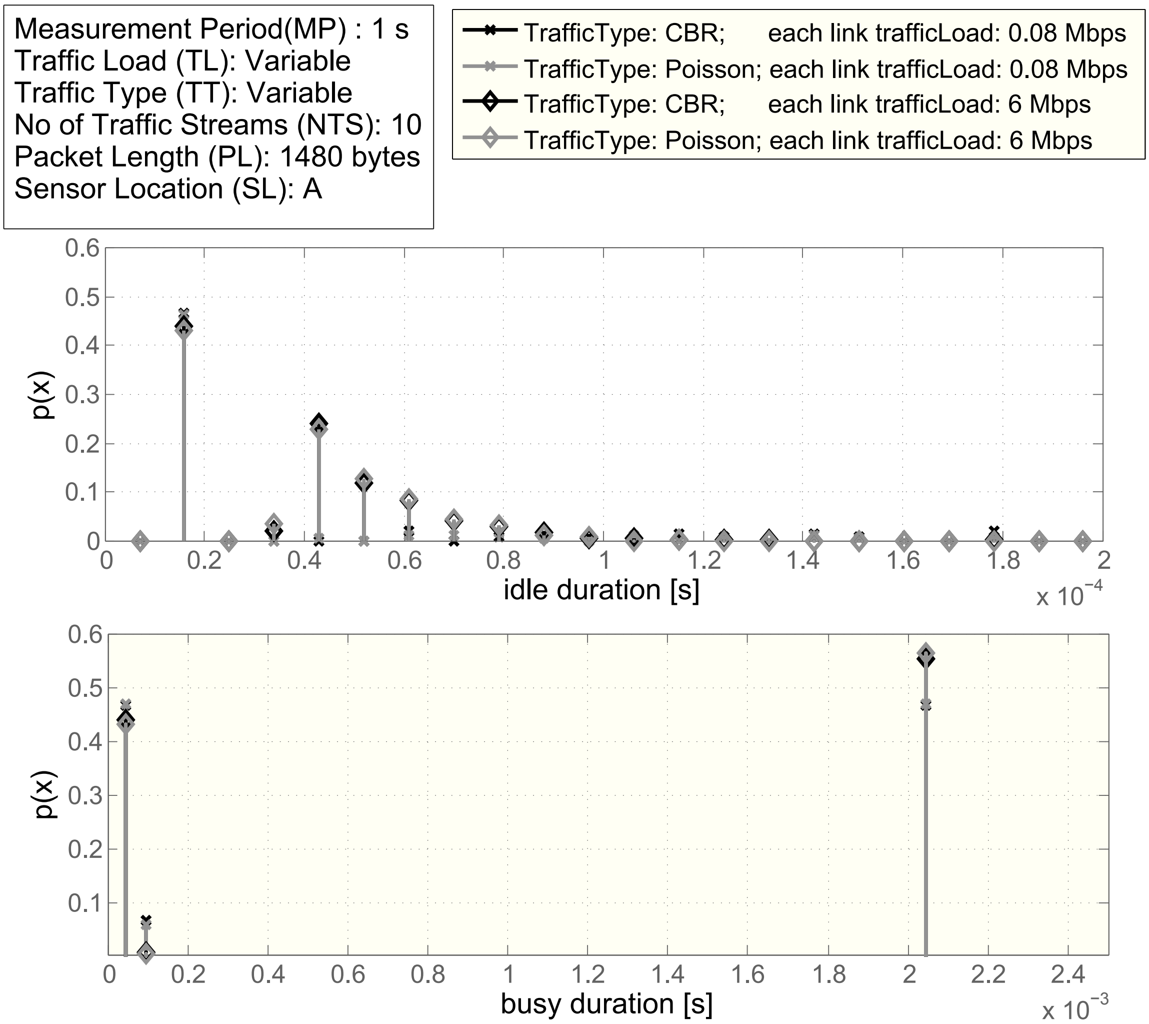


Figure 5.12: The PDFs of idle and busy period durations for different traffic load scenarios

evaluation) general patterns are not seen in the PDFs, e.g., the number of Beacon packets is higher than the number of DATA packets as shown in figure 5.14, which results in a lower probability of duration equal to DATA, SIFS, ACK. In such a case, a higher measurement duration is suggested for further verification.

Packet Length: Figure 5.15 shows the PDFs of idle and busy period durations in two different packet length scenarios. Similar patterns like SIFS duration and DIFS plus slot durations are visible in the PDFs of idle period durations. In the case of busy period duration PDFs, two different busy period durations corresponding to two different frame transmission time are noticeable.

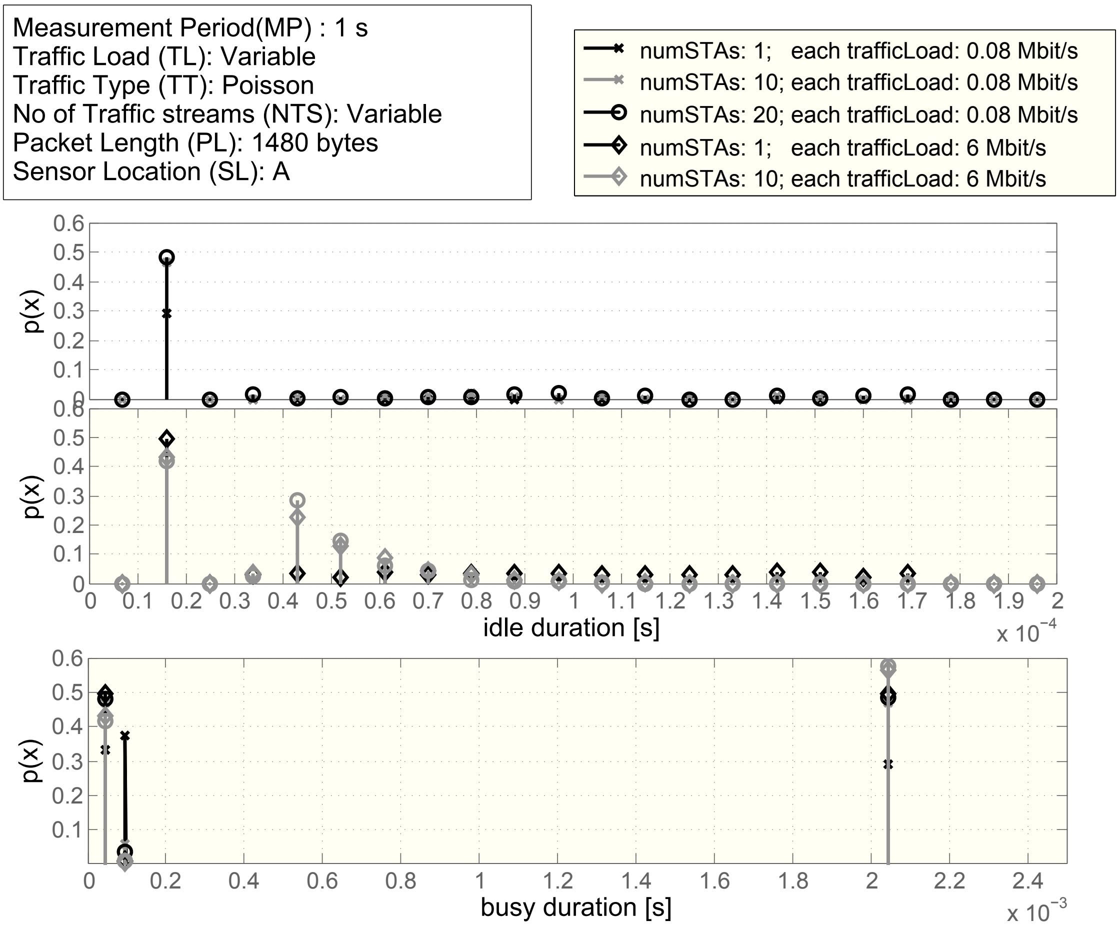


Figure 5.13: The PDFs of idle and busy period durations for different values of number of stations

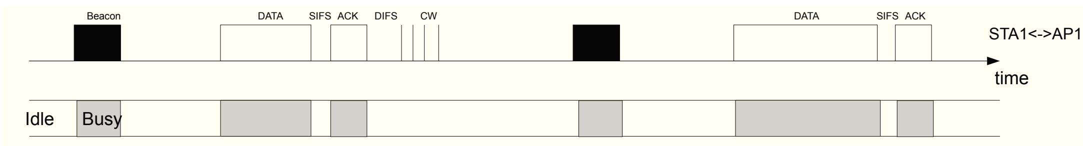


Figure 5.14: Idle and busy period durations in case of very low traffic

Sensor's position and stations' location: Figure 5.16 shows the PDFs of idle and busy period durations detected by the sensor node located in two different positions **Position A** and **Position B**, as shown in Figure 5.2. In this scenario, the channel access method experiences the situation like in case 4, where transmitting at the same time does not effect both DATA packets to be lost. That is why, from the sensor point of view, the numbers of sensed busy period durations equal to ACK durations and equal to DATA durations are almost the same. The probability of idle period

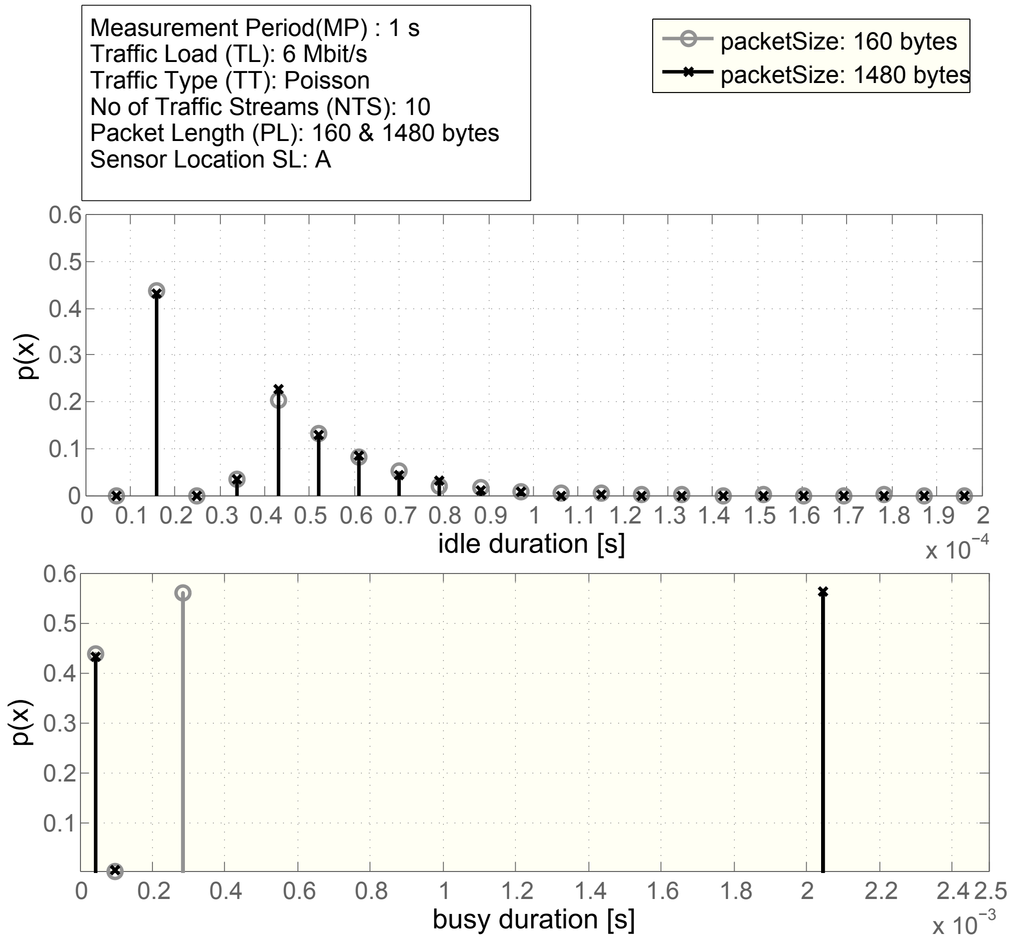


Figure 5.15: The PDFs of idle and busy period durations for two different packet lengths

durations equal to SIFS durations is also equal to that of ACK durations.

5.4.2 Analysis of 802.16 Channel Occupation

Figure 5.17 shows three different possible cases during the IEEE 802.16 channel occupation. In the figure the channel access by the stations and the idle and busy period duration measured by the sensor are shown. Idle period durations are due to unused capacity, inter subframe spaces and random access durations. Busy period durations are due to frame control information and DL as well as UL bursts.

- **Case 1**: In this case, low load is considered, so that, the capacity is not fully used, resulting in bigger idle period durations.

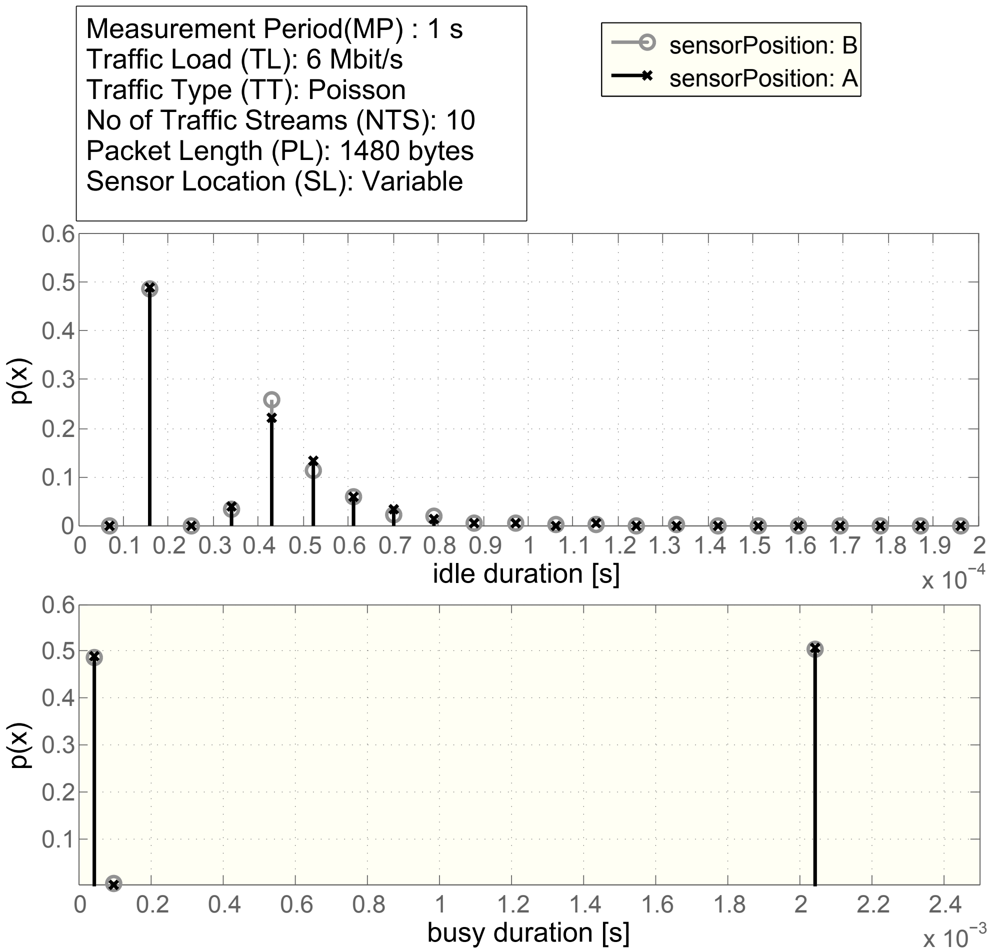


Figure 5.16: The PDFs of idle and busy period durations for different sensor locations

- **Case 2**: In this case, saturated traffic load is considered for both DL and UL. According to the OFDM PHY specifications [60], a PHY burst, DL or UL, has an integer number of OFDM symbols forming the MAC PDUs. To form an integer number of OFDM symbols, if some portions of the burst are not used, it is padded by 0xFF bytes to fill the remaining space.
- **Case 3**: In this case saturated traffic load is considered for both DL and UL. In the implementation, padding is not considered.

For the rest of the analysis, PDFs of idle and busy period durations are investigated from the simulation results for the following parameter space:

- Measurement period

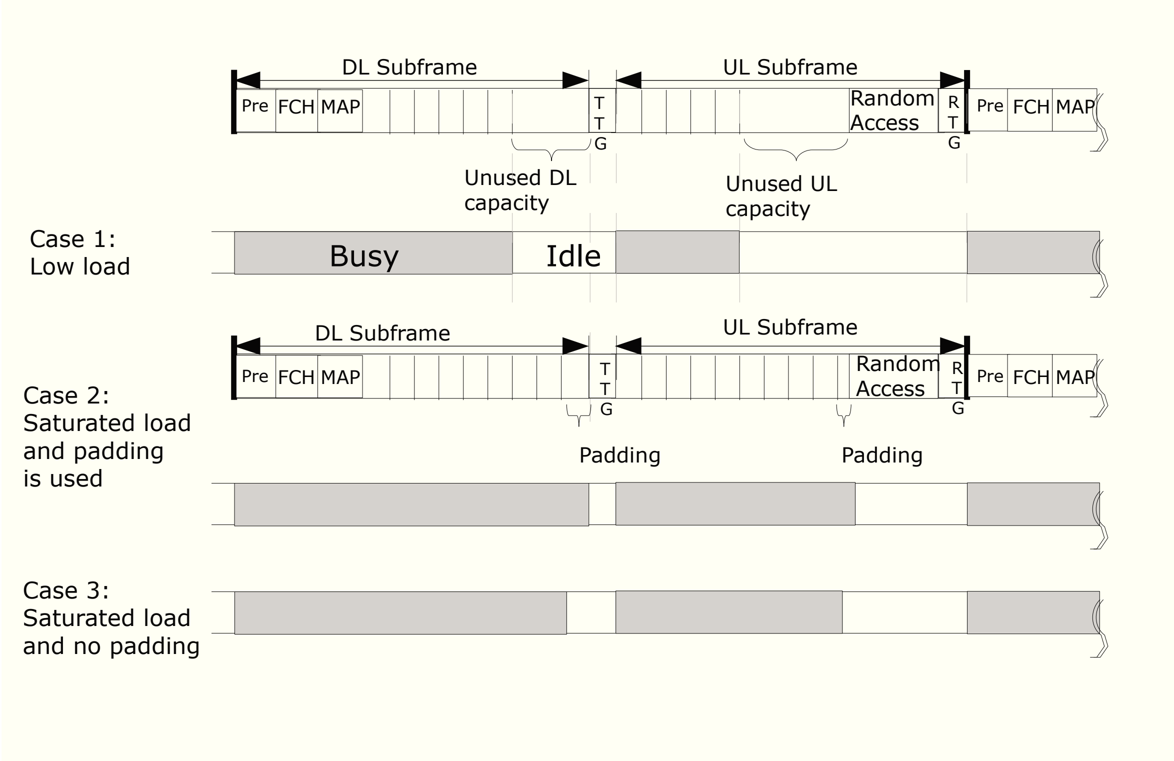


Figure 5.17: Different cases observed during the IEEE 802.16 channel occupation measurement

- Traffic load
- Traffic type
- Packet length.

Measurement duration and traffic type: Figure 5.18 shows the PDFs of idle and busy period durations for different measurement durations and different traffic types, with the general configuration as shown in the top of the figure. There is no significant difference for the above two variables. Like in Case 3, due to saturated traffic and no padding, two different idle period durations are observed, a smaller and a larger one at the end of the DL and the UL subframe respectively, which results in 50 % probability for each. The busy period duration distribution also follows the same principle, there are two different busy period durations for the actual UL and DL resource utilization.

Traffic type and traffic load: Figure 5.19 shows the PDFs of idle and busy period durations for varying traffic type and traffic load. Saturated traffic results are shown for comparison. With low load and CBR traffic, as expected, idle period durations are bigger, busy period durations are smaller

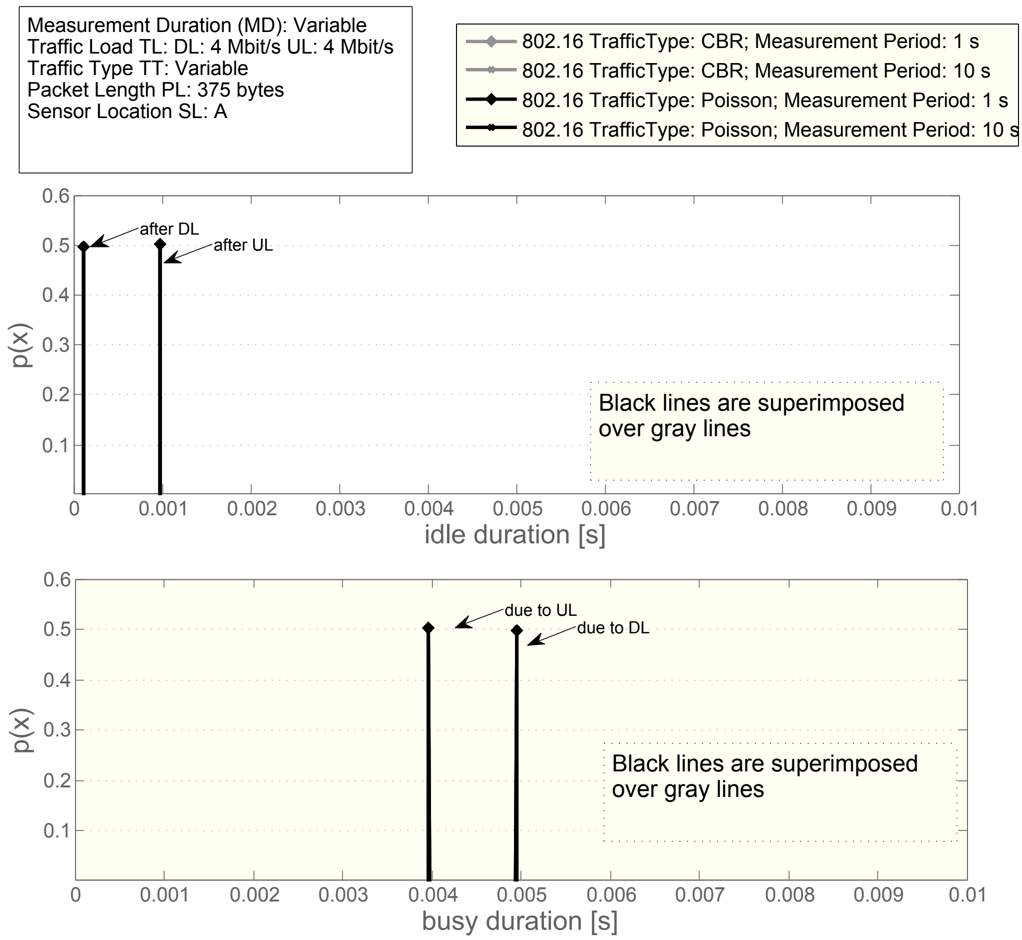


Figure 5.18: The PDFs of idle and busy period durations for different measurement periods

and they are almost fixed to few discrete values, where as in the case of Poisson traffic, idle period durations are distributed between 0 to 10 ms and busy period durations are mostly distributed exponentially between 0 to 3 ms.

Packet length: Figure 5.20 shows the PDFs of idle and busy period durations for varying IEEE 802.16 packet length in saturated traffic load. Due to smaller packets, more packets can be put into the subframe resulting in relatively lower idle durations.

From the above analysis of the channel occupation by the IEEE 802.16 system, there is no specific pattern of idle or busy period durations observed like in the case of the IEEE 802.11 system, where SIFS and ACK are quite often observed. However, one specific characteristic is expected to be present, i.e. the cyclic channel occupation. The interval of starting a

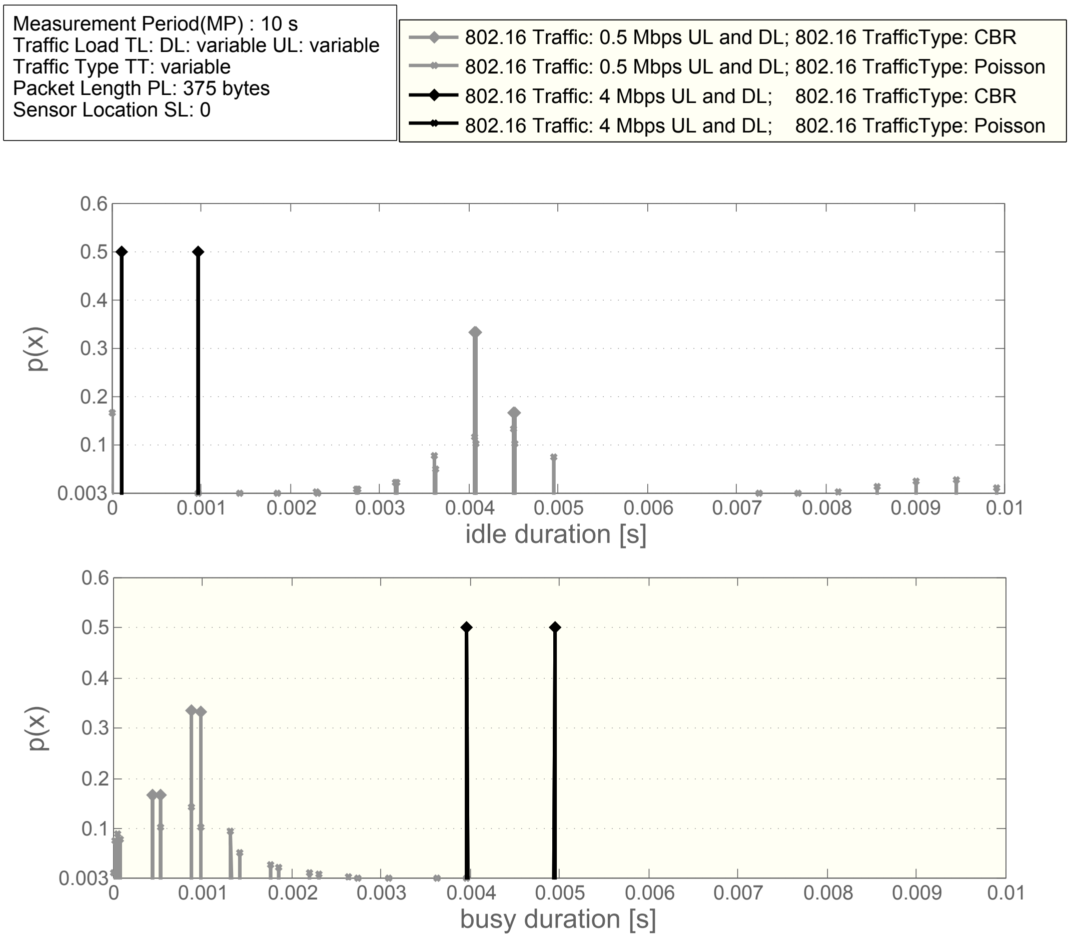


Figure 5.19: The PDFs of idle and busy period durations for different traffic types and load scenarios

busy period is expected to be more deterministic. Based on this statement, a different approach is considered for identifying the IEEE 802.16 system, which is the autocorrelation function, described in Section 5.3.2.3.

As a first step, the starting times of busy periods are measured by means of the RSS-based detection method, described in Section 5.3.2.1, when an IEEE 802.16 system is in operation and no interference or any kind of other errors occur. To quantize the starting time, a slot duration of 1 ms is assumed. It should be mentioned here that the IEEE 802.16 system, whose channel occupation is measured, has a frame duration of 10 ms and the DL and UL resource allocation is almost 50 %: 50 % (i.e. 5:5 in ms). In such a case the binary sequence vector is like [1000010000100001....]. In Figure 5.21, the autocorrelation coefficients (ACCs) are shown for different measurement durations, which represents different numbers of samples consid-

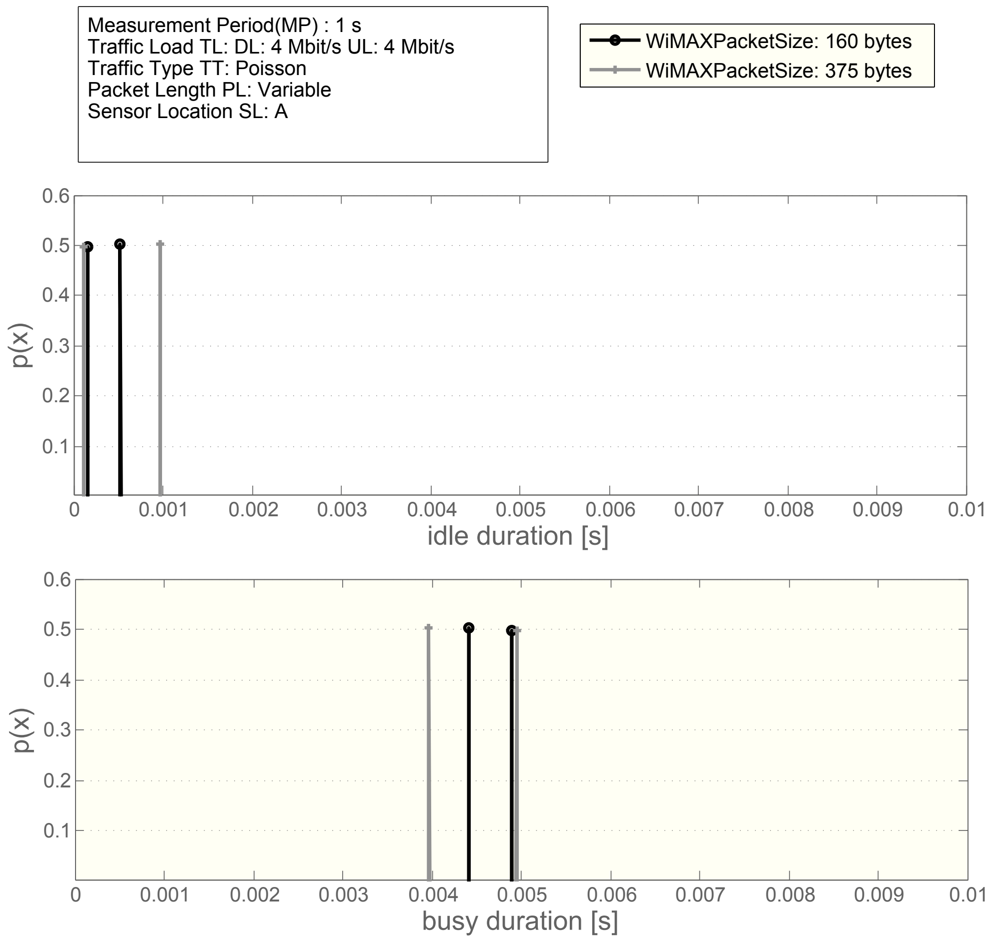


Figure 5.20: Th PDFs of idle and busy period durations for different packet lengths

ered for ACC calculation. In the figures the ACCs are shown for up to a lag value of 100. Lag values could be realized as milliseconds as the slot duration is equal to 1 ms. In the figures, the starting of the busy period is shown in gray line to show the characteristics of the autocorrelation function: the ACC values become higher at the time points where the periodic nature in the sequence is repeated. It is clear from the figures that the ACC values are significantly higher when the number of samples for the ACC calculation is higher. With less samples, for example N = 100, the threshold values are hard to detect as interesting ACC values are sharply decreased. From the nature of the figures, it is found that the ACC at the lag where cycle repeats is as follows.

$$r_k = 1 - \frac{k}{N} \text{ where } k = 10, 20, 30, \ldots \tag{5.9}$$

From above discussion, a good indication is found that a higher number of samples should be considered during measurements to find the significantly higher values of the ACC, so that further decisions based on ACC values can be taken confidently. From this analysis, a sample of 1000 representing a measurement duration of 1000 ms or 1 s is taken as the least sample size.

The upper two diagrams in Figure 5.22 show the ACC for different DL and UL ratios. It is significantly different from the previous 50 %:50 % case in a way that the ACC after each 10 lags is much higher compared to others. This outcome is exploited and interpreted as follows. The lag gap between the higher ACC values eases to predict the cyclic duration (frame durations). It can be seen that the change of DL to UL ratio, does not change significantly the ACC values at the points of interest. From this and the earlier analyses, it is concluded that by maintaining the least sample

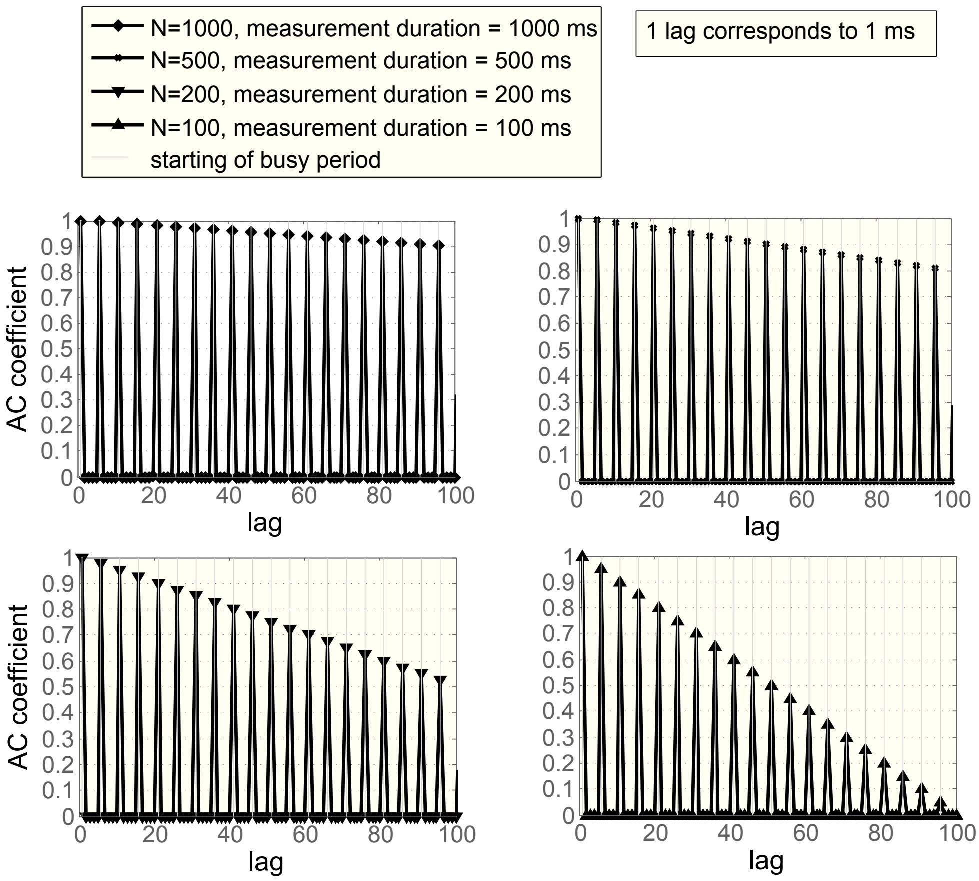


Figure 5.21: Autocorrelation coefficient for the binary time sequence of the busy period start by IEEE 802.16 system

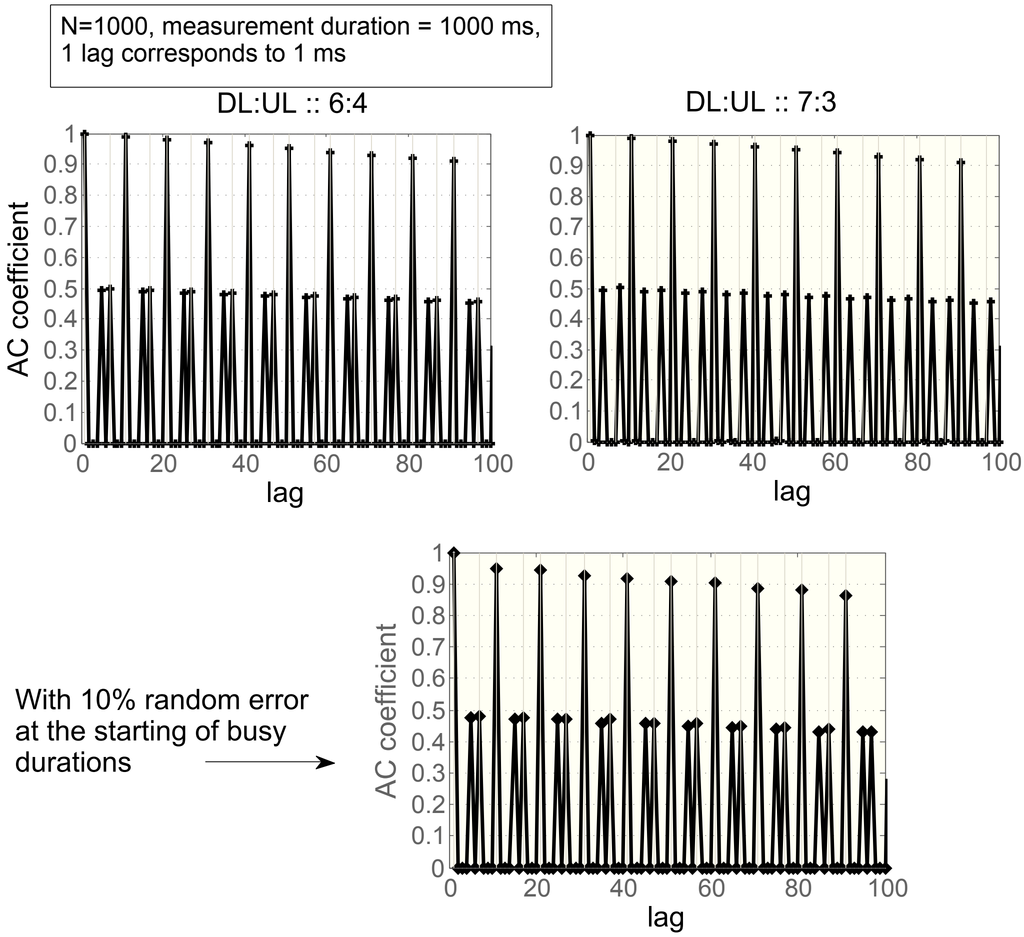


Figure 5.22: ACC for different cases in binary time sequence of start of busy period by IEEE 802.16 system

size during the measurement and assuming the 10 % error margin, an ACC threshold of 0.8 to 0.9 can be considered.

5.4.3 Identification of System Type based on Channel Occupation

Once the analysis has been done and the characteristics of the system type are found, they are used as conditions for system identification. The steps to identify the system type are as follows:

If one or more of the following characteristic patterns have been detected in the idle and busy period duration distribution, it is likely that an IEEE

802.11 system is operating in close vicinity:

- The probability for idle period durations less than the SIFS duration is zero.
- The probability for idle period durations equal to an SIFS duration is higher than other idle period durations.
- The probability for idle period durations equal to an SIFS duration is less than 50% and higher than $x\,\%$ (= $50\,\%$ - $plr\,\%$), where plr is packet loss of the observed networks in percentage.
- The probability for busy period durations equal to the length of ACK frame duration is higher than $x\,\%$, or if less, then at least the sum of the probability for busy period durations equal to ACK and beacon frame duration is higher than $x\,\%$.
- The probability for a busy period duration longer than the transmission time of a maximum PHY packet length in the most robust PHY modulation and coding scheme (MCS) is zero.
- The probability that a busy period equal to ACK occurs just after an idle period equal to SIFS is higher than (= $100\,\%$ - $plr\,\%$).

Note that Equation 5.6 are not applied to the above matching factors to provide fuzzy tolerance. If there is less confidence on the results than specified by the above matching factors, then the received channel occupation pattern is not considered as an IEEE 802.11 system. In this case, next steps are as follows. The measured time sequence of the busy periods starts is used to be represented by a binary vector. The ACC of the binary sequence vector is determined. What could be decided from the ACC is for example as following. A vector length of N=1000. a predefined threshold for the ACC of 0.8, and 10 % random error are assumed. The lag values for which the ACCs are above the threshold are identified, for example $q(ACC > 0.8)$. Those lag values are stored. Then the lag differences of consequent lags are determined. If these determined values are equal to or a sub-multiple of the IEEE 802.16 frame duration within a high (95 %) confidence range, then the channel occupied system is identified as IEEE 802.16.

Once the system type is identified then the traffic demand estimation is required.

5.5 Traffic Demand Estimation

There are parameters which represent an 'underlying physical setting' in such a way that the values of the parameters have direct or indirect impacts on the distribution of the measured data. By definition, estimation deals with predicting the values of those parameters based on measured/empirical data.

Traffic demand estimation can be done for one's own system and the other system. For the own system TDE, the input is the measured number of incoming bits into MAC layer queues and for the other system TDE, the input is the measured busy period durations resulting of the other systems transmissions. In both cases the input sample is the total measured value per unit time slot. In the following, the TDE for other systems is described and analyzed for the 802.16 systems.

Based on the measurements of the channel occupations done previously, the busy period durations $B(t_j)$ are calculated. For the traffic demand estimation those can be processed to calculate accumulated busy durations in a particular time window w (say 'measurement slot', e.g. 10 ms). Measurement slots are identified by n, where $n = 1,...,t_{meas}/w$ and t_{meas} is the total measurement duration.

The accumulated busy durations for nth measurement slot can be realized by the following equation:

$$B(n) = \sum_{j>n}^{j \leq n+w} B(t_j). \tag{5.10}$$

Each B value is considered as a sample input. Based on measured $B(n)$ values, the stations of the own system can estimate the traffic demand of the other system at time instance t_n. $B(n)$ values include all the overheads including signaling overheads.

Two methods are considered in the following for estimating the traffic demand.

5.5.1 Exponential Moving Average

One of the methods is to estimate the expected traffic demand for the next time 'window' (it depends on the method specification), according to an estimate of the traffic demand, measured during the last time window, $B(n)$. After each measurement sample, the traffic demand estimate is updated according to following equation

$$B'(n+1) = \alpha B(n) + (1-\alpha)B'(n) \tag{5.11}$$

where, $B'(n)$ and $B'(n+1)$ are the mean traffic demand estimates at time window n and $n+1$, $B(n)$ is the measured traffic demand in The last window and α is the weighting factor for the contribution of the latest estimate to the total estimate.

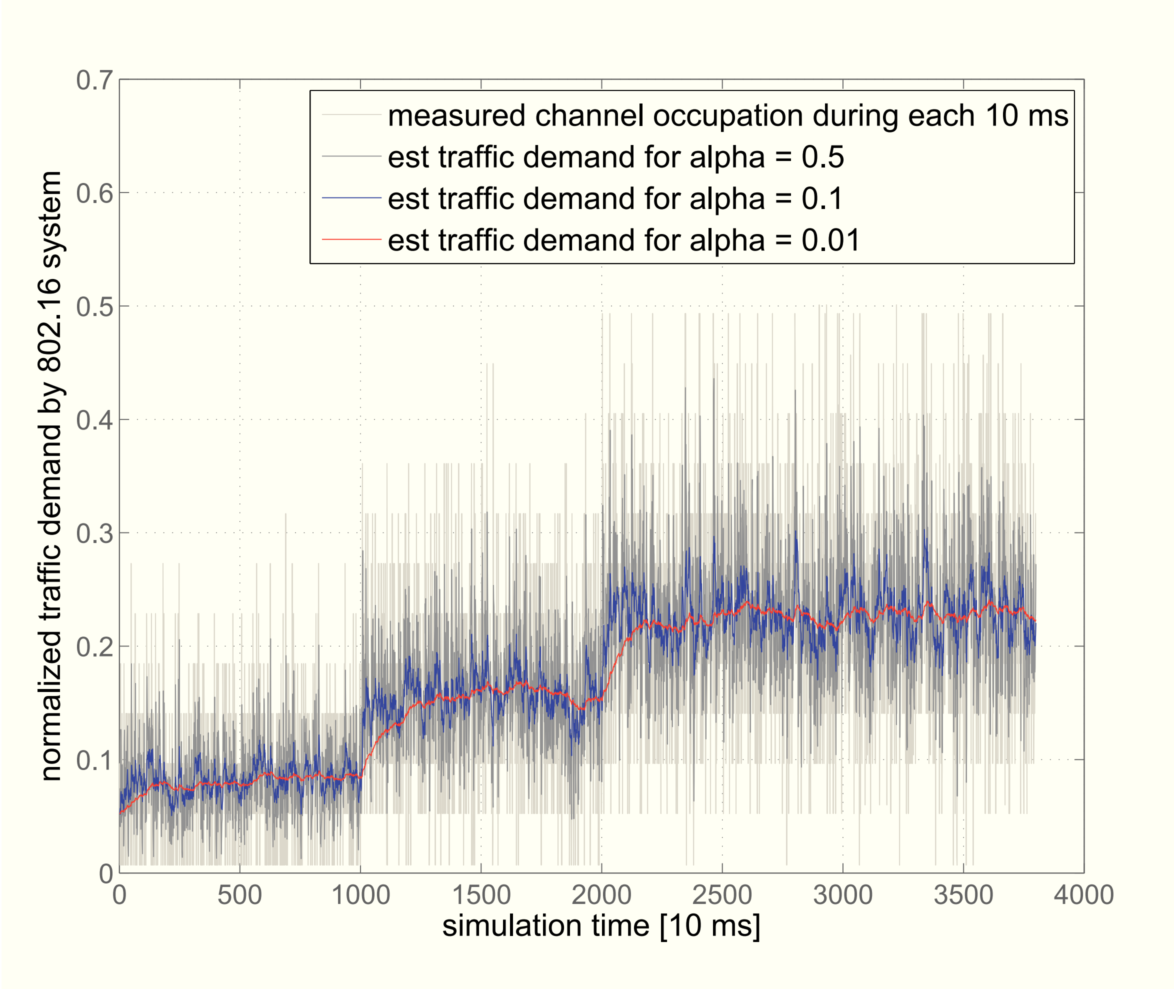


Figure 5.23: Traffic demand estimation for different α

The above mentioned method is known in theory as exponential moving average (EMA) or sometimes it is also called exponentially weighted moving average (EWMA). Mathematically it is equivalent to the low pass filter.

In this method, the weighting for older data decreases exponentially which is managed by the weighting factor α, which is also known as smoothing factor, a value between 0 to 1. A higher α gives more importance to the recent measurement, while older measurements are still not discounted.

Figure 5.23 shows the measured channel occupation by an IEEE 802.16 system by the light gray line, where each sample represents, as discussed before, a 10 ms measurement window. The channel occupation time is normalized by the whole window duration, that is why in the figure, the y-axes is denoted as 'normalized traffic demand by IEEE 802.16 system'. During the simulation time, the traffic load is intentionally increased by 1 Mbps from 1 Mbps to 3 Mbps after each 10 s. The busy durations measurement results reflect the load changes in the other system, though the randomness is seen clearly due to the traffic type distribution.

In this case, for showing the effect of α, measurements are done uninterruptedly for the whole simulation time. However, in the implementation of sensing methods, different approaches could be followed, for example, sense in a periodic manner (sensing time interval) for a specific time duration, discussed later in section 5.7.

The impacts of α on the estimation is shown by the rest of the curves in Figure 5.23. For $\alpha = 0.5$, 50 % weightage is given to the latest measurement. Thats why, there is a high fluctuation on estimation. For lower α values the curves, showing the estimation of mean traffic are becoming smoother.

The estimation error is calculated by taking the absolute value of the difference between the actual traffic demand measurement value in the next time duration window and the estimated value. In this case, the consideration of the next time duration is definition dependent. It could be equal to

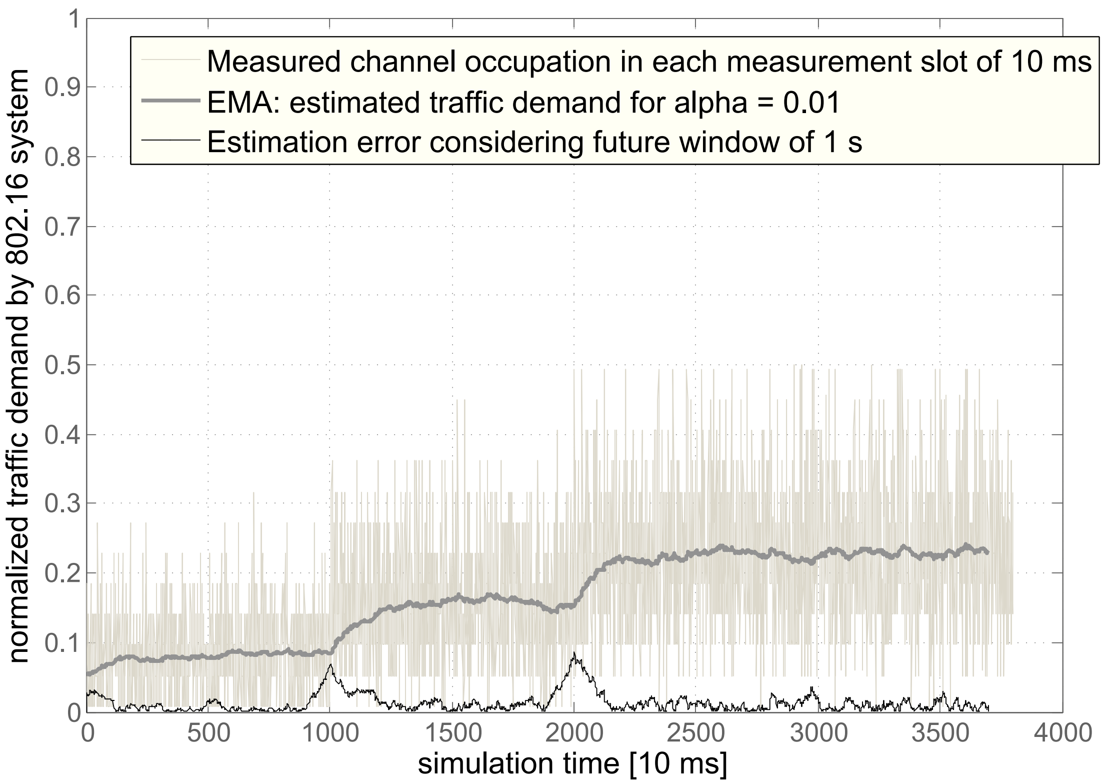


Figure 5.24: Estimation error for $\alpha = 0.01$ and future window of 1s for IEEE 802.16 system

only one measurement window w or a multiple of it. In the following, the estimation error $E(n)$ in time instance t_n is calculated,

$$E(n) = |\frac{1}{W} \sum_{k=n}^{n+W} B(k) - B'(k)| \tag{5.12}$$

where, W is denoted as *future window*, which is a multiple of w, $B(k)$ is the aggregated busy duration (see Equation 5.10), i.e, traffic demand measured at the end of the kth measurement slot for that particular slot and $B'(k)$ is the estimated traffic demand at the beginning of the kth slot.

Figure 5.24 shows the traffic demand estimation error when the estimation is performed by EMA with $\alpha = 0.01$. In this case, the size of the future window is considered as 100 times the measurement slot w, i.e. 1 s (100 * 10 ms). It is found that the estimation error is becoming higher during the period when the mean traffic load actually changes in the other system.

5.5.2 Statistical Distributions

The estimator estimates the parameters of a physical model based on measured data. Similar to before, the measured data is composed of the accumulated busy durations in the measurement slot of 10 ms. In this case, the traffic demand estimation is done by estimating the four different parameters (like mean, 50-, 90-, 95-percentile) from the empirical distributions, with the consideration that future data also will follow that. In the rest of the results, measurements are done in the simulation where the other system is an IEEE 802.16 system having exponentially distributed packet interarrival times.

Figure 5.25 shows the empirical distributions based on measurement data, when the measurement duration is varied. It can be seen that the bigger the measurement duration (the higher the number of measurement slots), the more reliable is the empirical distribution, based on which parameters are estimated. The next figures will give a closer look in this respect.

In these figures, values for four parameters are shown with respect to a 10 ms block (measurement slot) of simulation time. For each point on the x-axis, the four parameters' values are estimated based on the empirical distribution (ED), which considers a particular number of the last measurements slots, which is defined as the sliding window (measurement duration). The bottom diagram of Figure 5.26 shows the impacts on estimation of four parameters (mean, 50-, 90-, 95-percentiles) with measurement values for a measurement sliding window size of 1 s. It is seen that in different points of time, the values of the estimated parameters are different. This is expected and the cause is random traffic load. Four points in the figure are marked for explanation.

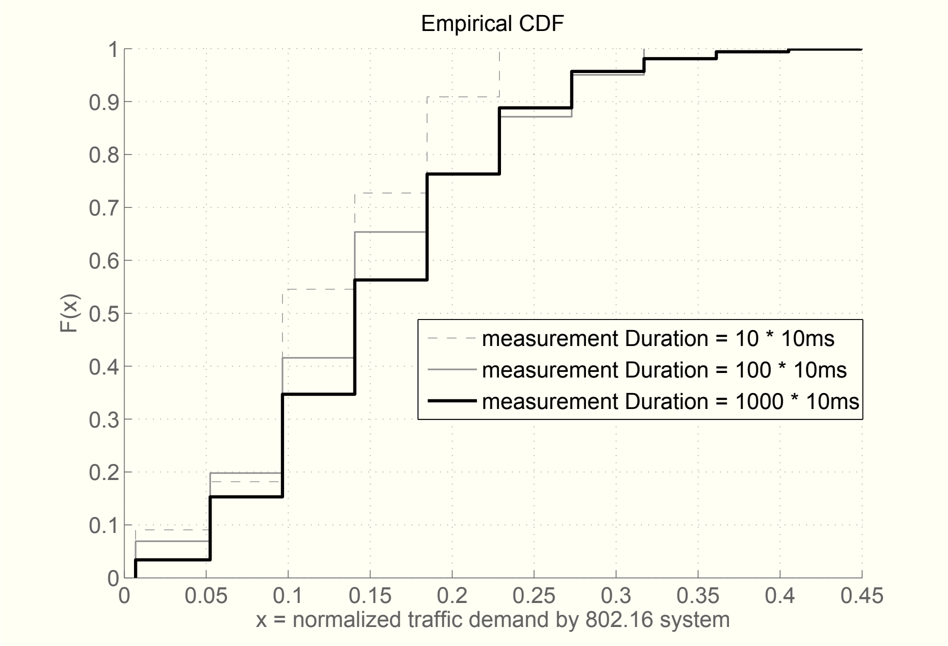


Figure 5.25: CDF of channel occupation (10 ms measurement slot) for different measurement durations

- (A) In 50 % of the cases, the measured load is below 5 %, in 90 % of the cases, the measured load is below 14 %, in 95 % of the cases, the measured load is below 18 %.
- (B) In 90 and 95 % of the cases, the measured load is below 18 %, which means some higher measured values (> 14 %) are considered in the sliding window.
- (C) In 50 % of the cases, the measured load is below 10 %, in 90 % and 95 % of the cases, the measured load is below 18 %. This means in the last sliding window, the measured values (> 5 %) are increased. That is why the mean is also increased.
- (D) In 50 % of the cases, the measured load is below 5 %, in 90 % and 95 % of the cases, the measured load is below 14 %. This means in the last sliding window, the measured values (> 5 % and > 14 %) are decreased. That is why the mean is also reduced.

The impacts on estimation of the four parameters (mean, 50-, 90-, 95-percentiles) for the two different sliding windows are shown by providing two diagrams in Figure 5.26. The results are shown for 10 s model time which is enough to show the tendency of the parameters, when the mean traffic load is fixed. It is found that the changes in parameter values are more stable in the bottom diagram, where the sliding window size is 1 s, than in the top

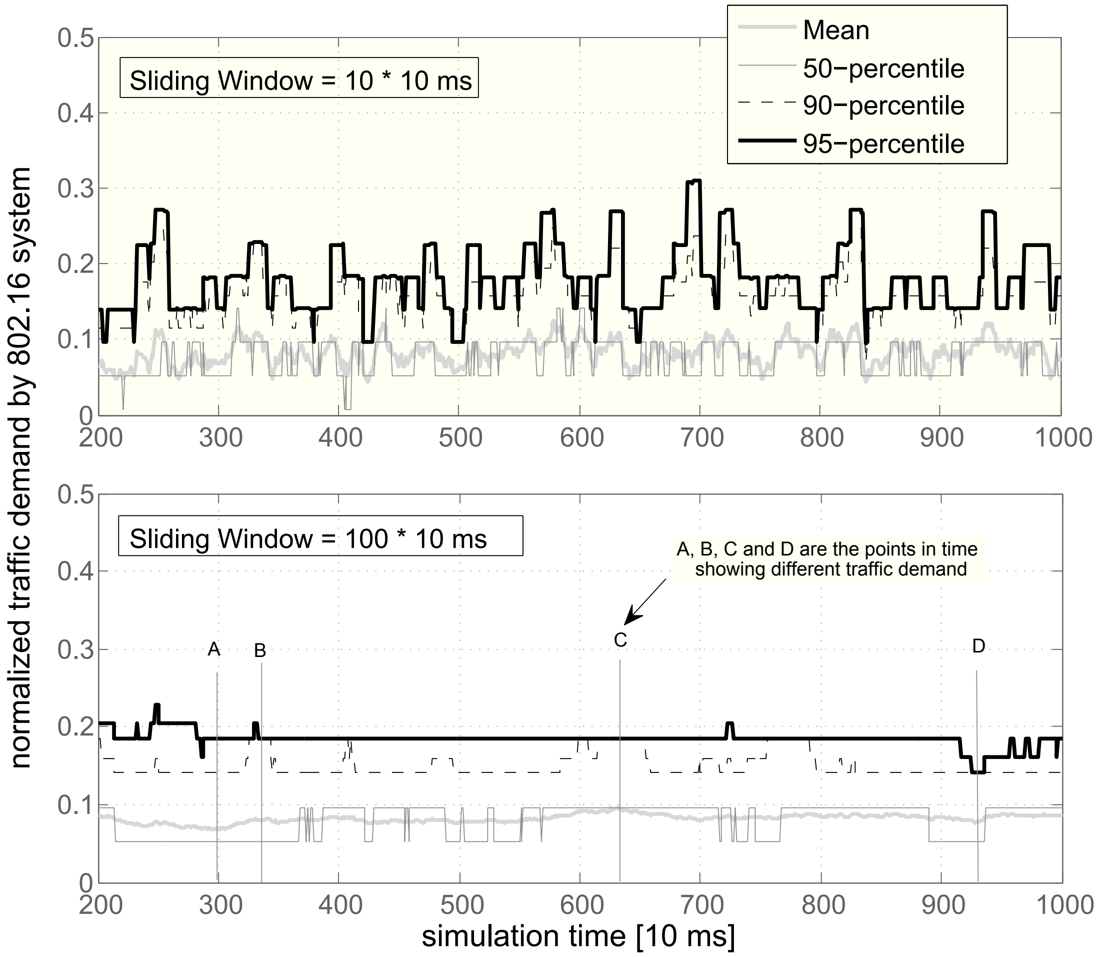


Figure 5.26: Mean and 50-, 90-, 95-percentiles of channel occupation (10 ms measurement slot) for sliding window of 0.1 s (above) and 1 s (bottom)

diagram with a sliding window size of 0.1 s.

For further analysis, the traffic load of the other system is changed as follows. After every 50 s, the traffic load is increased by 0.5 Mbps, up to 3.5 Mbps at 300 s. Figure 5.27 shows the parameters' values, representing the traffic demand estimation, against simulation time and the impacts of traffic load changes on the parameter are clearly visible.

As the resource allocation to the other system is fixed to near to 50 % and the traffic load is increased to 2 Mbps (33 % considering the PHY mode (6 Mbps) and without overhead), the upper diagram in Figure 5.28 already

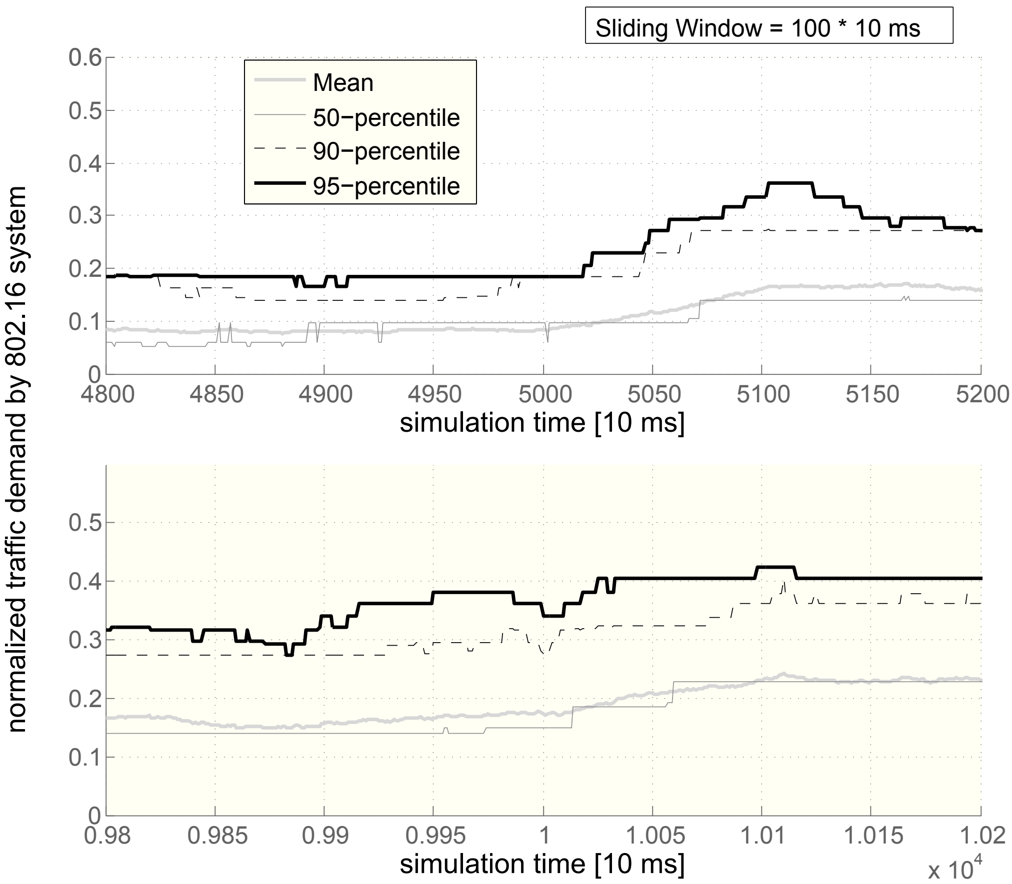


Figure 5.27: Mean and 50-, 90-, 95-percentiles of channel occupation while changing traffic demand in two different regions on the model time

shows that in 95 % of the cases the load is below 50 %, however, for 5 % above cases it might be more. It already gives an indication that the resource allocation can be increased. When the traffic load is increased to 2.5 Mbps, the 90- and 95-percentile already coincide (resulting in a truncated distribution), which clearly indicates that 10 % of the traffic might not be served or served with delay, based on the methods like buffer management. In other words, the difference between the 99-percentile and the 95-percentile is almost zero, which gives a hint that there is a high probability that the channel allocation by the other system is limited to corresponding parameters' values. It is also an indication of increased traffic demand. The lower diagram shows that even the difference between the 50- and the 90- percentile is almost zero, which indicates that the traffic load of the other system is saturated

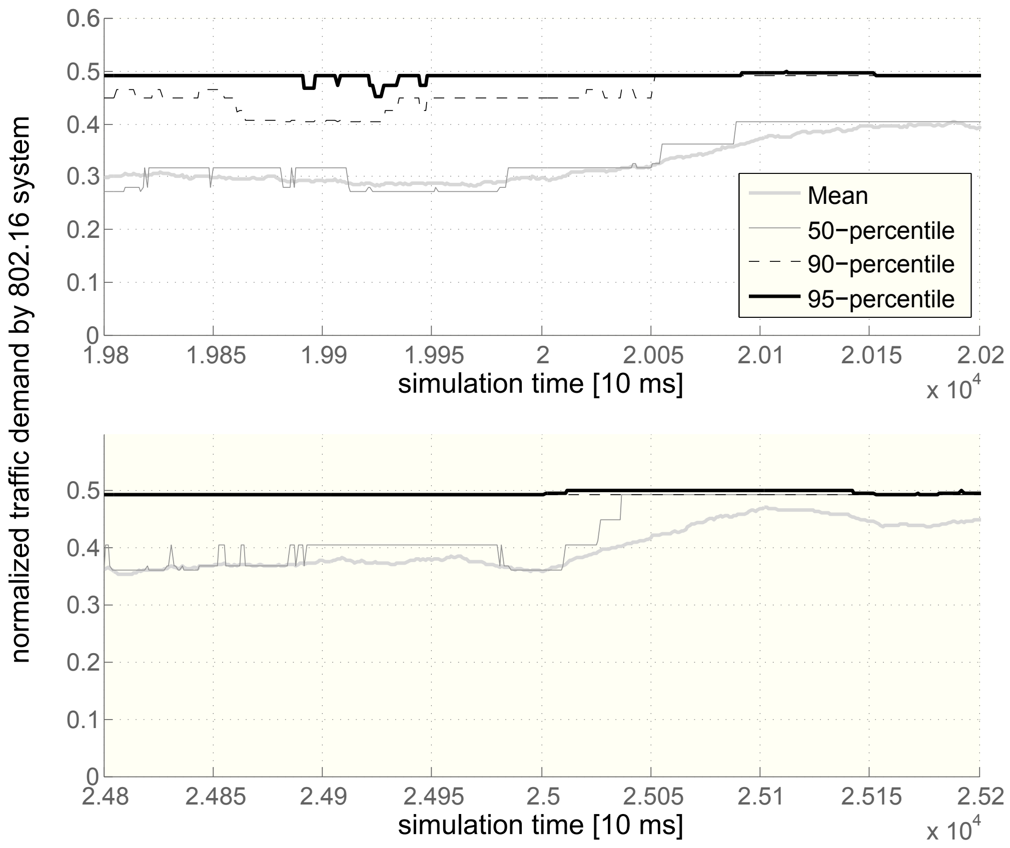


Figure 5.28: Mean and 50-, 90-, 95-percentiles of channel occupation while changing traffic demand in another two different regions on the model time

considering the allocated resource. This is true because the traffic load of the other system is increased to 3 Mbps after 250 s.

Figure 5.29 shows the effect of the packet size on the channel occupation. The figure shows that the variance increases with increased packet size. It should be noted that for a fixed PHY data transmission rate, the mean time to serve each PHY Protocol Data Unit (PPDU) corresponds to the packet size. The effect of adaptive modulation and coding (AMC), which chooses a higher PHY data rate than 6 Mbit/s, is also shown. In this case, a scenario consisting of a packet size of 3000 bits and a traffic load of 0.5 Mbit/s is configured. As expected, a higher data rate results in a smaller mean service time and thus shorter channel occupation. Estimated parameters against simulation time are shown for above scenarios in Figure 5.30.

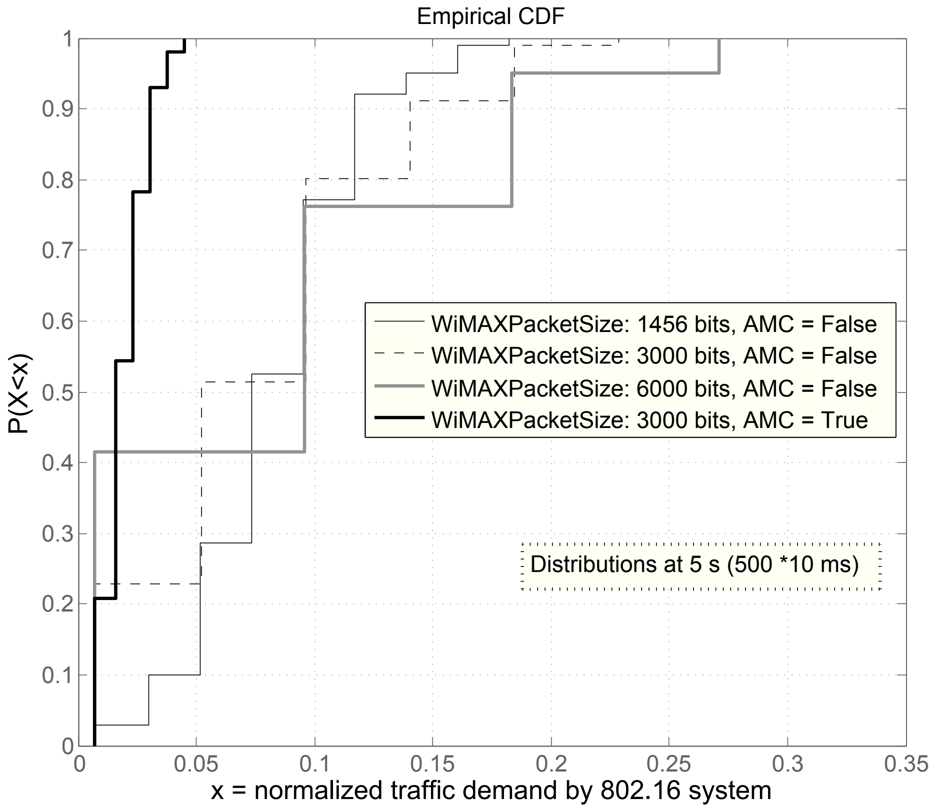


Figure 5.29: CDF of channel occupation for different packet lengths with and without adaptive modulation and coding scheme (AMC)

By having obtained the knowledge about the distribution and its parameters, the traffic demand of the coexisting system, in this case the IEEE 802.16 system, is estimated. This eventually helps configuring the spectrum sharing parameters like the resource allocation for the own system, which is discussed in the next chapter.

What has been described up to now is the measurement of the channel occupation and the traffic demand estimation for the other coexisting system. However, for the own system, two possibilities are there: traffic specification and estimation of traffic demand. The traffic specification, provided from the upper layer, is considered as the best case situation. However, when it is not available, the second case is considered. In the second case, estimation is based on the observation of the corresponding buffers. This is done by having socalled 'buffer sensors', which measures the incoming bits in the buffers per unit time, resulting in estimated traffic load distribution.

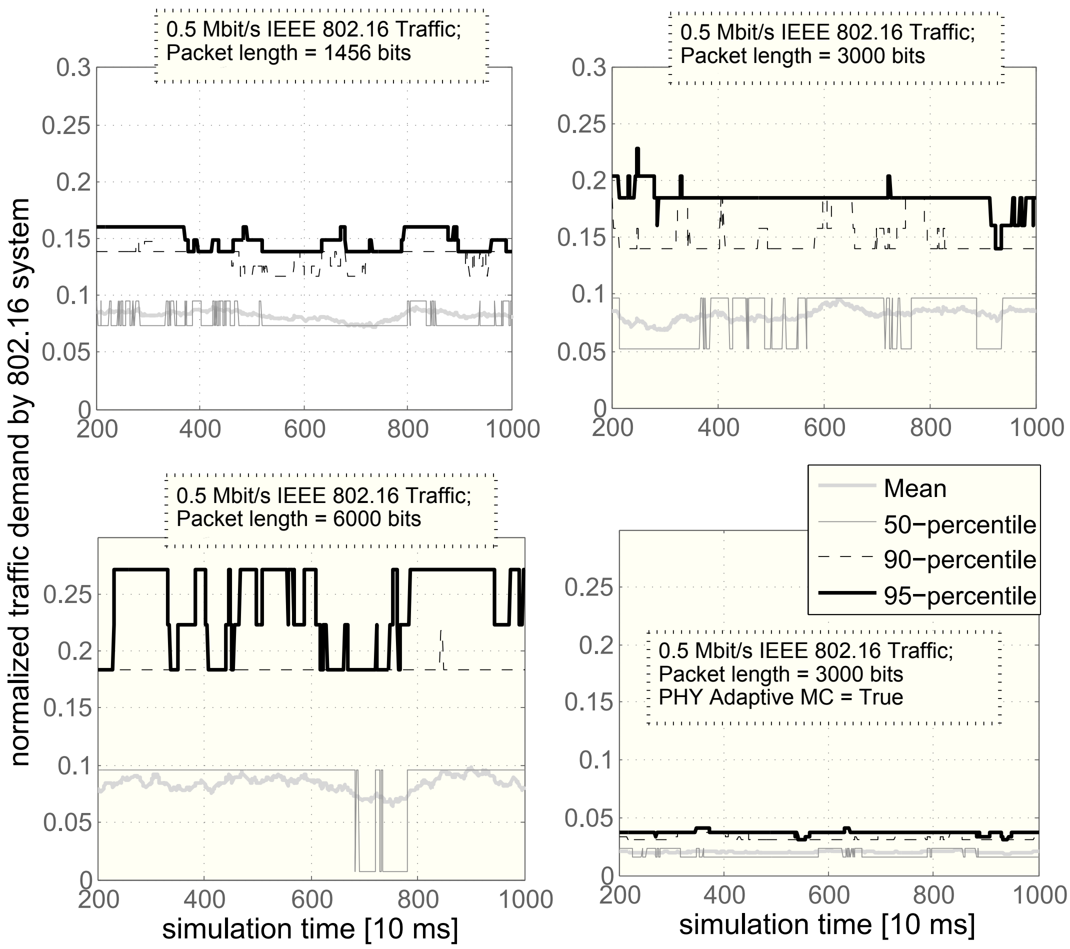


Figure 5.30: Mean and 50, 90, 95-percentiles of channel occupation (10 ms window) for different packet lengths with and without adaptive modulation and coding scheme

In the case of empirical distribution based estimation, more detailed characteristics of the traffic demand are achieved compared to the EMA based estimation, which in some extent enhance the capability to maintain the QoS level for the different traffic classes inside the system. For example, in the case of a system where QoS requirements need to be met, the x-percentile parameter value can be used for resource allocation calculation. However, the cost for computation and memory usage is higher in latter method than the former EMA based estimation method.

In the following section the architecture for buffer filling measurement and own traffic demand estimation are described.

5.6 Buffer Sensing Architecture

The block diagram of buffer sensing method for the own traffic demand estimation is shown in Figure 5.31 and described as follows:

- **Incoming Traffic Measurement**: The size of the packets coming into the MAC buffer is measured. In this case, packets are without MAC and PHY overhead.

- **Measurement Data Processing**: The number of incoming bits into MAC layer buffer in a particular time window (say 'measurement slot', e.g. 10 ms, as considered in traffic demand estimation for the other system) is determined in this block for the own traffic demand estimation (TDE).
  Measurement slots are identified by n, where $n = 1,...,t_{meas}/w$ and t_{meas} is the total measurement duration.
  The accumulated incoming bits $B_{in}(n)$ at the nth measurement slot can be calculated by the following equation:

  $$B_{in}(n) = \sum_{j>n}^{j \leq n+w} PL(t_j). \tag{5.13}$$

  where, $PL(t_j)$ is the packet length in bits of the packet coming into the MAC buffer at time instance t_j. B_{in}, representing incoming bits per unit time, is normalized by the PHY data rate. Each normalized B_{in} value is considered as a sample input for TDE method. Based on measured $B_{in}(n)$ values, the stations of the own system can estimate the traffic demand of the own system at time slot n.

- **Processed Data Management**: In the scope of this block, the required raw and processed data are stored for next steps.

- **DIEngine_own**: In this block, the processed information is analyzed in order to estimate the own TD. Similar estimation methods discussed in previous section, the exponential moving average and the empirical distributions are used for this purpose in the **traffic demand estimation** block. Details with simulation results are not provided due to similarity. **Traffic type identification** block is provided in the architecture as an optional block, where algorithms like pattern recognition based method could be applied to identify the traffic type. This would help to optimize resource allocation based on traffic type and its QoS requirement when traffic specification is not provided from the upper layer.

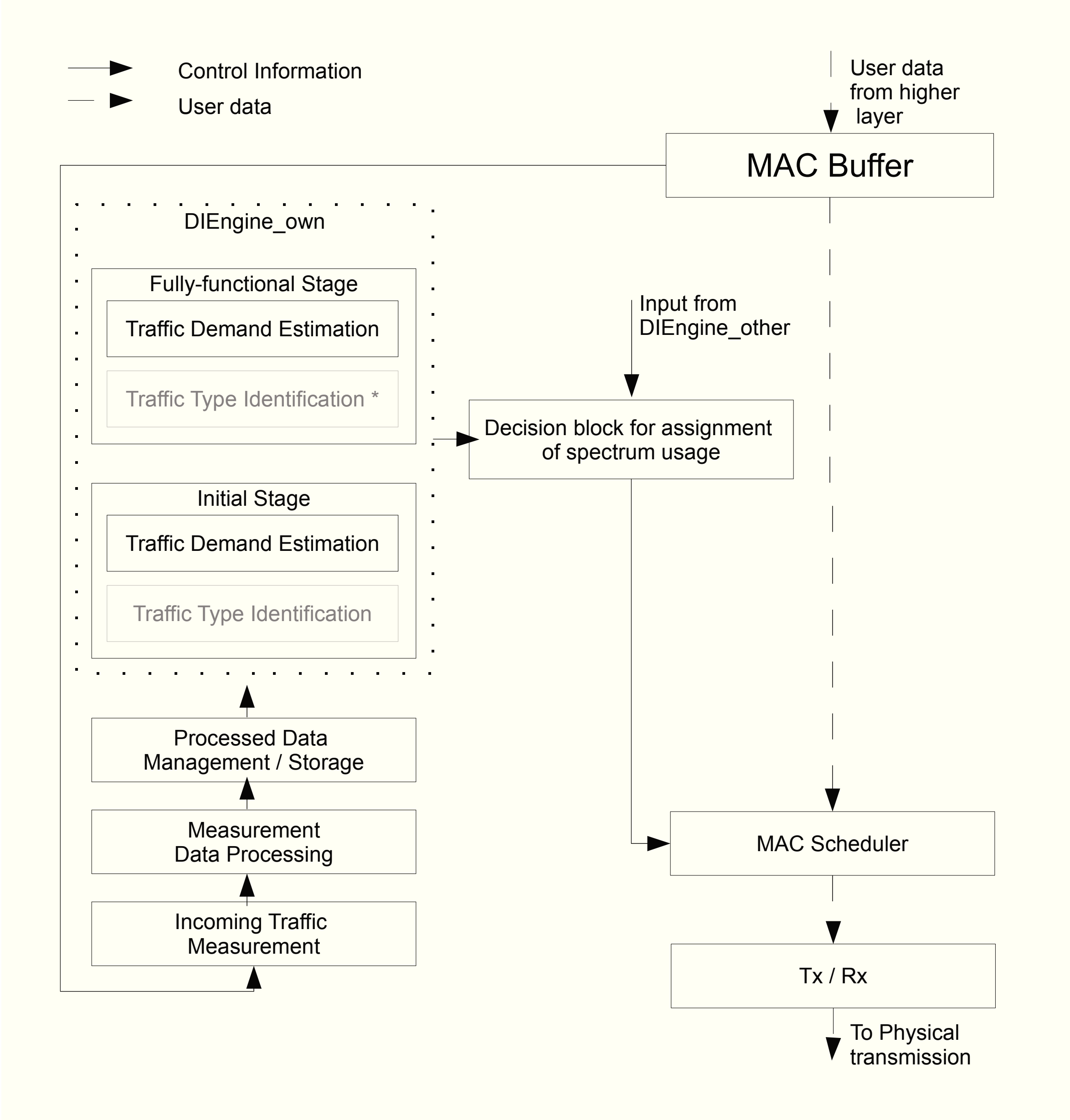


Figure 5.31: Block diagram of functional blocks for estimating own traffic demand

- **Decision Block for Assignment**: Outcome of TDE in **DIEngine_own** is fed into this block which has the responsibility to decide on the resource allocation for the own system and for the other system. This block also gets input from **DIEngine_other** shown in Figure 5.1. User data scheduling in the **MAC Scheduler** is done based on resource allocation.

5.7 Sensing Strategy Solution Space

In this section, a solution space is provided for spectrum sensing considering different types of system configuration. A single mode station is the main focus of this analysis.

- **Single Mode - Single Interface**
  A station cannot decode the packets from other technologies, rather the station senses the other transmissions as noise. To sense properly the transmission of other systems, the station has to quiet its own transmission. The station has only one interface for transmission (Tx) and reception (Rx). In this case, it is very important to manage the sensing method based on how and when to sense.
  - Option 1: Periodic
    Sense the transmission of other systems in a periodic manner, i.e, sense the channel for specific time duration (*sensing duration*) in a specific time interval (*sensing period*).
  - Option 2: On demand
    Sensing is triggered by the system based on the performance evaluation. Some examples are as follows.
    - the packet loss ratio reaches a threshold
    - the number of delayed or lost Beacons (in case of IEEE 802.11)/ frame control header (in case of IEEE 802.16) reaches a threshold.
  - Option 3: Utilizing the RCA method
    In the RCA method, channel access is more periodic. So there is a possibility to sense the channel during the time when the own system becomes idle. In this way, the sensing overhead is reduced.
    - Option 3.1:
      - Just after own transmission stops, start sensing.
      - Just before own transmission starts, stop sensing.
      - It could be realized for stable case.
    - Option 3.2:
      - Start sensing at the time where the ending point of transmission for own system is predicted according to the estimated own resource allocation.
      - Stop sensing at the time where the starting point of transmission for own system is predicted according to the estimated traffic demand of the other systems.

- **Single Mode - Dual Interface**
  In this case, a station has two interfaces: one interface for transmission and reception among the stations of own technology and another interface for sensing.
  - Option 3 of the previous case is more suitable in this case.
  - The second interface senses the overall ongoing channel occupation and later subtracts the channel occupation by the own system to deduct the channel occupation by the other system.
- **Dual Mode - Dual Interface**
  The station can decode the packets from other technologies. It would be a trivial case for sensing. So it is not discussed further in the framework of this thesis.

5.8 Conclusion

In this chapter, two functional architectures are provided: one is for detecting channel occupation, identifying the system which is occupying the channel and lastly estimating the traffic demand of that system from channel occupation, and the other one is for estimating one's own traffic demand based on the aggregated incoming bits in the MAC queues of own system. The former one is more elaborately discussed in the chapter. Statistical analysis on channel occupation traces from the simulation is performed and illustrated for clear understanding, from where the specific threshold values for system identification method are concluded. In this respect, analytical formula to estimate the probabilities of different idle and busy period duration events are provided as well. Two different traffic demand estimation methods, the exponential moving average and the statistical distributions are developed and evaluated.

CHAPTER 6

SPECTRUM SHARING METHODS

At the beginning of this chapter, different domains for spectrum sharing are described with referencing the existing knowledge and development in the context. A coexisting wireless networks scenario, where sharing of spectrum in frequency and space domain might not be possible for all systems due to a high density of wireless networks/systems and a low number of available channels, is considered as a problem solving scenario. This highlights the requirement of a spectrum sharing method in time domain by means of proper scheduling and synchronization among the systems. Then a generic spectrum sharing approach called Regular Channel Access (RCA) is proposed and described, which is modeled and evaluated considering the fully overlapping homogeneous and heterogeneous coexisting networks scenarios in Chapter 8 and 9 respectively. These two scenarios are discussed in Chapter 4.

The chapter begins with an introduction and the current state of the art in spectrum sharing methods in Section 6.1. The concept developed inside the framework of this thesis is presented in Section 6.3. Section 6.4 gives the overview of the simulation tool which is used throughout the thesis work for the evaluation of different methods, like RCA. The chapter ends with a summary in Section 6.5.

6.1 Introduction and State of the Art

The term *spectrum* usually refers to frequency bands. However, technically the concept of spectrum sharing is not only limited to the context of sharing the frequency bands, but spectrum can also be shared in the time, space and power domain. So there are principally four domains which are explored to have an optimum spectrum sharing method.

- **Frequency domain**: Spectrum sharing in the frequency domain means the coexisting systems should not use, or at least try to avoid transmission in overlapping frequency bands. The spectrum sharing concept Dynamic Frequency Selection (DFS) [59, 70] is an example in this context. A multi-carrier modulation approach like OFDM is a way to exploit several smaller idle frequency bands to combine and create a proper transmission opportunity for a system [57]. A similar approach is mentioned in [95] by two ways: 1) adjusting the bandwidth by means of adjusting the number of OFDM subcarriers, 2) the total no. of OFDM subcarriers can be divided over different frequency bands (channels) with a synchronization symbol (pilot), based on identifying several smaller idle frequency bands (opportunity). A hybrid approach combining the above two can provide even better spectral efficiency.

- **Space domain**: Spectrum sharing in the space domain is trivial in some perspectives. When the systems are located in such distant places that there is no possibility of overlapping of transmission coverage areas, then the systems can share the same frequency bands. This kind of approach is generally followed in cellular networks for frequency planning and reusing the spectrum. Mobile cellular networks are operating in the licensed spectrum bands, which are very expensive, for example, Universal Mobile Telecommunications System (UMTS) licenses. Non overlapping cells reuse the same spectrum bands. The basic and advanced frequency planning in the case of cellular networks are discussed in [80].

- **Time domain**: When the density of systems exceeds the number of available (orthogonal) channels in the same location, then spectrum sharing in time domain is inevitable. Spectrum sharing in time domain means that systems use the same frequency band in different time periods. The CSMA concept is an example in this context. Using the idle periods in TDMA fashion is another possibility, however, in this case coordination/synchronization among the systems – direct or indirect – needs to be present. In [4] Berlemann and Walke propose a mechanism called Spectrum Load Smoothing (SLS). Using the extensions of IEEE 802.11e and additionally applying SLS assures a periodic channel occupation improving the performance of coexisting systems.

- **Power domain [57, 56]**: Spectrum in the power domain can be shared as follows. A system can transmit in a specific power level in any of the above domains (time, frequency, space, or any combination) in such a way that its transmission does not exceed the tolerable interference threshold of receivers from other systems. Transmission opportunities in this case are called 'grey spaces' [56]. Spread spectrum techniques like Wideband Code Division Multiple Access (WCDMA), Ultra-Wideband (UWB) are examples in this context. Transmission Power Control (TPC) [59], by shortening the coverage range of the propagation by means of reducing the transmission power level, can also be considered as an example where power and space domain are exploited.

As discussed above, there are four possible domains where spectrum sharing is possible for transmission and this is often referred to as transmission opportunity. A transmission opportunity, also called 'spectrum hole' or 'white space', can be obtained in any or the combination of these four domains.

6.2 A Generic Analysis of Interference in Coexisting Scenarios

In this section, a generic analysis of interference due to different types of wireless networks, which are based on following channel access (ChA) methods are discussed.

- Pure ALOHA: User terminals transmit their data packets as soon as they have the packets. The system accesses the channel randomly and does not have a mechanism like *Carrier Sense Multiple Access (CSMA)*.
- CSMA/CA (which includes random backoff): Extension of Pure ALOHA in two directions: includes *Carrier Sense Multiple Access (CSMA)* and collision avaidance by means of including a random backoff mechanism. User terminals transmit their data packets as soon as they have the packets and get the positive indication by these two mechanisms. The packets might be buffered, e.g., the IEEE 802.11 DCF protocol.
- Controlled ChA: Tightly scheduled channel access method where, most of the cases, a central coordinator synchronizes the channel allocation by means of a scheduler. The packets are generally buffered, e.g., the IEEE 802.16 TDMA/TDD protocol.
- Controlled ChA + CS: Extension of controlled ChA in the direction that the scheduled transmissions are not just started on scheduled time, rather the stations use *carrier sense* as well. This lead to two cases: (1) if at the starting scheduled transmission time the channel

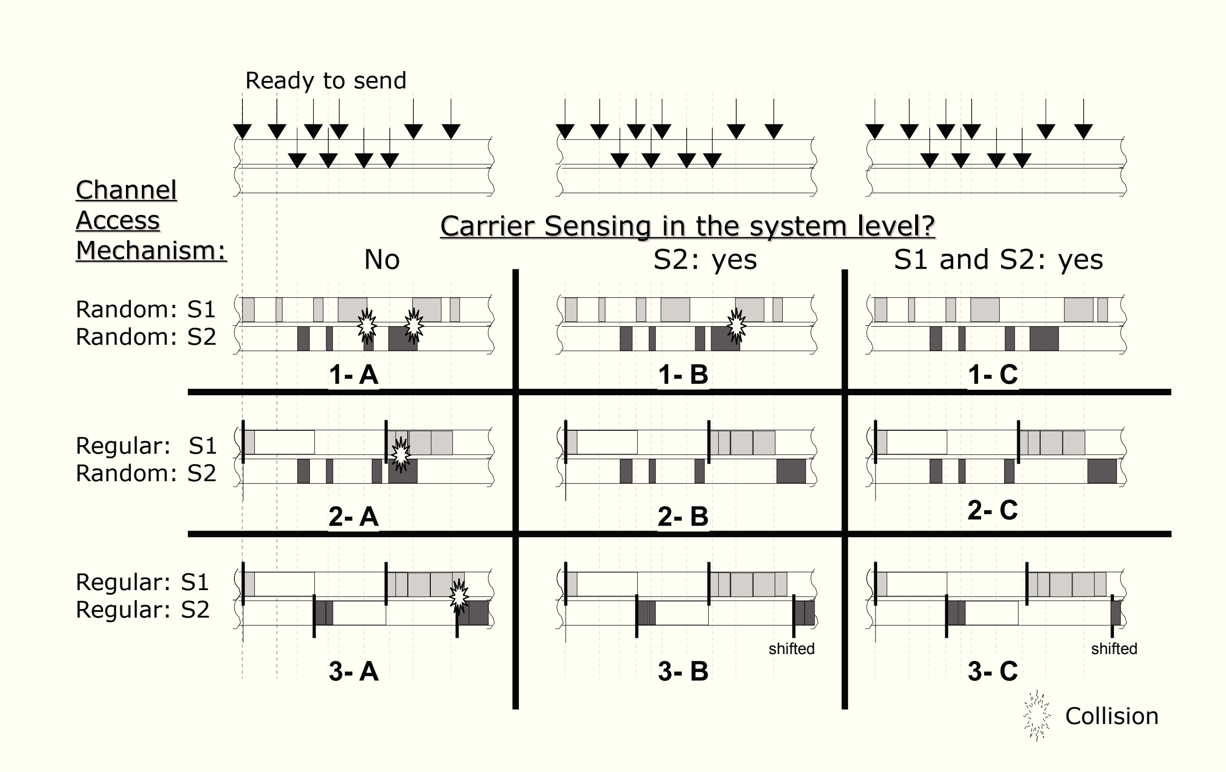


Figure 6.1: The interference events due to different types of access methods in the coexistence of the respective example networks scenarios: low traffic load condition

is busy, then all the transmissions are deferred relatively, (2) if at the starting of the scheduled transmission time the channel is idle, but during the packets exchange duration an another system, which does not have CS, starts transmitting, that leads to a collision zone followed by deferral, e.g., the IEEE 802.11 HCCA protocol.

Figure 6.1 and Figure 6.2 show the different combinations of the above channel access methods focusing on the possible interference events (collisions and deferral) in the coexistence scenarios of their respective example networks. Note that here the collisions in the context of transmission of different stations inside the own system is not shown.

- **1-A:** Pure ALOHA - Pure ALOHA
- **1-B:** Pure ALOHA - CSMA/CA
- **1-C:** CSMA/CA - CSMA/CA: An example of this kind of coexistence scenario is between two IEEE 802.11 DCF based wireless networks.
- **2-A:** Controlled ChA - Pure ALOHA

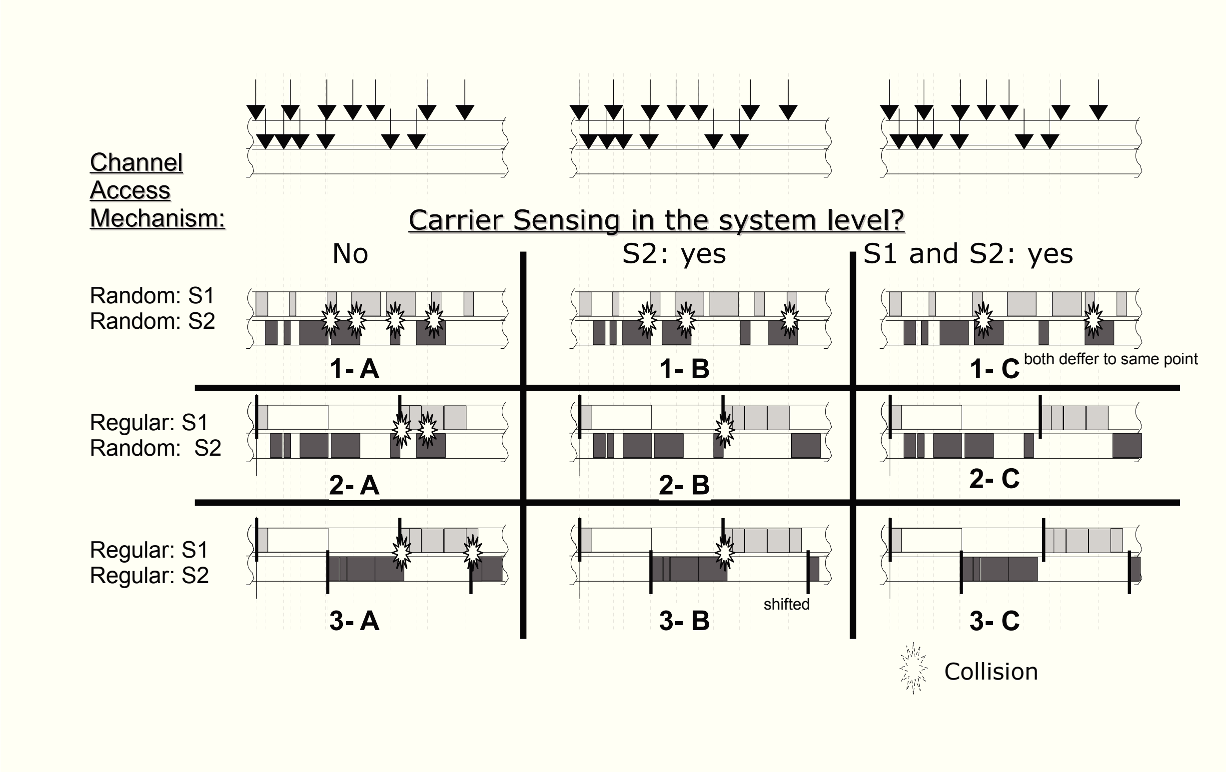


Figure 6.2: The interference events due to different types of access methods in the coexistence of the respective example networks scenarios: high traffic load condition

- **2-B:** Controlled ChA - CSMA/CA: An example of this kind of coexistence scenario is between IEEE 802.16 TDMA/TDD and IEEE 802.11 DCF based wireless networks.
- **2-C:** Controlled ChA + CS - CSMA/CA: An example of this kind of coexistence scenario is between IEEE 802.11 HCCA and IEEE 802.11 DCF based wireless networks.
- **3-A:** Controlled ChA - Controlled ChA: An example of this kind of coexistence scenario is between two IEEE 802.16 TDMA/TDD based wireless networks.
- **3-B:** Controlled ChA - Controlled ChA + CS: An example of this kind of coexistence scenario is between IEEE 802.16 TDMA/TDD and IEEE 802.11 HCCA based wireless networks.
- **3-C:** Controlled ChA + CS - Controlled ChA + CS: An example of this kind of coexistence scenario is between two IEEE 802.11 HCCA based wireless networks.

6.3 Spectrum Sharing Algorithms

In the following a generic spectrum sharing method, proposed, developed and designed by the author of this thesis, is described. The concept used in this method was developed and originated during the joint work between the Department of Communication Networks at the University of Bremen (ComNets Bremen) and the Department of Communication Networks at RWTH Aachen University (ComNets Aachen) on the project Policy-based Spectrum Sharing for unlicensed Mesh networks (PoSSuM). The method itself and its performance evaluation are published in [96, 99, 84, 83, 97] for different homogeneous and heterogeneous coexisting networks scenarios.

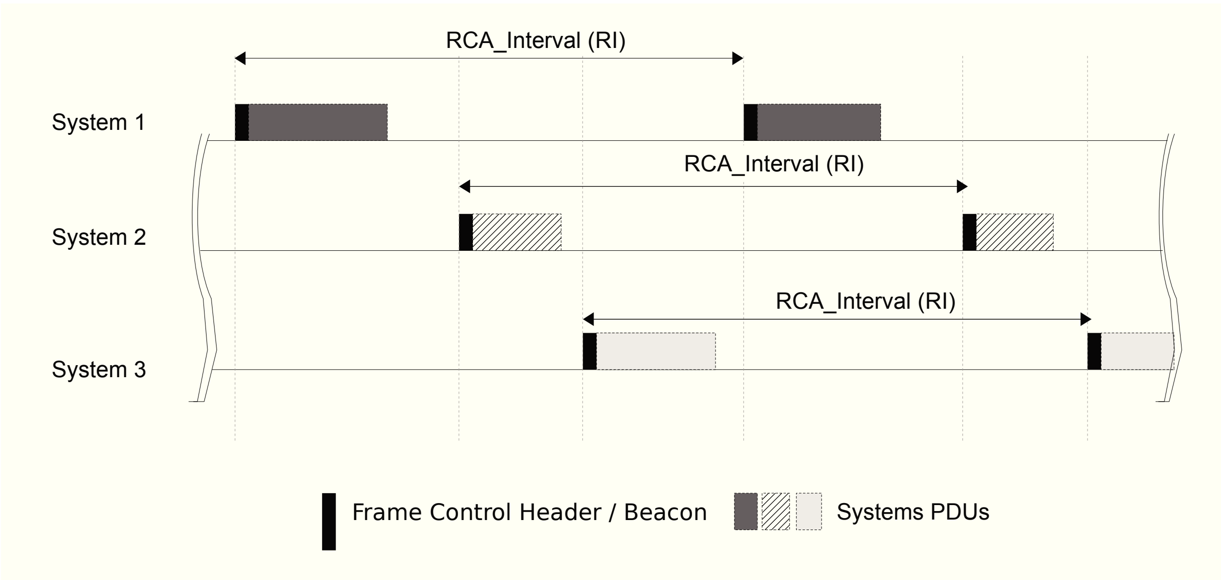


Figure 6.3: Regular Channel Access Method: Systems provide idle periods and shift their frame start to enable coexistence

6.3.1 Regular Channel Access Method

Figure 6.3 illustrated the basic access mechanism of the *Regular Channel Access* (RCA) Method, which allows systems to coexist by multiplexing their channel access in the time domain. It is seen as 'TDMA between systems' as shown in the figure. Each system leaves some capacity which can be seen as 'spectrum opportunities' or 'idle periods' by other systems, provided that the system itself can satisfy its users up to a predefined and application oriented acceptable level. Distributing idle periods randomly results in collisions. Hence one of the main features of this mechanism is that the system introduces idle periods in a regular pattern during its channel occupation, which is done in a cyclic way. Due to this feature of regularity, the method is referred to as Regular Channel Access.

One special characteristic of this method is that all the systems are required to synchronize to the same periodic interval which is denoted as *RCA_Interval* (RI) for further reference. The length of RCA_Interval is an adaptable parameter depending on, for example, the Quality of Service requirements such as the delay bound.

The method helps, on the one hand, systems to reliably predict the length of the idle periods and their offset in the superframe during the detection phase as they are more regular; on the other hand, it helps systems to utilize the idle periods for own transmissions causing less or no collisions with each other due to orthogonality in time.

The above described spectrum sharing method is considered as a cooperative method, in the sense that one system keeps space for other systems based on the estimation of their traffic demand. By this way, a fair spectrum sharing among the systems can be achieved.

Mathematically, the time period duration allocated to the own system, RA_{own} and the time period duration kept free for other systems, RA_{other} is as follows

$$RA_{own} = \frac{TD_{own}}{TD_{own} + TD_{others}} \cdot RI \tag{6.1}$$

$$RA_{others} = \frac{TD_{others}}{TD_{own} + TD_{others}} \cdot RI \tag{6.2}$$

provided that,

$$TD_{own} + TD_{others} < 1. \tag{6.3}$$

Here, RA and RI mean resource allocation and *RCA_Interval* respectively. TD (traffic demand) is defined as a ratio which is within the range [0,1], where 1 means the demand is equal to the channel capacity. The estimation of TD based on channel measurement is done as mentioned in Section 5.5.

The method described above exploits the scenario where the aggregated bandwidth requirements of the coexisting systems are less than the capacity of the particular channel based on the following fact. The systems apply the Dynamic Frequency Selection (DFS) technique to locate and switch to the less occupied channel, which reduces the probability of saturated channel conditions.

It is considered in the design, when the system identifies that aggregated traffic demand is more than the channel capacity i.e., $TD_{own}+TD_{others} > 1$, the system applies the DFS method to switch to the less occupied channel based on the estimated aggregated load conditions $(TD_{own} + TD_{others})$ of the other channels. Because, $TD_{own} + TD_{others} > 1$ leads to an unstable situation in resource allocation resulting in unfair spectrum sharing. So the bottom line is that, both DFS and RCA methods are deployed together, where the DFS method is used to avoid the saturated conditions and to find the less occupied channel in the first place, and secondly, the RCA method is used to optimize the channel usage by mitigating the interference in that non-saturated channel.

Parameterization is one of the important features of the proposed RCA method. Misconfiguration of RCA parameters (resource allocation and offset) is in some cases resulting in rather poor performance compared to legacy systems, which is expected as well. So that there is a need of constant reconfiguring of its parameters in varying traffic conditions (in different scale) and varying scenario topology in order to have a sustainable coexistence method in a larger time scale. A contribution towards this direction is the focus of the next section.

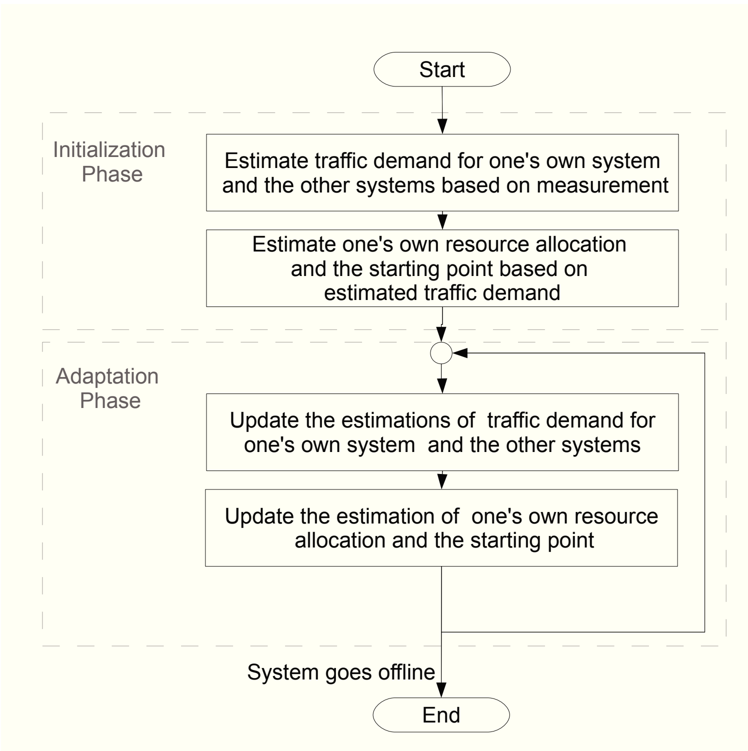


Figure 6.4: Adaptive Regular Channel Access (aRCA) method

6.3.2 Adaptive Regular Channel Access Method

The concept of an adaptive RCA (aRCA), which is an extension of the previously described RCA method, is proposed and described as follows with a flowchart as shown in Figure 6.4. The method is published in [98]. The Traffic Demand Estimation (TDE) based on the measurements, which is a challenging part of the concept, is integrated in this method. Here, the traffic demand estimation is considered for both own and other systems. For the own system, two possibilities are there: traffic specification and estimation of traffic demand. The traffic specification, provided from the upper layer, is considered as the best possible case. However, when it is not available, the second possibility is considered. In the second case, estimation is based on the observation of the corresponding buffers, as mentioned in detail in Section 5.6. This is done by having so-called 'buffer sensors', which measure the incoming bits in the buffers per unit time, resulting in estimated traffic load distribution. The PHY data rate can be used for normalization. On the other hand, estimation of the traffic demand of other systems is based on the measurements of the channel occupation time by other systems. Results shown in Section 5.5.1 and 5.5.2 give a promising indication in this respect.

The method consists of two phases – initialization and adaptive phase – which are described as follows, from the IEEE 802.11 system's perspective.

6.3.2.1 Initialization Phase

The complete initialization phase is shown in Figure 6.5. Before starting operation in the channel, the system does measurements on the channel for a system specific time duration to have an estimation of the traffic demand by other systems operating on the environment scenario, as discussed in Section 5.5. If the estimation shows that the channel is not used by the other systems entirely or less than the expected value (user-defined), the time period duration allocated to one's own system is equal to a maximum threshold of RA_{own}^{max}. This is done to reserve some capacity for the admission of other systems. In this state, a minimum traffic demand for one's own system (TD_{own}) is assumed. If the channel is found used by the other system, then the time duration period allocated to the own system is configured equal to a minimum threshold, RA_{own}^{min} or RA_{own}, whichever is higher. The formula to calculate RA_{own}^{min} is given in the next section. Once the starting point is determined following the above steps, the first Beacon frame is sent for the association process. After the association, stations do measurement for the incoming bits in their MAC buffers for a system specific time duration and then send back the estimated own traffic demand to the main

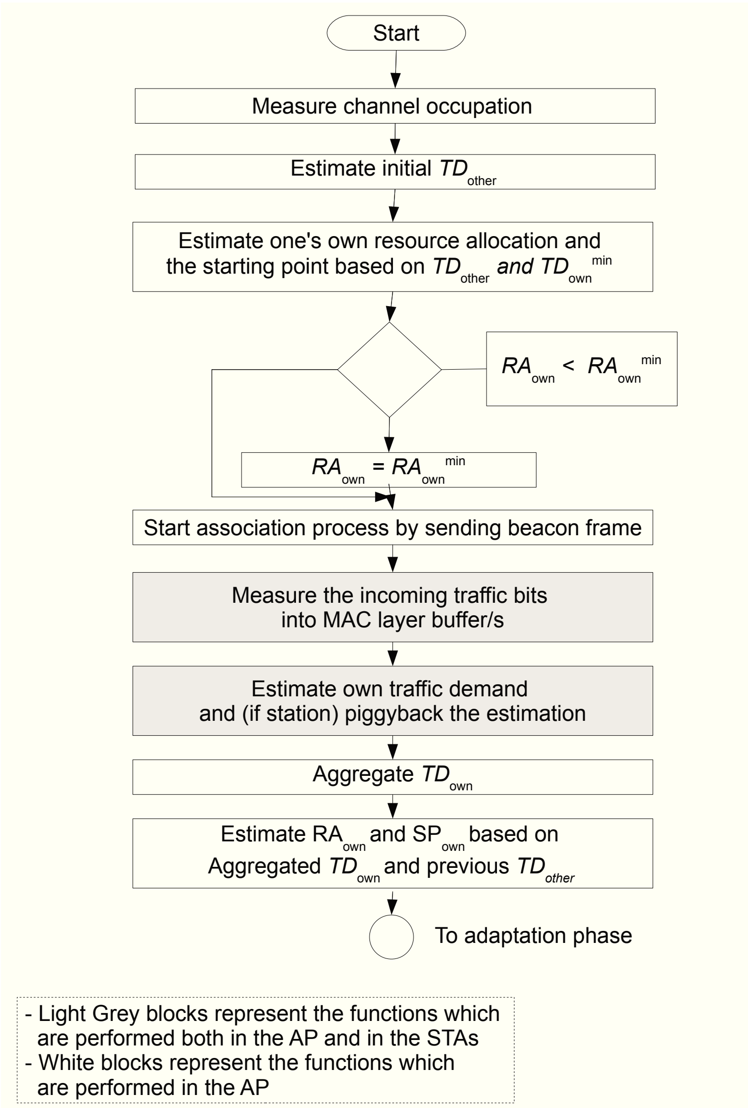


Figure 6.5: aRCA: Initialization phase

controller, which is the access point (AP) in the case of IEEE 802.11 system. The AP re-estimates the resource allocation for the own system and the starting point. Then the adaptation phase starts.

6.3.2.2 Adaptation Phase

The complete adaptation phase is shown in Figure 6.6. In this phase, three parallel processes are running:

1. determine the resource allocation and starting point
2. estimate one's own traffic demand

3. estimate the traffic demand of the other systems.

Note that the granularity of reiteration of these three processes is different. These three processes are semi-independent in the sense that process (1) does not have to wait and stop for the outcome of the processes (2) and (3). If there is no change in both TD_{own} and TD_{other}, process (1) results in the same resource allocation and starting point.

Process 1: Using the estimated traffic demand for own and other systems, resource allocations to systems are calculated according to the equation (6.1 and 6.2), however under the consideration of the following constraint in the next step: a minimum resource allocation time is required to keep the link active. This minimum allocation time is calculated as follows

$$RA_{own}^{min} = \frac{PL_{max}}{E(PDR)} \tag{6.4}$$

where, E means expected value, PL_{max} is the maximum packet length and PDR is the physical layer data rate, which depends on the PHY modulation and coding scheme (MCS). In the next step a generic smoothing function, like moving average, is applied, which is considered as an optional step. Here, the RA_{own} is calculated in iteration i considering the history as follows

$$RA_{own}(i) = \alpha RA_{own} + (1-\alpha)RA_{own}(i-1). \tag{6.5}$$

Then the difference between the already assigned allocated time in the previous iteration and the newly calculated allocation in this iteration is determined as follows:

$$RA_{diff}(i) = RA_{own}^{old} - RA_{own}(i). \tag{6.6}$$

If the absolute difference value is not more than RA_{own}^{step}, for example, calculated according to Equation 6.7, then the allocation time is not changed.

$$RA_{own}^{step} = \frac{E(PL)}{E(PDR)} \tag{6.7}$$

This step size is realized as the minimum allocation unit and it is an open parameter to be defined. If the above condition becomes true, then the allocation time is changed (increased or decreased) according to the following equations

$$RA_{own}^{changed} = \pm\lfloor \tfrac{|RA_{diff}(i)|}{RA_{own}^{step}} \rfloor * RA_{own}^{step} \tag{6.8}$$

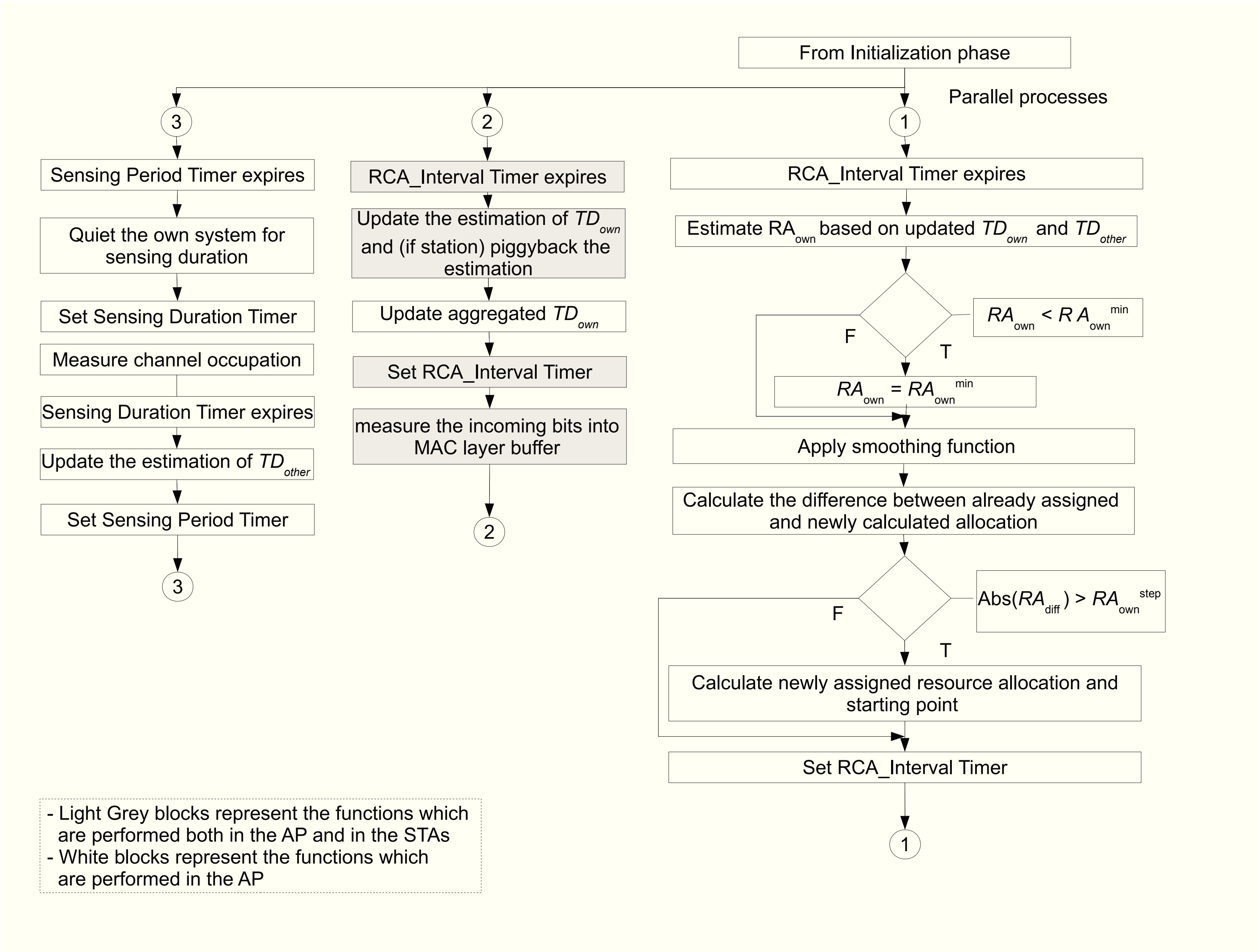


Figure 6.6: aRCA: Adaptation phase

$$RA_{own}^{new} = RA_{own}^{old} + RA_{own}^{changed}. \tag{6.9}$$

The same steps are reiterated after each RCA_Interval.

Process 2: In this process, the stations are mainly measuring the incoming traffic bits in their MAC buffers for each RCA_Interval duration and send back the estimated TD_{own} to the AP. The AP aggregates all TD_{own} and updates the corresponding parameter, ready to be used by Process 1. Details on this is given in Chapter 5.

Process 3: In this process, the AP follows the predefined sensing period, makes silent its own system for the duration equal to the sensing duration. In this duration, the channel occupation measurement is done and the estimated value for TD_{other} is updated. Details on this are given in Chapter 5.

In the above described adaptation phase, when the calculated resource allocation is inside the specified range, i.e. no change is required in time allocation, then this phase is referred to as the Steady State Phase. However, when any significant change occurs in the calculated resource allocation (above threshold), the allocation will be changed and the service starting point will be moved. This is referred to as the Transient Phase.

6.3.3 Applicable Scenarios

The proposed method can be applied to homogeneous and heterogeneous coexisting wireless networks where systems are fully overlapping, that means all stations can hear all others. Wireless networks based on IEEE 802.11 and IEEE 802.16 are considered in the evaluation. It can be applied in the 'apartment scenario' and 'office scenario' in highly dense urban areas where most of the non-overlapping channels (for example, in the case of 2.4 GHz ISM band, channel 1, 6 and 11 are non-overlapping channels) are already used by different wireless systems and systems have to share one single channel. Details concerning those two scenarios are given previously in Sections 4.4.1 and 4.4.2.

6.4 Simulation Tool

To implement the model of spectrum sharing methods, mentioned in Section 6.3.1, and to evaluate the performance of those methods in scenarios of collocated wireless networks, mentioned in Section 6.3.3, a basic platform of a stochastic discrete event simulator is required to be developed from

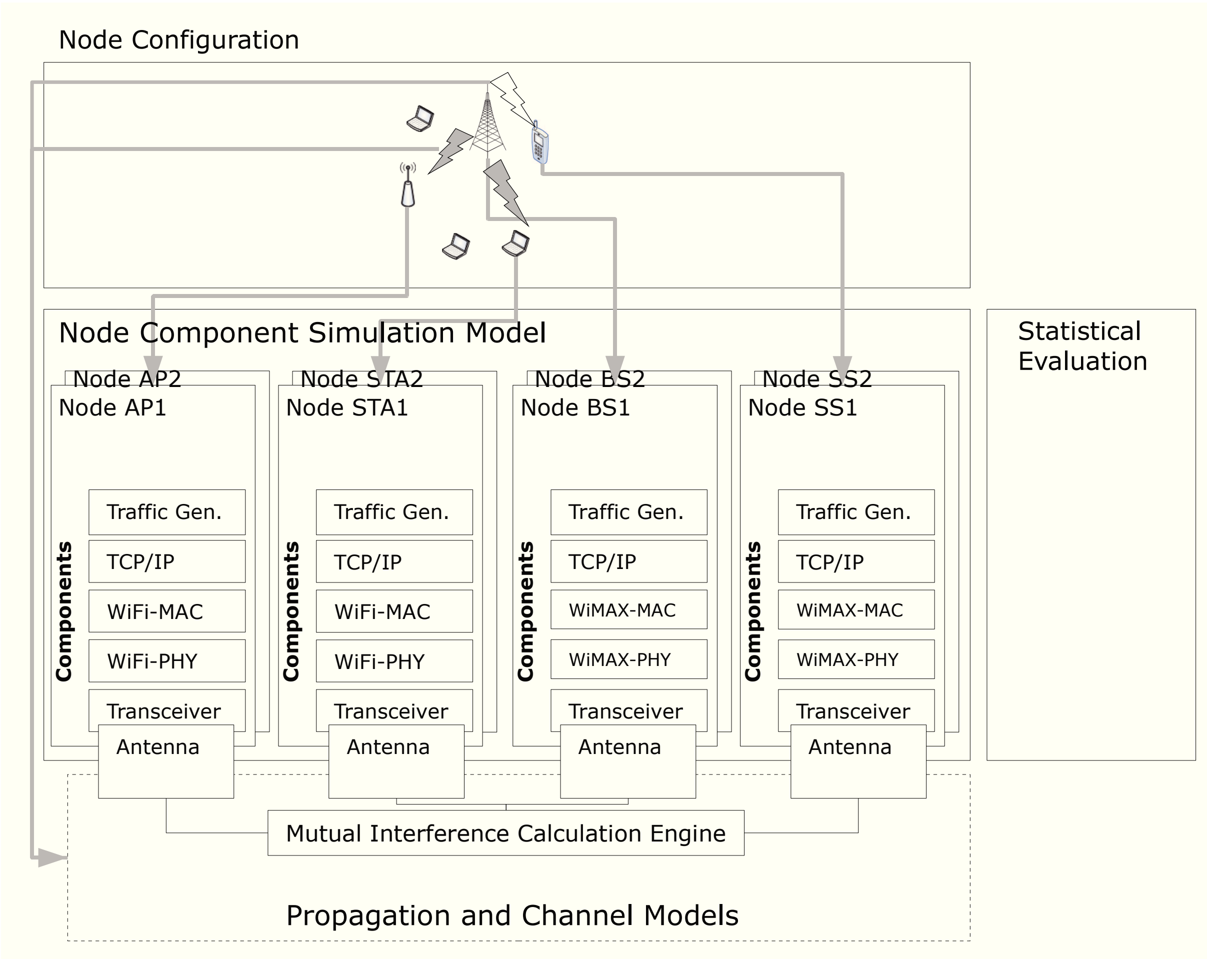


Figure 6.7: open Wireless Network Simulator Structure

scratch, or an existing simulator from the research community is required to be extended. In Discrete Event Simulation (DES), time advances from event to event in chronological order and the state changes only when events occur and at the same time, state variables are updated.

In the context of this thesis, a stochastic discrete event simulator called open Wireless Network Simulator (openWNS) [29] is extended. The main structure and components are shown in Figure 6.7. The basic platform of openWNS is developed at the Chair of Communication Networks (ComNets), RWTH Aachen University. openWNS is an open source simulation tool, which is released under the GNU Lesser General Public License in [30]. The programming languages that are used to develop openWNS are: C/C++ for implementation and Python for simulation setup, control and configuration. The important details are given in Appendix B by referencing [29, 42, 82].

6.5 Conclusion

The generic concept of spectrum sharing is provided in this chapter, followed by the description on parameterization in resource allocation. The concept is modeled and evaluated in the coexistence of IEEE 802.11 and IEEE 802.16 based systems in the following two chapters. The method is extended and described conceptually to become flexible in varying traffic conditions in a larger time scale.

The basic structure of the simulation tool (openWNS), used in this thesis, is provided in this chapter and related models, described in Appendix B as much as the scope of this thesis, is linked to this chapter. OpenWNS is extended to model the spectrum sharing concept, which is described in the next chapters.

CHAPTER 7

IEEE 802.11 CAPACITY BOUNDARY

This chapter provides a substantial catalog of the current state of the art considering the mathematical model to calculate the throughput and delay of IEEE 802.11 networks in Section 7.1. A mathematical approach to compute the airtime required to transmit a data packet accompanied by protocol header and signaling overhead is given afterwards in Section 7.2 which already gives a hint on MAC layer capacity. Based on the computed airtimes, the maximum capacity boundary is eventually computed, which is provided in Section 7.3. The chapter is summarized in Section 7.4.

7.1 State of the Art

In [38], Bianchi provided an analytical model, based on two dimensional Markov chain to calculate the saturation throughput in the case of the IEEE 802.11 channel access method called Distributed Coordination Function (DCF). The DCF is the random channel access method based on the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), described in Section 2.1.4.3. An alternative model, based on elementary conditional probability theorems, is provided from the same author in [39] to calculate saturation throughput. The author suggested this model as a simpler solution. It also provides a model to calculate the average access delay based on Little's law.

In [79], a simple and general analysis framework is provided to compute the throughput, compared to [38]. The fixed point solution and performance measures are studied, and a simple throughput formula is provided.

In [100], it has been shown by analytical calculation that directly increasing the PHY layer bit rate does not lead to a significant increase of throughput with the legacy IEEE 802.11 because of heavy overhead. The throughput limit with theoretically infinite PHY bit rate is shown. With infinite bit rate, though infinite number of data bits per symbol (N_{DBPS}) can be achievable, however as the formula shows one OFDM symbol is still required to transmit the data MPDU and additionally other parts like backoff, PHY header, SIFS and ACK frame need to be considered. It is also shown that in case of IEEE 802.11e, the same phenomenon is present as well, however in lesser extent, as in 802.11e more data frames can be transmitted with aggregation, and different PHY layer techniques can be considered which have the potential to increase the throughput, for example, MIMO OFDM.

Table 7.1: The mathematical symbols and values of the parameters used in the thesis (in case of 20 MHz channel spacing)

Symbol	Value
$T_{\text{PLCP-PRE}}$	$16\,\mu$s
T_{SIGNAL}	$4\,\mu$s
$T_{\text{OFDM-SYM}}$	$4\,\mu$s
L_{MPDU}	$16\,\mu$s
N_{DBPS}	24
T_{PIFS}	$25\,\mu$s
T_{SIFS}	$16\,\mu$s

7.2 Estimation of Frame Transmission Time

In the following the transmission times for different types of IEEE 802.11 frames are mathematically calculated. Later, the transmission times for the downlink and uplink frames in the case of IEEE 802.11e HCCA are derived, showing the different components including protocol overhead and signaling overhead.

7.2.1 General IEEE 802.11 Frames Transmission Time

The transmission time for a general Physical layer packet data unit (PPDU) frame, as shown in the Figure 2.11 is calculated as follows:

$$T_{frame} = T_{\text{PLCP-PRE}} + T_{\text{SIGNAL}} + T_{\text{OFDM-SYM}} \left\lceil \frac{8 \cdot L_{\text{MPDU}} + 16 + 6 + L_{\text{Pad}}}{N_{\text{DBPS}}} \right\rceil . \qquad (7.1)$$

Here, T_{frame} is T_{PPDU}. $T_{\text{PLCP-PRE}}$, T_{SIGNAL} and $T_{\text{OFDM-SYM}}$ are the time durations of PLCP preamble, the PHY SIGNAL and one OFDM symbol. N_{DBPS} is the number of data bits per symbol, which depends on the PHY modulation and coding scheme (MCS) as given in Table 17-3 in the standard [63]. L_{Pad} is the number of padding bits which is calculated as follows

Table 7.2: Type and subtype of frames, used in this thesis

Type	Subtype	L_{MAC}	L_{P}
Management	Beacon	24	64
Control	ACK	14	0
Data	Data	30	variable (e.g, 100)
Data	QoS CF-Poll (no data)	30	0
Data	QoS Null (no data)	30	0

$$L_{\mathrm{Pad}} = N_{\mathrm{DBPS}} - (8 \cdot L_{\mathrm{MPDU}} + 16 + 6) \mod N_{\mathrm{DBPS}} \tag{7.2}$$

In the above two equations, L_{MPDU} is the length of MAC PDU, or in other words the MAC frame, which is can be expressed as

$$L_{\mathrm{MPDU}} = L_{\mathrm{MAC}} + L_{\mathrm{Upper}} + L_{\mathrm{P}} \tag{7.3}$$

where, L_{MAC} is the length of MAC header including the FCS, L_{Upper} is the header added by the upper layers (assumed as zero in the rest of the thesis unless stated otherwise) and L_{P} is the actual packet length generated by the application.

Equation 7.1 can be rewritten as follows

$$\begin{aligned} T_{frame} &= T_{\mathrm{PHY}} + T_{\mathrm{MAC}} + T_{\mathrm{Pad}} + T_{\mathrm{MSDU}} \\ &\text{where } T_{\mathrm{PHY}} = T_{\mathrm{PLCP\text{-}PRE}} + T_{\mathrm{SIGNAL}} + T_{\mathrm{OFDM\text{-}SYM}} \left\lceil \frac{16+6}{N_{\mathrm{DBPS}}} \right\rceil \\ &T_{\mathrm{MAC}} = T_{\mathrm{OFDM\text{-}SYM}} \left\lceil \frac{8 \cdot L_{\mathrm{MAC}}}{N_{\mathrm{DBPS}}} \right\rceil \\ &T_{\mathrm{PAD}} = T_{\mathrm{OFDM\text{-}SYM}} \left\lceil \frac{8 \cdot L_{\mathrm{PAD}}}{N_{\mathrm{DBPS}}} \right\rceil \\ &T_{\mathrm{MSDU}} = T_{\mathrm{OFDM\text{-}SYM}} \left\lceil \frac{8 \cdot L_{\mathrm{MSDU}}}{N_{\mathrm{DBPS}}} \right\rceil = T_{\mathrm{MAC\ frame\ body}}. \end{aligned} \tag{7.4}$$

T_{frame} can be justified as a function of frame type, N_{DBPS} and L_{P}. Applying the corresponding parameter values from Table 7.1 and 7.2 in Equation 7.4, the transmission time for different types of IEEE 802.11 frames are calculated and shown in Figure 7.1. The frames in the figure are mainly considered in this thesis. In this calculation, a BPSK modulation scheme with Coding rate of 1/2 is considered as an example, which provides 6 Mbps physical data rate when 20 MHz Channel spacing is used. It is important to see how much auxiliary transmission is required to transmit the actual

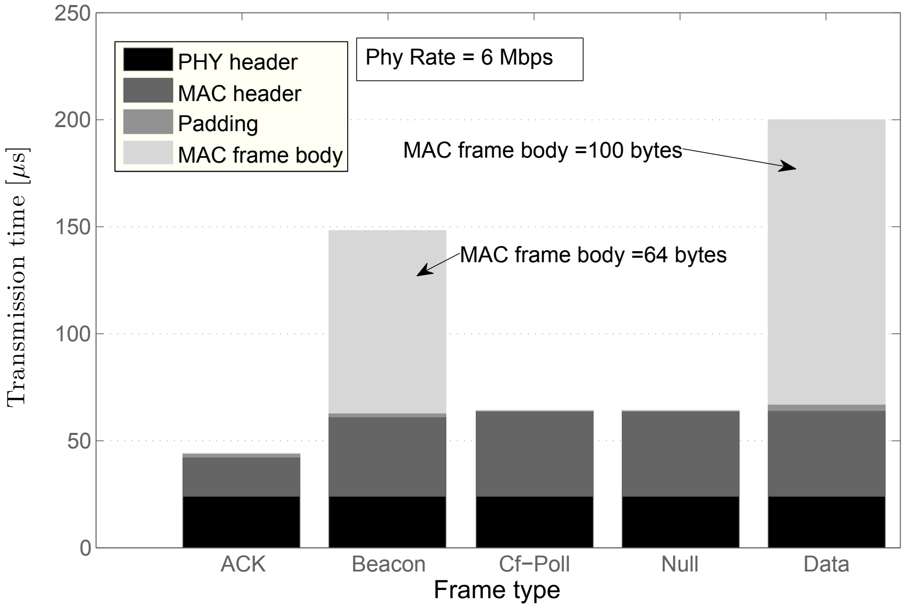


Figure 7.1: Different parts of transmission time for five types of MAC frames

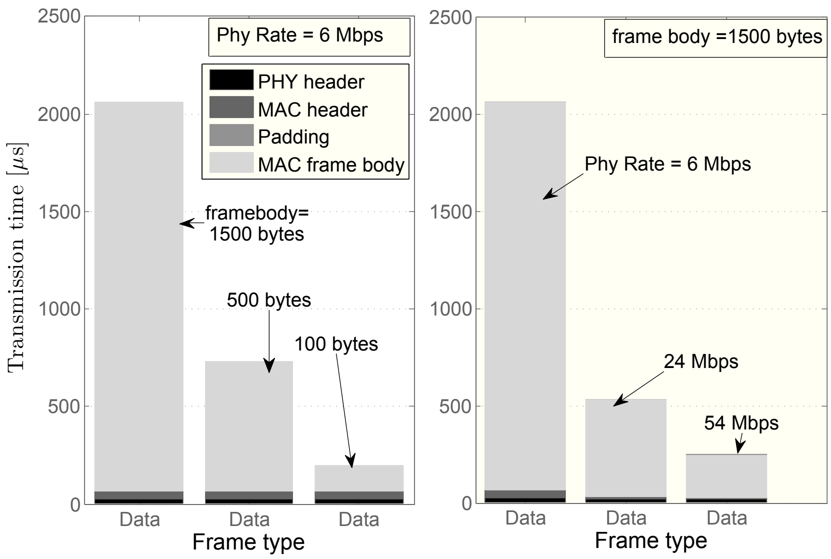


Figure 7.2: Different parts of transmission time for MAC data frame for varying MSDU size and varying PHY bit rate

payload in a data frame and that this overhead is almost constant per frame transmission. The transmission time which is considered here, is the channel busy duration mentioned in Chapter 5.

Transmission times of different parts of data frame for variation of the two parameters MAC frame body length (L_{MSDU}) and data bits per OFDM symbol (L_{DBPS}) are shown in Figure 7.2. The value of L_{DBPS} depends on PHY Data rate.As it is seen in the figure, the transmission of a smaller frame experiences the effect of transmission overhead more significantly, which can be realized in the case of VoIP transmission where the frames are quite small in size. The overhead is also a significant part in case of higher bit rate which cannot be avoided.

7.2.2 Frame Transmission Time in IEEE 802.11e HCCA

Now, the frame exchange sequence in case of IEEE 802.11e HCCA, which is considered in the RCA method, is shown in Figure 7.3. Following this diagram, in the case of downlink and where TXOP consists of a single data packet, the transmission time of a downlink frame T_{dl}, accompanied by interframe spaces and an ACK frame is calculated as

$$T_{dl} = T_{\text{PIFS}} + T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}}. \tag{7.5}$$

T_{DATA} and T_{ACK} can be calculated by Equation 7.4, example values are shown in Figure 7.1.

In the case of uplink and where TXOP consists of a single data packet, the transmission time of a uplink frame T_{ul}, accompanied by interframe spaces, a QoS CF-Poll and an ACK frame, is calculated as

$$T_{ul} = T_{\text{PIFS}} + T_{\text{CF-Poll}} + T_{\text{SIFS}} + T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}}. \tag{7.6}$$

The transmission times, showing all the overhead and data payload Tx time, for varying MSDU length are illustrated in Figure 7.4 to transmit a single frame in downlink according to Equation 7.6.

To achieve a clearer understanding, Figure 7.5 illustrates the actual proportionality of different parts of the total transmission time for each MSDU length. It shows that for a smaller packet (e.g., length of 160 bytes), the overhead is more than 40 %. This indicates the maximum capacity at the MAC layer for this specific scenario only less than 60 % of the PHY data rate. For larger packets (e.g., length of less than 1400 bytes), the maximum capacity will be less than 90 %.

The normalized transmission time taken by each part for varying MSDU length is shown in Figure 7.6 to transmit a single frame in uplink direction

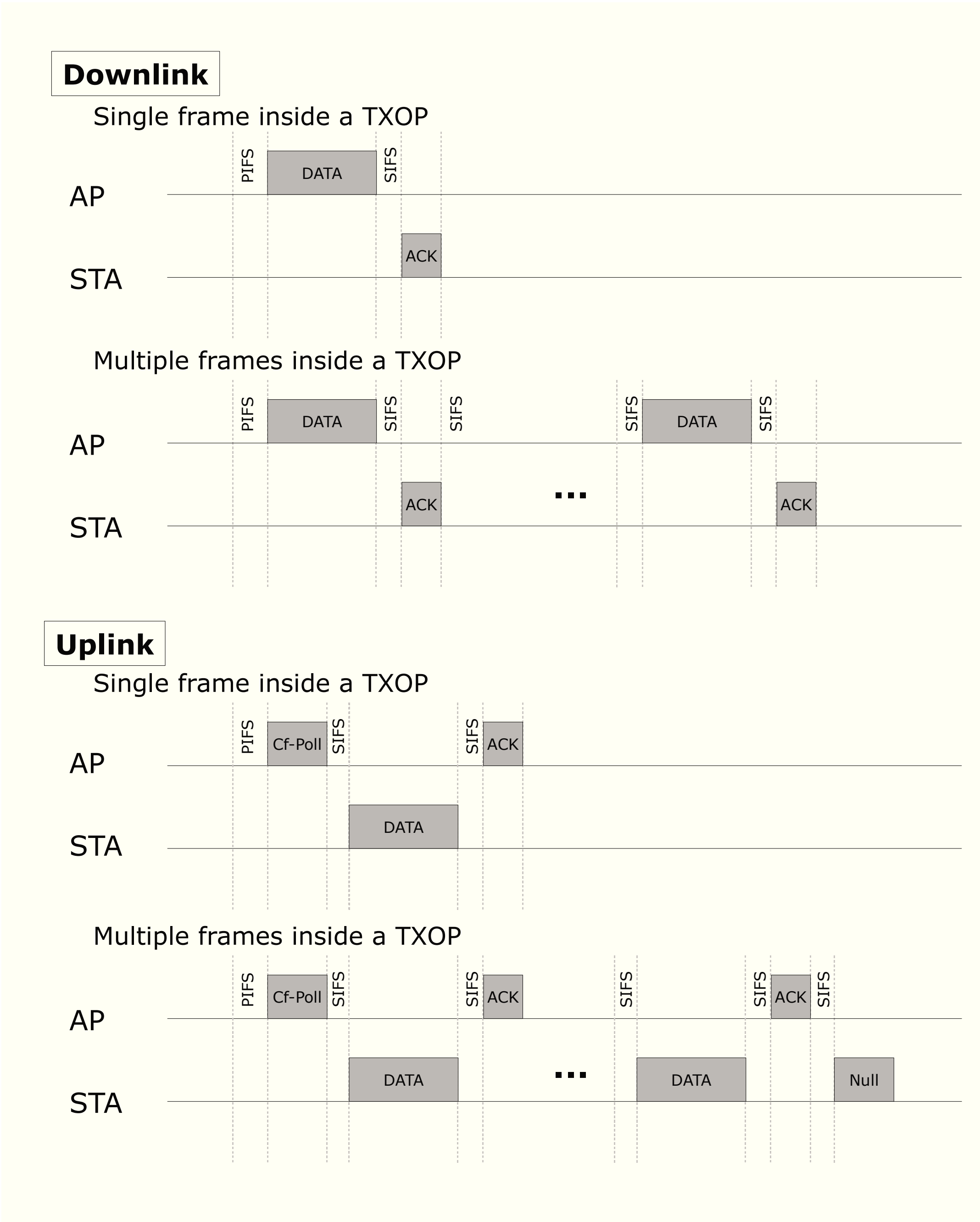


Figure 7.3: Frame exchange in IEEE 802.11e HCCA

according to Equation 7.6. Additional signaling overhead due to the QoS CF-Poll frame is added to the total transmission time. For a smaller packet (e.g., length of 160 bytes), the maximum capacity at the MAC layer for this specific scenario is only less than 50 % of the PHY data rate.

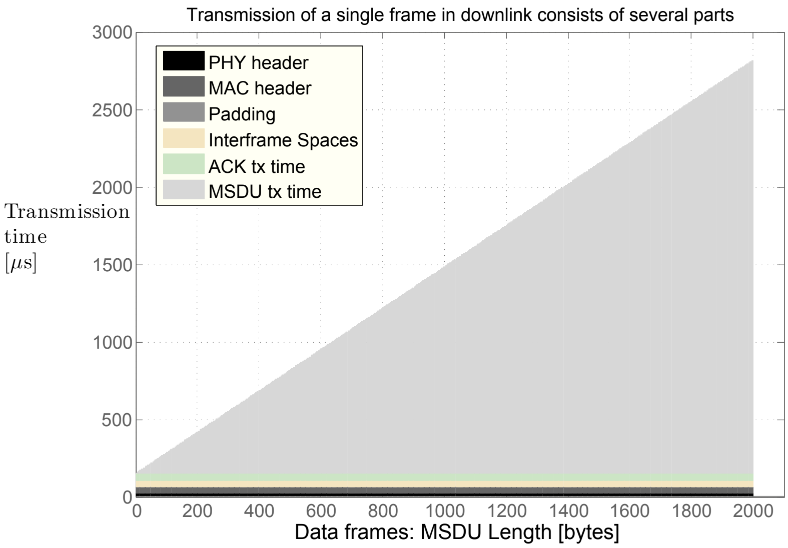


Figure 7.4: Different components including protocol overhead and signaling overhead in time domain during the transmission of a single frame (in BPSK modulation and 1/2 coding scheme, which provides PHY rate of 6 Mbps)

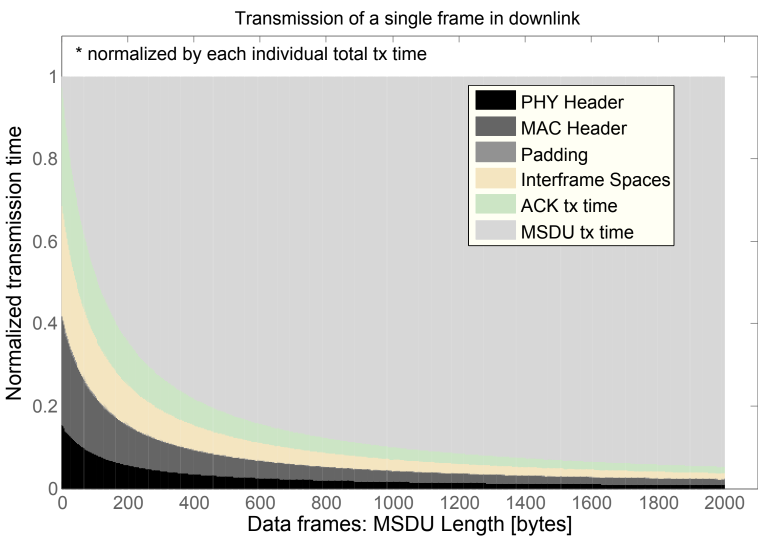


Figure 7.5: Different components including protocol overhead and signaling overhead in time domain during the transmission of a single frame, normalized by total Tx time

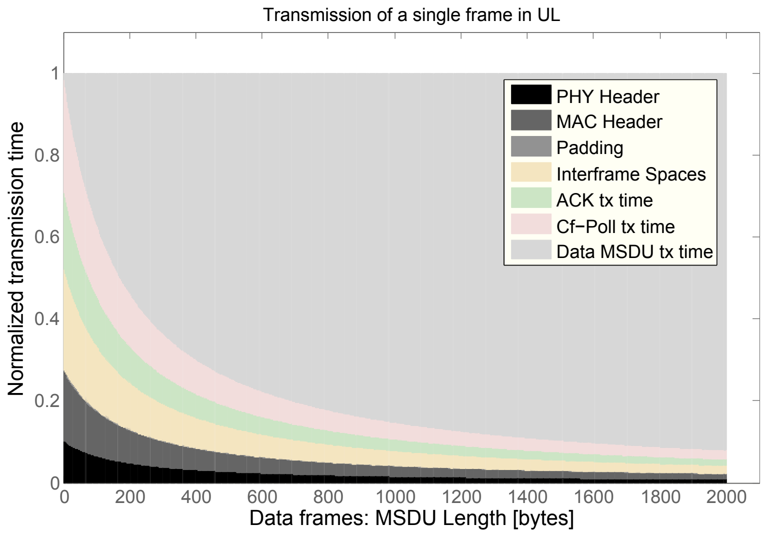


Figure 7.6: Protocol overhead and signaling overhead in time domain during the transmission of a single data frame in uplink direction, normalized by total time

On the other hand, in case of 64-QAM modulation and 3/4 coding scheme, which provides a PHY rate of 54 Mbps, the normalized transmission times taken by each part are shown in Figure 7.7 to transmit a single frame in uplink direction. It is seen that a major part of the transmission time is due to overhead. For a smaller packet (e.g., length of 160 bytes), the maximum capacity at the MAC layer for this specific scenario is only less than 10 % of the PHY data rate.

In the case of uplink where TXOP consists of multiple data frames, the transmission time for all uplink frames T_{ul}, accompanied by interframe spaces, a QoS CF-Poll, a QoS Null and ACK frames, is calculated as

$$\begin{aligned} T_{ul} = T_{\text{PIFS}} + T_{\text{CF-Poll}} + n_{\text{DATA}} \cdot (T_{\text{SIFS}} + T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}}) \\ + T_{\text{SIFS}} + T_{\text{Null}} \end{aligned} \tag{7.7}$$

where, n_{DATA} is the number of data frames that fits into the TXOP. In this, a small gain is achieved by reducing the number of QoS CF-Poll frames.

Figure 7.8 shows the transmission times, showing all the overhead and data payload tx time, for varying MSDU length when n_{DATA}=5 in Equation 7.7. Compared to Figure 7.6, a small reduction is visible in overhead transmission time.

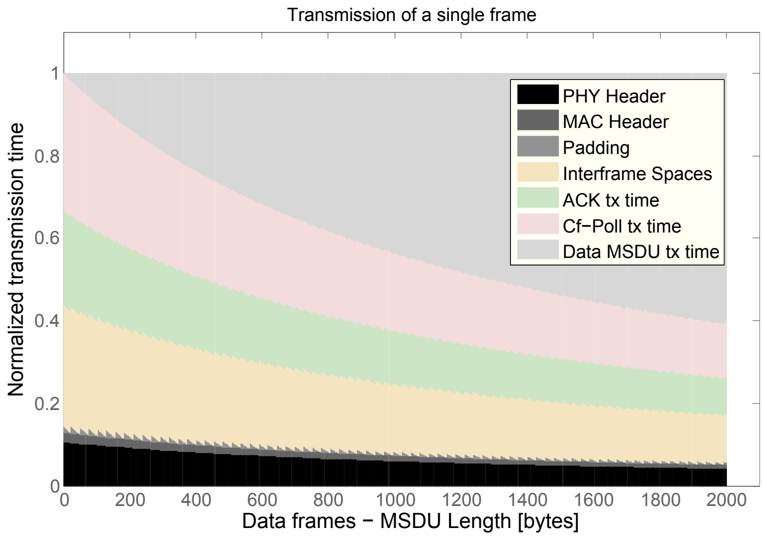


Figure 7.7: Protocol overhead and signaling overhead in time domain during the transmission of a single data frame in uplink direction, normalized by total time (in 64-QAM modulation and 3/4 coding scheme, which provides PHY rate of 54 Mbps)

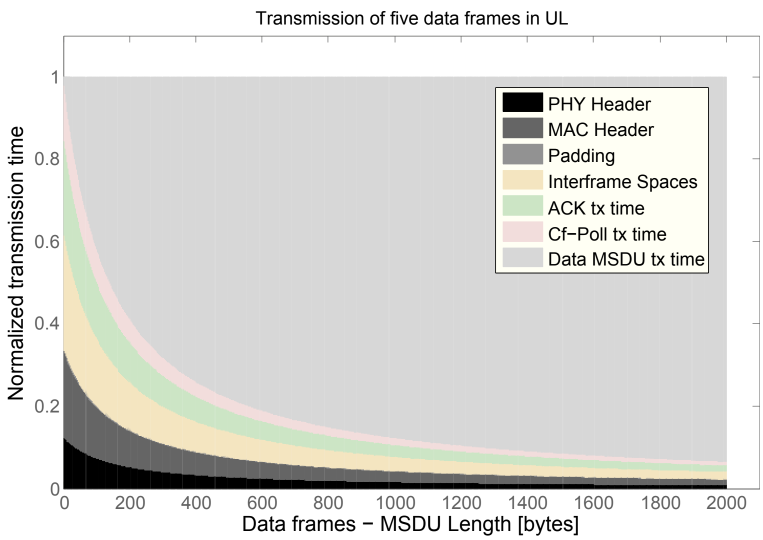


Figure 7.8: Protocol overhead and signaling overhead in time domain during the transmission of multiple data frames in a single TXOP in uplink direction, normalized by total time

7.3 The Maximum Capacity Boundary in IEEE 802.11e HCCA

In the following the maximum capacity in IEEE 802.11e HCCA is calculated for both standalone and coexisting network scenarios.

7.3.1 Standalone Network Scenario

The total transmission time required to send multiple packets in the uplink direction is already calculated in Equation 7.7. The concepts of Transmission Opportunity (TXOP) and Service Interval (SI) are not considered in the above calculation. In the following the maximum capacity is calculated.

The time reserved for each station considering the equilibrium resource allocation is:

$$TXOP = (SI - (T_{\text{PIFS}} + T_{\text{Beacon}})) \cdot \frac{1}{N_{STA}} \tag{7.8}$$

where N_{STA} is the number of stations.

The mean number of packets that could be served in the $TXOP$ is:

$$n_{\text{DATA}} = \left\lfloor \frac{TXOP - (T_{\text{PIFS}} + T_{\text{CF-Poll}} + T_{\text{SIFS}} + T_{\text{Null}})}{T_{\text{SIFS}} + T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}}} \right\rfloor. \tag{7.9}$$

The maximum throughput, S_{max} is calculated as follows:

$$S_{max} = \frac{n_{\text{DATA}} \cdot 8 \cdot L_{\text{MSDU}}}{SI} \cdot N_{STA} \tag{7.10}$$

whose normalized version is

$$S^n_{max} = S_{max} \cdot \frac{T_{\text{OFDM-SYM}}}{N_{\text{DBPS}}}. \tag{7.11}$$

Figure 7.9 shows the normalized throughput for two different MCSs which provide PHY data rates of 54 and 6 Mbps, i.e N_{DBPS} of 216 and 24 bits per OFDM symbol. The lowest and the highest MCS is considered in this figure. For both MCS cases the number of stations is varied. In all cases, there are ripples in the curves which are mainly due to unused portions in TXOP. In each ripple, the lowest point is due to the maximum amount of unused portion in TXOP and the highest point is due to the minimum amount of unused portion in TXOP. With increased number of stations, the number of TXOP allocations is increased by N_{STA} times and so does the unused portion in TXOP. A heuristic method of dynamically changing the TXOP duration could recover the unused portions, and result in smoother curves. The normalized capacity in case of 54 Mbps is less than that of 6 Mbps, which is due to the fact that the ratio of overhead is simply higher in the former case as shown in the Figure 7.7.

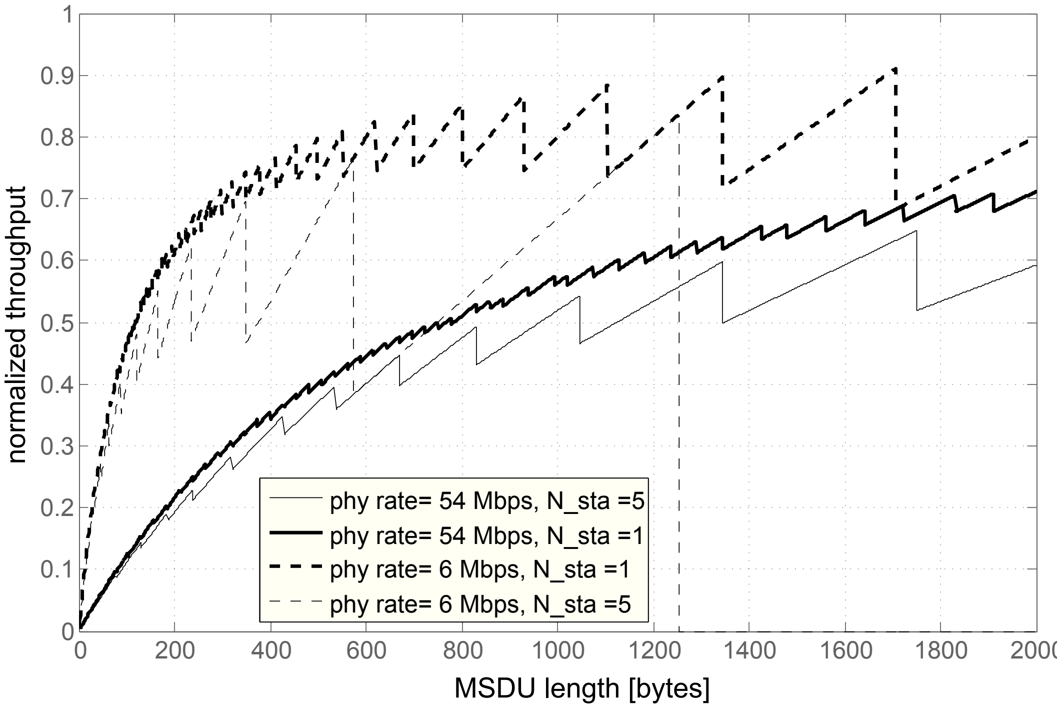


Figure 7.9: Normalized throughput in IEEE 802.11 HCCA

7.3.2 Coexisting Network Scenario

Assuming that systems have an equal number of associated stations, the time reserved for each station considering the equilibrium resource allocation is:

$$TXOP = (RI - N_{System}(T_{\text{PIFS}} + T_{\text{Beacon}})) \cdot \frac{1}{N_{STA} \cdot N_{System}}. \tag{7.12}$$

Here, RI is RCA_Interval which is defined in Section 6.3.1. The number of packets served inside the $TXOP$ is calculated by Equation 7.9. The maximum throughput and its normalized version are then calculated as follows:

$$\begin{aligned} S_{max} &= \frac{n_{\text{DATA}} \cdot 8 \cdot L_{\text{MSDU}}}{RI} \cdot N_{STA} \cdot N_{System} \\ S^n_{max} &= S_{max} \cdot \frac{T_{\text{OFDM-SYM}}}{N_{\text{DBPS}}}. \end{aligned} \tag{7.13}$$

7.4 Conclusion

This chapter provides the mathematical approach to calculate the transmission time for the IEEE 802.11 frames considered in this thesis. The calculation is done considering the frame structure defined in the standard [63]. Based on the frame transmission time, the frame exchange durations are modeled for both the downlink and the uplink phases in the case of the IEEE 802.11e HCCA method, with an additional focus on the protocol and signaling overhead. The frame exchange durations eventually support to approximate the maximum capacity for IEEE 802.11e based network in the standalone and coexisting scenarios. This gives a general idea of expected higher boundary of normalized throughput in the case of mentioned scenarios, that can be compared against the simulation results, provided in the next two chapters.

CHAPTER 8

SPECTRUM SHARING BETWEEN IEEE 802.11 SYSTEMS

IEEE 802.11 based Wireless Local Area Networks (WLANs) are operating in unlicensed bands. However, on the one hand the number of 802.11 systems is increasing day by day for providing Internet access, and on the other hand several new services are added in daily life, like telephony e.g. Voice over WLAN (VoWLAN), entertainment services, e.g., home audio and video streaming, which are using the 802.11 technology. Moreover, new technologies and services are using the unlicensed bands as well, for example to reduce the cost. Due to all these mentioned reasons, there is a high risk of interference, which degrades the performance and fails to support Quality of Service (QoS) for systems operating in these bands. So there is a growing need to have spectrum sharing techniques among collocated 802.11 systems. In this chapter, the proposed method in 6.3 is adapted for coexisting Wireless Local Area Networks (WLANs) in a Voice over Internet Protocol (VoIP) usage scenario where QoS support is highly required. In this case, IEEE 802.11e Hybrid Coordination Function (HCF) controlled channel access (HCCA) is used to provide a decision method for sharing the airtime among more than one system. The simulation results show that the proposed algorithm provides fair sharing with an excellent QoS support. It proves that 'unlicensed' and 'unreliability' are not always fully inclusive terms.

The structure of this chapter is as follows. State of the art in spectrum sharing among 802.11 networks is given in Section 8.1. The adaptation and evaluation of the performance of the RCA method in the coexistence scenario are discussed in Section 8.3 based on the publication [99]. Section 8.4 describes the model for adaptive RCA in case of homogeneous networks followed by the performance evaluation. The problems in the partially overlapping Scenario are identified and possible extensions in the RCA method are provided in Section 8.5. In Section 8.6, the RCA method is extended for the coexistence scenario of more than two IEEE 802.11 systems. The concept of applying the RCA like method in case of legacy IEEE 802.11 based systems is provided in Section 8.7. Section 8.8 summarizes the chapter.

8.1 State of the Art

As mentioned in Chapter 6, the spectrum sharing methods can be accomplished in four domains: frequency, time, space and power. Coexistence methods called Dynamic Frequency Selection (DFS) in [76] and Transmission Power Control in [77] are evaluated for IEEE 802.11 systems in the frequency and space plus power domains. In the case of the DFS algorithm, the system selects a channel, which is less interfered than the one currently in use, from a pool of channels. However, when the above techniques are not available or the density of IEEE 802.11 systems exceeds the number of available (orthogonal) channels, then spectrum sharing in the time domain is inevitable. The problem of overlapping IEEE 802.11 systems is often mentioned in literature as Overlapping Basic Service Set (OBSS) [49, 55]. [49] provides a solution by using two levels of carrier sensing, whereas [55] gives a solution by regulating the channel access parameters of the OBSSs and coordinating them in the time domain. The IEEE Standards Coordinating Committee 41 is currently working on enabling network coexistence through dynamic spectrum access and cognitive approaches. In [37] Berlemann and Walke propose a mechanism called Spectrum Load Smoothing (SLS). Using the extensions of IEEE 802.11e and additionally applying SLS assures a more regular channel occupation improving the performance of coexisting systems. In [84] a coexistence scheme for homogeneous IEEE 802.16 systems in scenario (1) of Figure 4.4 is presented and its performance is evaluated analytically.

The issue of overlapping BSSs is briefly mentioned in [63], however, how to detect the interference from an overlapping BSS and what to perform, e.g. an inter-HCCA backoff, Dynamic Frequency Selection, or inter-BSS scheduling or other techniques is described as out of the scope of the standard.

8.2 Interference in Homogeneous Scenarios

The legacy IEEE 802.11 DCF method inherently provides a mechanism to reduce collisions, resulting in low CRC loss. However, it does not provide QoS guarantees. Increasing the number of stations in a fully overlapping coverage area, increases the possibility of collisions. Moreover, in the case of DCF, interference can be measured as an effect on the access delay.

8.3 RCA as an Algorithm

Regular Channel Access proposed in Section 6.3.1 is adapted for IEEE 802.11e systems, e.g., Wireless Multimedia Extension compliant systems [17]. The previously introduced office scenario in Section 4.4.2 can be modeled as a scenario which comprises two fully overlapping systems, each with one access point and a varying number of associated stations. All stations follow the Hybrid Coordination Function Controlled Channel Access (HCCA) so that stations transmit only when polled by their access points/hybrid coordinators. The access points schedule the PDUs belonging to the stations in a way that creates a channel occupation pattern as shown in Figure 8.1.

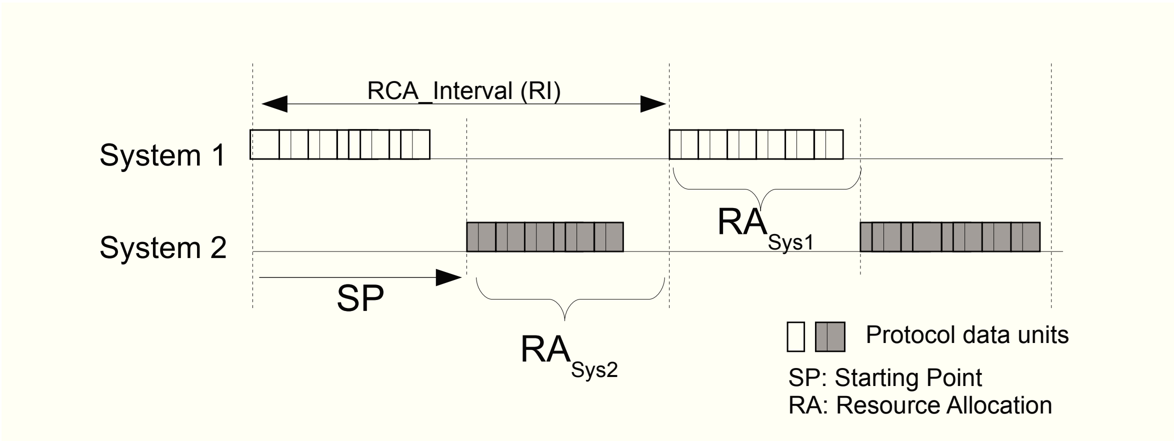


Figure 8.1: Regular channel access in 802.11e based Networks

Each station is polled sequentially to transmit for the duration of a maximum transmission opportunity (TXOP). If a station has no more data to transmit, it can inform the AP accordingly by using the QoS Null frame, so that the AP can then immediately poll the next station. The AP assures the estimated bandwidth requirement of all of its stations is allocated during an RCA_Interval by selecting an appropriate TXOP duration. The idle part remaining in an RCA_Interval can then be used by another coexisting system (e.g. System 2) using the same algorithm to switch its polling cycle to start when the first system (e.g. System 1) is expected (or even detected) to have finished transmission. This starting offset is calculated to

$$SP_{own} = RA_{others}. \tag{8.1}$$

Polling Method in IEEE 802.11e HCCA: The polling method, following the round robin strategy to select the station from the polling list,

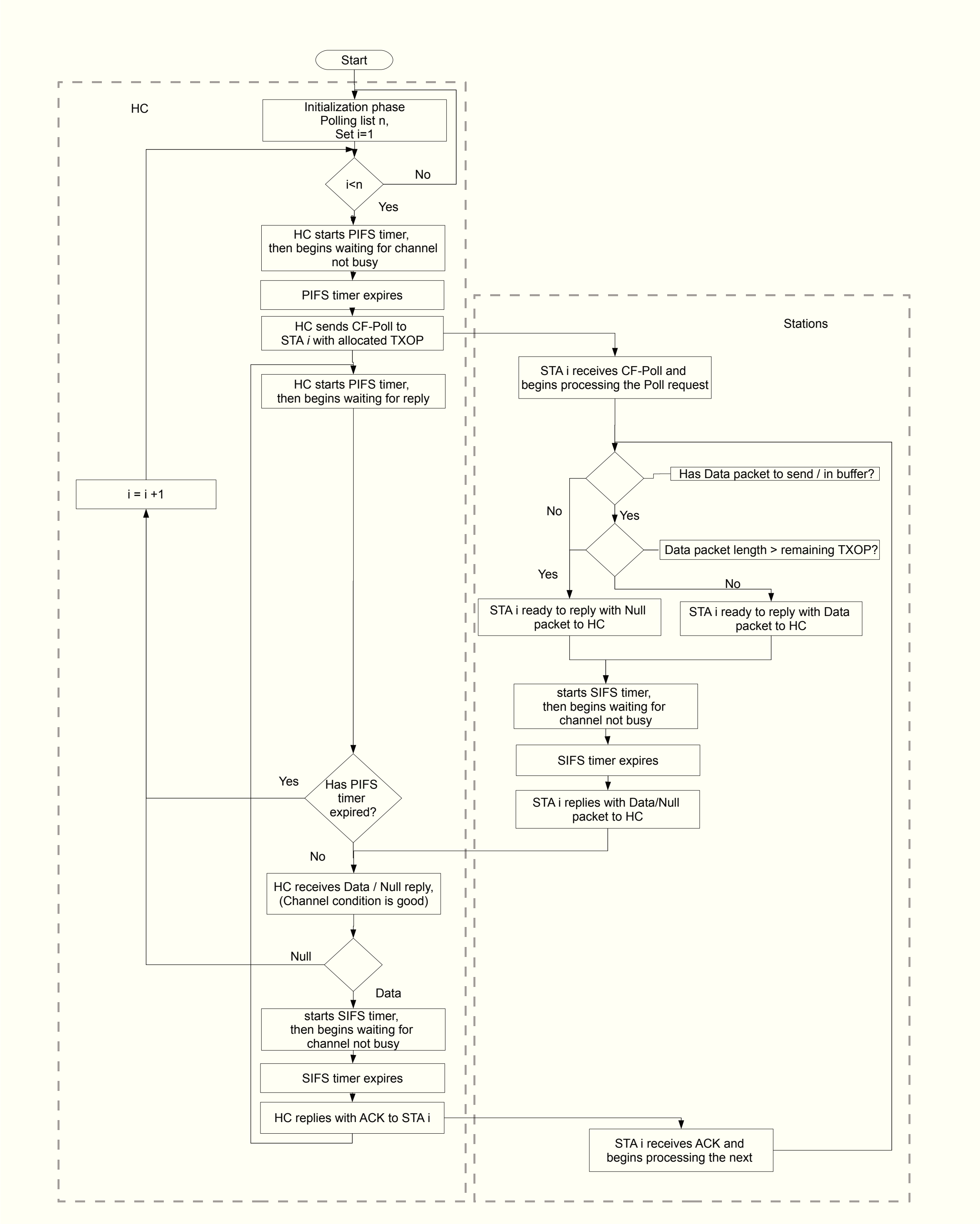


Figure 8.2: Polling mechanism in 802.11e based Network

is shown as flowchart in the Figure 8.2. This is shown from the context of one system/network. Here the AP/HC is assumed to have the *polling list*, the list of associated stations at the beginning. However, the list could be updated in course of time if a new station associates or an associated station disassociates. The HC selects the first station from the list and sends the QoS CF-Poll frame to the station and starts a timer with the duration equal to PIFS. The QoS CF-Poll frame contains information about the length of the TXOP. If the the station successfully receives the QoS CF-Poll frame, it sends 1) a Data frame or 2) a QoS Null frame depending on frame availability in the buffer after the SIFS period which is less than the PIFS period. After successfully receiving the Data packet, HC sends the acknowledgement frame to the station. The station sends a Data frame or a QoS Null frame depending on frame availability in the buffer like in the previous case. 1) If a QoS CF-Poll or a Data or a QoS Null frame is lost, the PIFS timer in the HC expires or 2) after receiving the QoS Null frame, the HC selects the next station from the list and sends the QoS CF-Poll to the next station and follows the same procedure. In this way, all the stations are served sequentially. After a full cycle, the first station is again selected for serving.

Under the concept of the RCA algorithm for coexisting systems, above mentioned polling method is exploited with introducing an idle period in each cycle between the end of the last station's service time and the beginning of the first station's service time in the next cycle. The required length of the idle period duration is basically determined based on the outcome of sensing methods described in Chapter 5. Some important features of the RCA algorithm are listed below.

- A lower RCA_Interval results in lower delays.
- To support the VoIP applications, call admission control needs to be applied for each system so that the total offered load of the admitted traffic streams does not exceed the allocated capacity of the own system. Otherwise, the delay would increase tremendously. According to the admitted streams, a polling list is created in the HC.
- To provide a continuous busy/idle period, the PDUs of admitted traffic streams of the same system are grouped in the time domain by scheduling them consecutively. The Round Robin (RR) scheduling is applied in the scope of this thesis. In the case of downlink, QoS CF-Poll and QoS Null are not required as the queues are in the HC.

By this proposed approach, the operation of coexisting systems is coordinated and synchronized indirectly with the help of regular channel occupation on the one hand and with the use of measurement techniques as described in Chapter 5 on the other hand. In the following, evaluation results of IEEE 802.11 system performance in the coexistence scenario are shown.

8.3.1 Simulation Model

The modified version of the 802.11 medium access control with HCCA model, which is a polling method, is shown in Figure B.6. Basically the polling and scheduling method are modeled by means of four functional units: TXOP11e, QoS CF-Poll, QoS Null and TXOP Dispatcher. Two different frames have been created: QoS CF-Poll and QoS Null. Generally the QoS CF-Poll frame is transmitted after a waiting time which is the PIFS. The Constant Wait Functional Unit (FU) is used to model the PIFS time interval. The TXOP dispatcher FU is used for multiplexing and demultiplexing as with other types of dispatcher. The implementation details of each FU are given in Section B.2.

8.3.2 Simulation Setup

The openWNS simulator is used for simulation. It implements the IEEE 802.11a protocol stack, which is extended for IEEE 802.11e HCCA by polling based scheduling and Regular Channel Access in the framework of this work as described above. A scenario of fully overlapping IEEE 802.11 systems is considered for simulation which reflects the realistic office scenario mentioned before in Section 4.4.2. A similar scenario is described in [45] by Cisco Systems which justifies the above statement. The system parameters are listed in Table 8.1. The most important parameters have been configured as follows:

- The simulation scenario consists of two IEEE 802.11 systems and a different number of stations in different simulation runs to investigate the effects of an increasing number of VoIP stations (one stream per station is considered) on QoS parameters and to identify
- The *Wireless VoIP*, to be more specific, *WiFi VoIP* or Voice over WLAN (VoWLAN) traffic is considered as an application scenario. WiFi VoIP phones and laptops using WiFi interfaces for VoIP service are two examples which are realized as VoIP stations establishing voice connections.
- Principally wireless VoIP traffic is bi-directional, that means downlink and uplink wireless connections and traffic flows are established in each

station.

- In the considered fully overlapping coexistence scenario, the number of traffic streams is more important than their link directions. This justifies the configuration of one uplink VoIP traffic flow per station. The following two facts justify as well the uplink-only configuration. For IEEE 802.11e HCCA, 1. each downlink requires less capacity than the uplink because the downlink does not need QoS CF-Poll and QoS Null packets for signaling, 2. Scheduling the downlink transmissions in the AP is less challenging than that of uplink transmissions. Considering the downlink will not degrade the performance results in the considered scenario.
- A VoIP traffic is generated by using a CBR traffic model which is based on a G.711 voice codec. G.711 is taken as an example here, which represents a realistic traffic pattern. The same parameters as in [43] with a mean data rate of 80 kbps, a packet size of 160 bytes, and a fixed packet and inter-arrival rate are considered.
- Both systems are using the most robust modulation and coding scheme (MCS) of binary phase shift keying (BPSK) with a coding rate of 1/2, which can provide a data rate of 6 Mbit/s at the physical layer. This is chosen for the simulation to show the fundamental operation of the algorithm. It is obvious that with higher MCS, more VoIP stations could be served.
- To see the effect of the RCA_Interval on the number of admitted VoIP streams and their experienced delay, different simulation runs are conducted with RCA_Intervals of 100 ms, 50 ms, 20 ms and 10 ms, which provide multiple service cycles (i.e., 1, 2, 5 and 10) inside each superframe (i.e., 100 ms).

8.3.3 Performance Metrics

Delay and throughput are evaluated as performance metrics. Generally, the delay is defined by the following equation.

$$Delay = D_{\mathrm{Q}} + D_{\mathrm{Ch}} + D_{\mathrm{Prop}} + D_{\mathrm{Tx}} + D_{\mathrm{Proc}} \tag{8.2}$$

where

- D_{Q} is the queuing delay, the waiting time for a protocol data unit in the queue
- D_{Ch} is the channel access delay (depends on the access mechanism)

Table 8.1: IEEE 802.11 System parameters

IEEE 802.11a	Slot Duration	9 μs
	SIFS	16 μs
	PIFS	25 μs
	DIFS	36 μs
	CW_{min}	15
	CW_{max}	1023
	shortRetryLimit	7
	longRetryLimit	4
IEEE 802.11e	RCA_Interval	10, 50 and 100 ms
	QoS CF-Poll Duration	56 μs
	QoS Null Duration	56 μs

- D_{Prop} is the propagation delay
- D_{Proc} is the processing delay
- D_{Tx} is the transmission delay, mainly the time needed to send the PDU, which depends on packet size and MCS.

In the case of packet loss, the retransmission delay is added to the channel access delay. In our model, D_{Prop} is neglected (i.e., set to zero) as the distances between the transmitters and the receivers are small and D_{Proc} is also ignored (i.e., set to zero), because it is expected that the processing times for performing the algorithms in high-speed micro-controllers are typically in the order of microseconds or less.

To evaluate the delay, the ITU recommendation [23] is taken as a reference. It is recommended that for very satisfied users the maximum tolerable one-way delay (i.e., 'mouth-to-ear' in the case of speech) between two users is 150 ms. It is noticed that there are several delay sources that affect the one-way delay, like the delay for encoding at the source and decoding at the destination, core network delay (i.e., the path from Internet gateway from one end to the other end) and jitter buffers delay. Jitter buffers or de-jitter buffers are used to counter jitter introduced by queuing so that a continuous playout of audio (or video) transmitted over the network can be ensured. According to [71] the single-hop mean delay of 10 ms and a 95-percentile of 15 ms are assumed as radio interface QoS requirement for VoIP applications by leaving some space for the above mentioned unavoidable delays and assuming that both ends are connected to Internet via WLANs.

Before going into the results, an analysis of delay performance in relation to RI and TXOP is provided in the following.

8.3.3.1 Delay Analysis

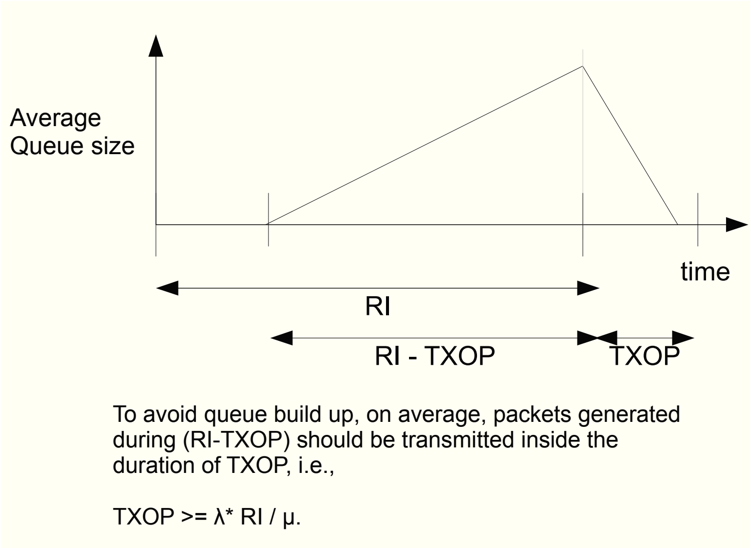


Figure 8.3: Average buffer size and its impact on delay performance

In the case of single-hop communication, the delay is a function of channel access time. In case of TDMA like channel access method like the RCA, the channel access time for each station depends on cycle duration, which is RCA_Interval (RI), and service duration (i.e., the number of time slots) assigned to that station. These parameters are required to be determined and optimized in the coexisting networks to satisfy the traffic load and to meet the delay constraint. Figure 8.3 depicts the growing of average queue size and its impact on waiting time from the perspective of a station. In RCA, each station stores the data in the queue until it can start data transmission over the link during the service period, i.e., the TXOP. The higher the duration of RI, the higher the number of stations which could share the same spectrum, however, the longer the waiting time will be for each station in accessing the channel. On the other hand, to handle the traffic load and to avoid queue buildup in each station, on average, data generated during a RI period, should be transmitted inside the duration of TXOP, i.e. if λ is the arrival rate and μ is the service rate, the TXOP duration should be

$$TXOP \geq \frac{\lambda RI}{\mu}. \tag{8.3}$$

This concludes that there should be a lower bound for the TXOP assigned to each station to avoid huge delays.

Table 8.2: Effect of RCA_Interval Parameters

RCA_Intervals (ms)	Maximum number of supported VoIP stations	Approx. Mean delay (ms)
100	36	50
50	28	25
20	22	11

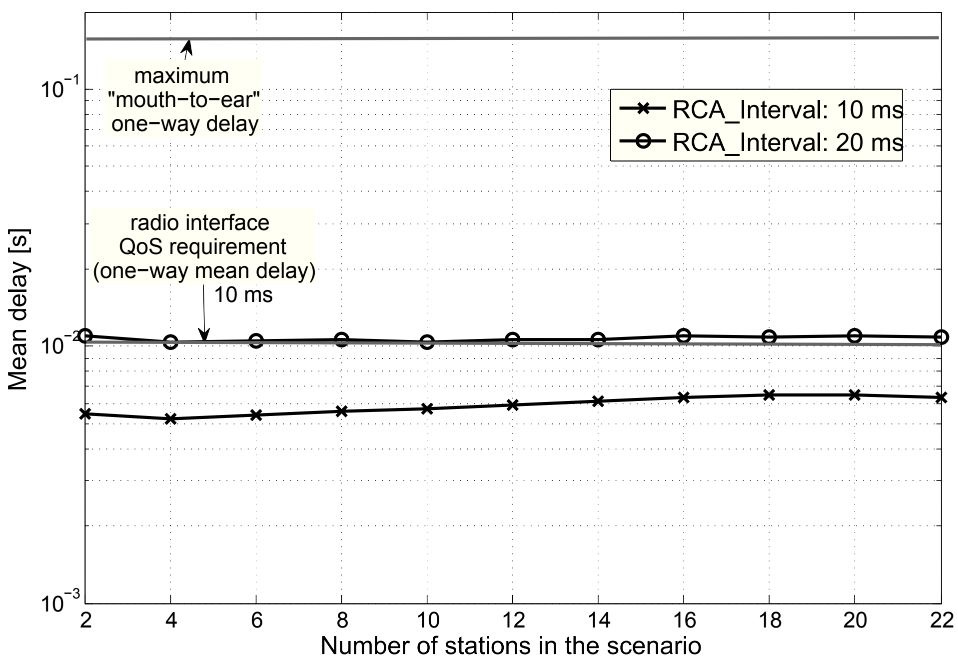


Figure 8.4: Performance metric: Averaged mean delay for different scenarios where the total number of admitted VoIP stations are increased in the coexisting scenario

8.3.4 Results and Evaluation

Table 8.2 shows the maximum number of VoIP stations supported during the different RCA_Intervals in the simulation configurations and corresponding mean delay and throughput experienced by the PDUs. This is combined results for two coexisting systems. It is clearly seen that the higher the value of the RCA_Interval, the higher the number of supported VoIP stations; however the mean delays are above the radio interface QoS requirement.

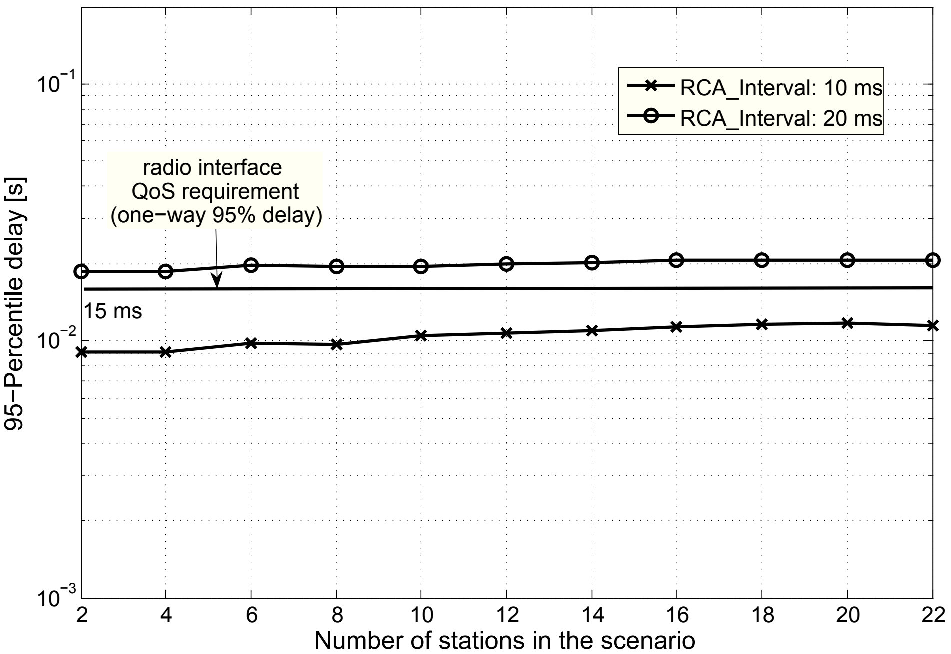


Figure 8.5: Performance metric: 95-Percentile delay for different scenarios where the total number of admitted VoIP stations are increased in the coexisting scenario

Figure 8.4 shows the averaged mean delay for different scenarios where number of stations (each supporting one VoIP call) are increased in the coexisting scenario of two WLAN systems/networks. Increasing the number of stations means lowering the assigned TXOP duration for each station. To observe the impact of RCA_Intervals, two different setup values – 10 ms and 20 ms – are considered during the evaluation of RCA method by the network simulation. Decreasing the RCA_Interval from 20 ms to 10 ms results in reducing the mean delay, which is below the QoS requirement; this is an excellent improvement compared to the 20 ms RCA_Interval.

Figure 8.5 shows that 95-percentile delay for above two RCA_Intervals with increasing number of VoIP stations. It is found that for 20 ms RCA_Interval, the 95-percentile delay is above the QoS requirement, whereas in the case of 10 ms, it is less than the QoS requirement for the number of stations in the scenario up to 22 (each system having 11 stations, in this case). Supporting the half of such numbers of stations (taking into account the downlinks) in the office scenario is satisfactory and realistic as well. One feature of the RCA method is that even when the number of stations is small and the overall load is less, the mean delays experienced are around the half of the RCA_Interval. This is common in the cyclic service based method.

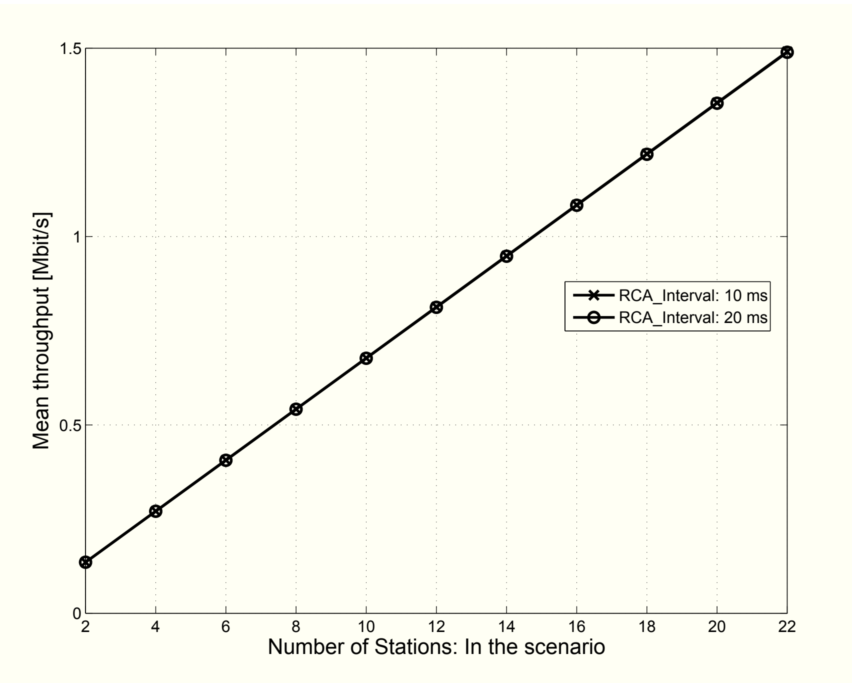


Figure 8.6: Performance metric: Mean throughput for different scenarios where the total number of admitted VoIP stations are increased in the coexisting scenario

Figure 8.6 shows the overall throughput achieved in the application layer. A large portion of bandwidth is consumed by signaling overhead for VoIP traffic (with small packet size).

Figure 8.7 shows the mean throughput and delay for the overall scenario when different configurations of the System 2's starting point (SP) offset from System 1 are considered. The SP offset is normalized by the RCA_Interval. The SP of System 2 is estimated based on the System 1's channel occupation measurements and thereof statistics of the starting

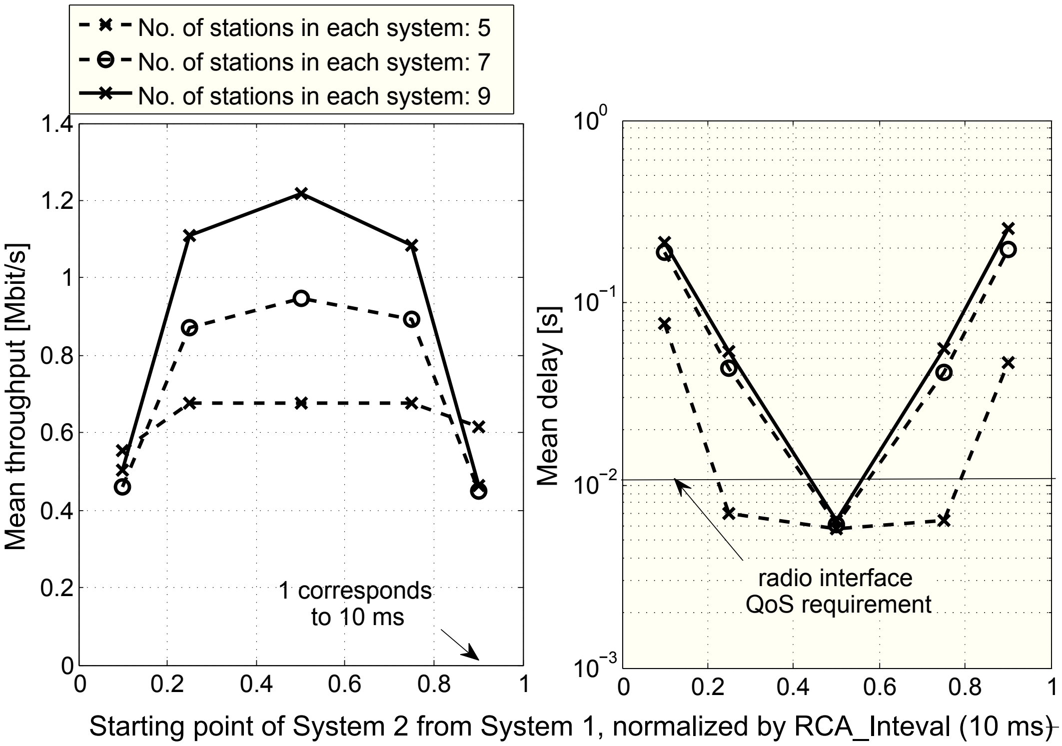


Figure 8.7: Mean throughput and delay against different configurations of the System 2's starting point offset from System 1 in the RCA_Interval

point, the end point and the traffic demand discussed in Chapter 5 and Chapter 6. In simulation and figure the RCA_Interval of 10 ms is considered and the configuration of System 2's SP offset is varied to 10 %, 25 %, 50 %, 75 % and 90 % of the RCA_Interval. It shows that the ratio of 50 % provides the best performance for three cases: the number of stations in each system is adjusted to 5, 7 and 9. The higher the load, the more important it is to choose the correct ratio. It justifies the requirement of the ratio according to the equation (4) in the algorithm. However, for the lower number of stations in each system, for example 5, which is around 25 % of total supported stations in the scenario, 25 % time offset provides almost the same performance as 50 %. This gives also the hints that by adapting the starting point (SP) ratio and resource allocation (RA) parameters, more collocated systems, for example a third system, can coexist keeping the satisfactory performance. In Section 8.6, the coexistence of more than two systems is discussed.

WLAN data deployment is evaluated and compared for the coexistence scenarios of DCF-DCF, RCA-RCA, and RCA-DCF. Details are given in Appendix C.2. The key finding of this comparison is the following. Applying

RCA method benefits the systems. In case of RCA-DCF, both systems benefit, however the DCF system benefits more from the traffic diversity of the RCA system.

8.4 Adaptive RCA

In this section, the application of the RCA method is extended to be able to reconfigure its RCA parameters, the starting point (SP) and resource allocation (RA) parameters, in varying traffic conditions based on the rules provided in Section 6.3.2. Note that parameterization is one of the important features of the proposed RCA coexisting method.

8.4.1 Simulation Model

In the case of coexistence of two aRCA enabled 802.11 systems, an important extension is taken into account. In the simulation model, the system, which starts its operation first, is identified as master system and the next system, which starts operation when the master is already in the environment, is identified as slave system. This extension supports the proper synchronization of transmission starting points of the systems.

8.4.1.1 Simulation Model Block Diagram

Figure 8.8 shows the functional block diagram of the simulation model for the adaptive RCA method. This implements the functions mentioned in Figure 5.1 and Figure 5.31. The different blocks in Figure 8.8 are implemented as different functional units (FU) in the openWNS simulator. Functions like Spectrum Occupation Measurement and Measurement Data Processing are implemented in the Channel State FU. In the Buffer FU, Incoming Traffic Measurement and Processing are modeled. Processed Data Management, DIEngine_other and DIEngine_own are modeled in the DIEngine FU. The Scheduler FU models the MAC scheduler with additional functions like a Decision Block for Assignment and Spectrum Sensing Control Method. The FUs have specific methods, depending on the identity of execution whether it is a station (STA) or an Access Point (AP). The signaling among the blocks is described in the following.

8.4.1.2 Functional Sequence Diagram

Figure 8.9 and Figure 8.10 show the sequence diagram for the adaptive RCA method considering functions and the signaling among the functional units

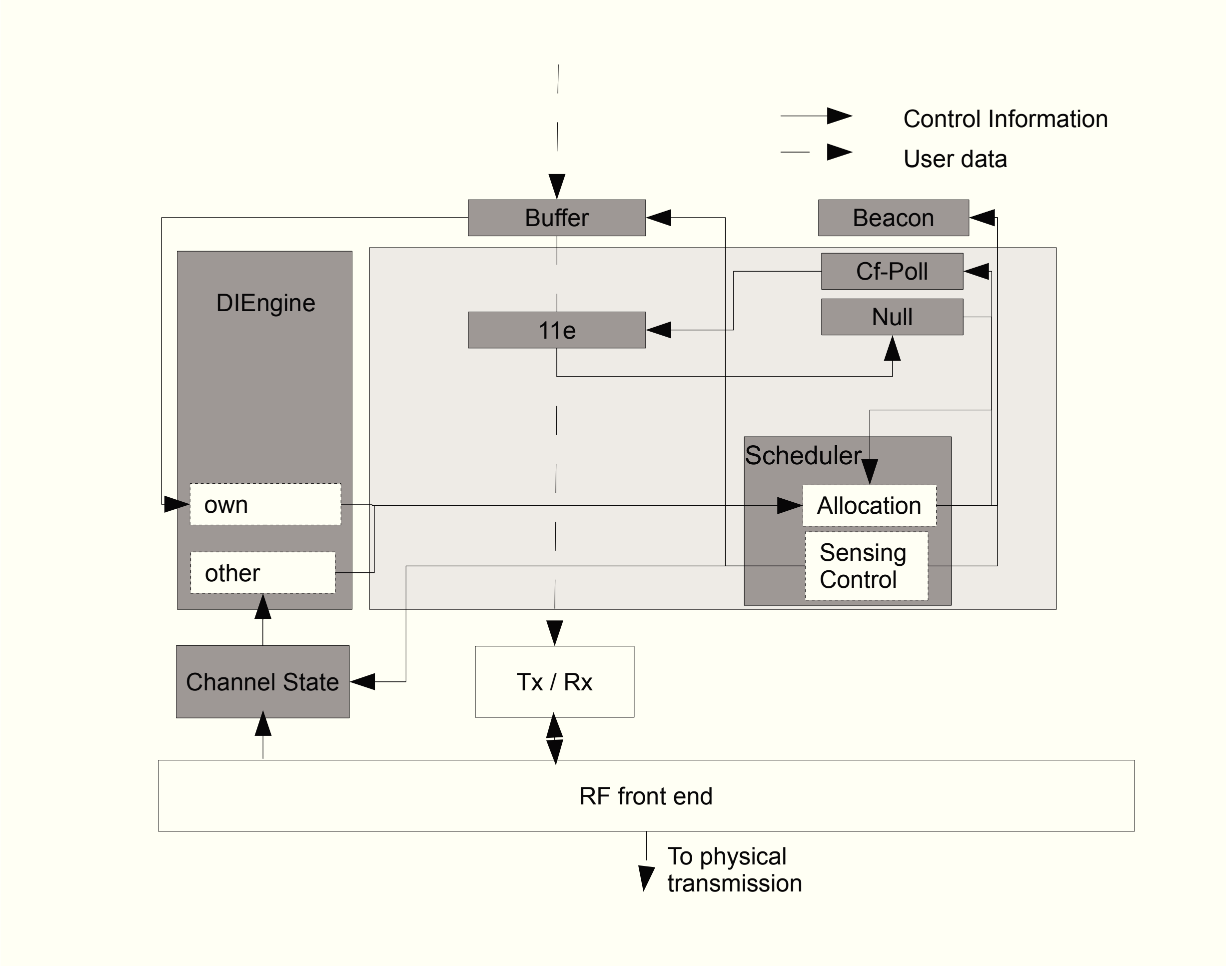


Figure 8.8: Block diagram of the simulation model to facilitate the adaptive RCA method

in the simulation model. They give a detailed and exemplary overview on the operational procedure of the aRCA method described in 6.3.2. They are drawn in the context of IEEE 802.11e, i.e all the functionalities and the signaling are happening in the IEEE 802.11e system. In the example, it is assumed that one IEEE 802.11e system is already operating in the intended channel.

Figure 8.9, which represents the initialization phase, is described in the following. At the starting, when the main coordinator of the IEEE 802.11e system, the AP, is switched on, it starts sensing the channel for the *initial channel measurement duration*. During this duration, the AP acquires the required information and processes this information (described in 5.3) for the next steps: system type identification (STI) and traffic demand estimation (TDE) of the other system (denoted as TD_{others} in the eq.).

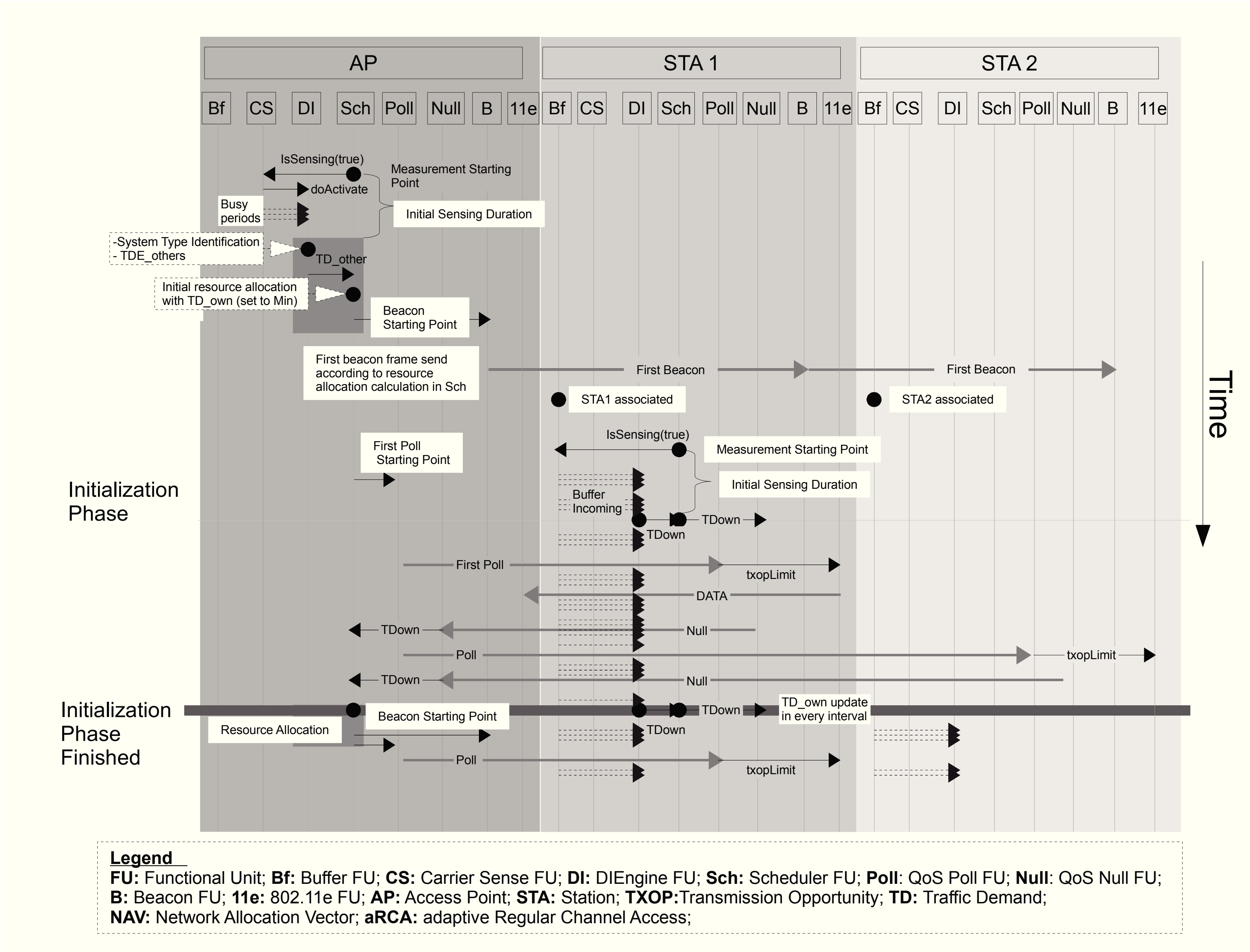


Figure 8.9: Sequence diagram of the adaptive RCA method: Initialization phase

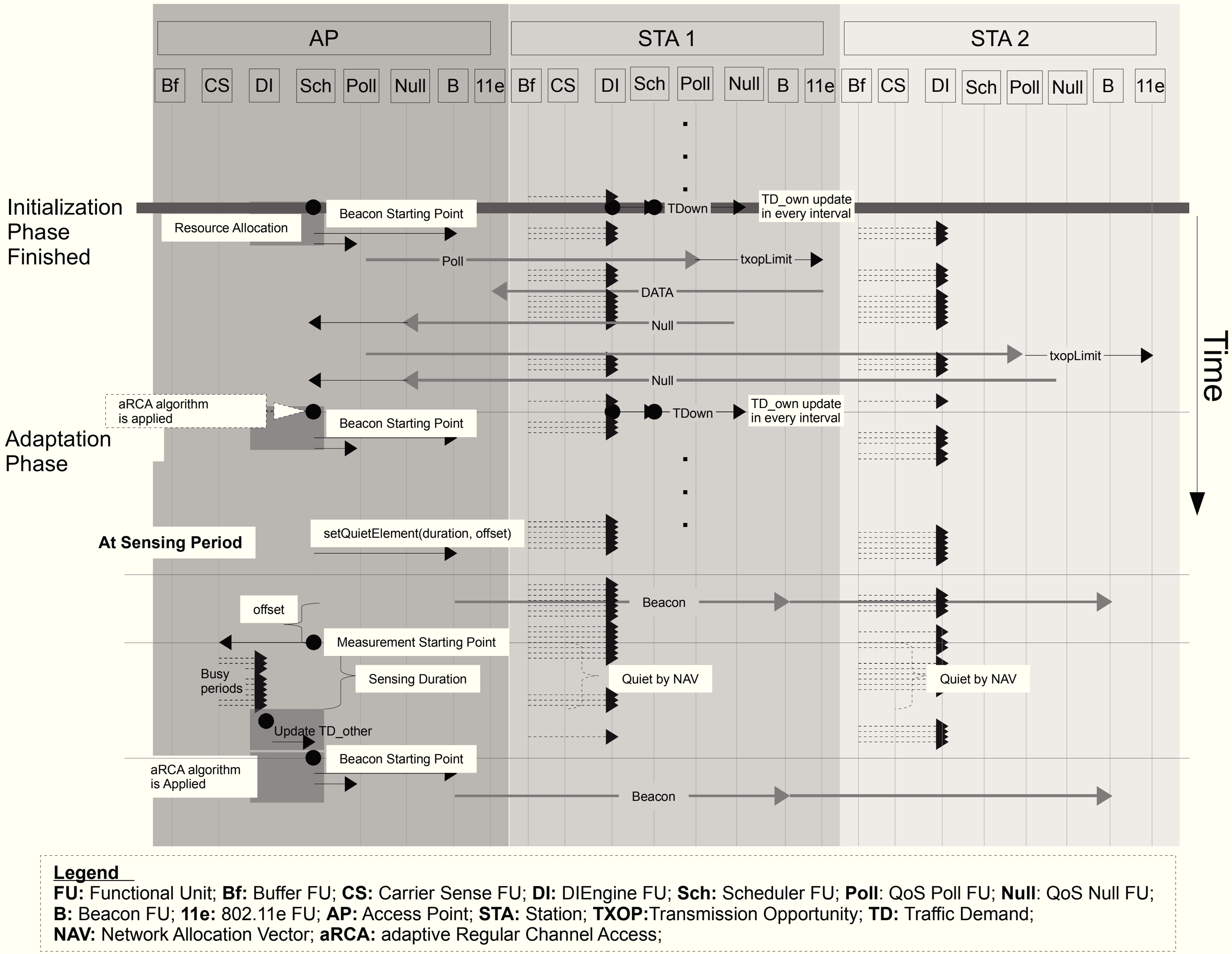


Figure 8.10: Sequence diagram of the adaptive RCA method: Adaptation phase

At the end of this duration two functions are executed: 1. The AP does the system identification based on algorithm described in 5.4.3 and 2. Based on the TDE of the other system, the AP does the initial resource allocation and the starting point for its own operation (provided that the summation of TD_{others} and TD_{own}^{min} is less than the saturation load, otherwise the AP will do the sensing on another channel as described in 6.3.1, which is out of the scope of this thesis). The AP sends the first Beacon frame so that stations can be associated. In this example, two stations are associated with the AP at this stage. Just after the association, the stations are asked to do measurements for incoming traffic bits on their MAC buffers for a duration equal to the *initial buffer measurement duration* and to do estimation of TD_{own}. At the end of this duration, the AP starts sending the Poll frames to the stations with initial resource allocation (in `txopLimit`). Stations piggyback the estimated traffic demand (TD_{own}) via QoS Null frames. This is the time point which is considered as the end of the initialization phase.

Figure 8.10, which represents the adaptation phase, is described in the following. The system now enters into the adaptation phase. The AP determines the resource allocation and the starting point for its own system based on TD_{others} and TD_{own}. It follows the process (Process 1 described in Section 6.3.2.2) iteratively with updated estimation of TD_{others} and TD_{own}. Note that the process of measurement of incoming traffic bits into the MAC buffers and estimation of TD_{own} are simultaneous processes and are running independently without interrupting transmission. However, the measurement of channel occupation to estimate the TD_{others} has to interrupt the transmission of the own system. The AP utilizes the Beacon frame for this purpose. At the starting of the next measurement (defined by *sensing period*), the AP sets *quiet element* of the Beacon frames with a duration equal to *sensing duration* and with an offset. The AP and its associated stations become silent for the sensing duration by means of using the network allocation vector (NAV). At the end of the sensing duration, estimated TD_{others} is updated. As mentioned before, the resource allocation scheduler in the AP uses the updated estimations on its next iteration.

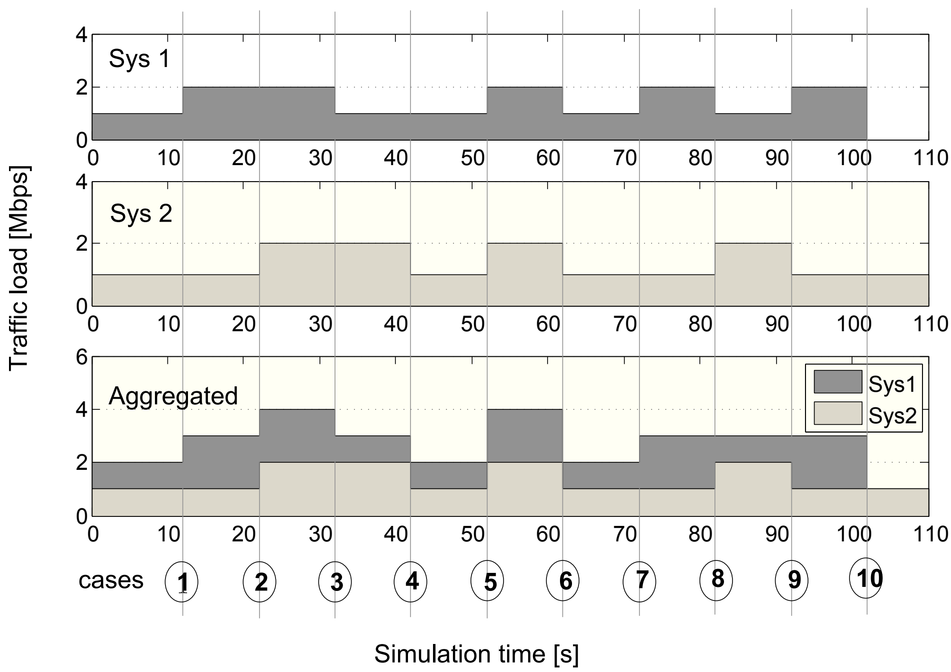
8.4.1.3 Extension of QoS Null frame

To facilitate the piggyback of traffic demand estimation measurement, an extension to the IEEE 802.11 standard is proposed. Basically, a QoS Null frame includes no frame body, however it includes QoS control fields. A new layout of the subfields of the QoS control field is proposed and utilized as shown in Figure 8.12. Bit 7 is set to '1' to recognize that the QoS Null frames sent by the stations carry the Traffic Demand (TD_{own}) information. An 8-

System 1	Increase	√				√		√		√	
	Decrease			√			√		√		√*
	Does not change		√		√						
System 2	Increase		√			√			√		
	Decrease				√		√				
	Does not change	√		√				√		√	√
Cases:		1	2	3	4	5	6	7	8	9	10

* decreases to zero

(a) Scenarios: cases



(b) Traffic load scenario for validation

Figure 8.11: Simulation scenario (traffic load) for Adaptive RCA validation

bit Traffic Demand (TD_{own}) subfield is introduced which actually carries the corresponding information. The AP may use this information.

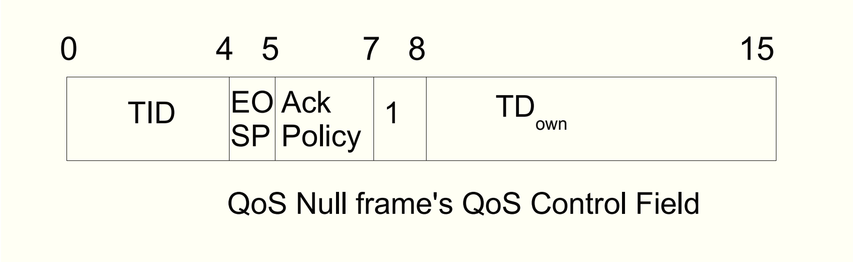


Figure 8.12: The new layout of the QoS Null frame's QoS control field

8.4.2 Simulation Setup

A coexisting scenario of two aRCA enabled 802.11 systems are evaluated in the following. They are denoted as Sys1 and Sys2 for further reference.

For validating the adaptive behavior of the aRCA method with the traffic dynamics, a dynamic traffic load scenario is developed. Three different mean traffic load transitions are considered from each system's point of view: increase, decrease and no change of traffic load. Considering the traffic load transitions for both systems, a traffic load transition matrix is determined as shown in Figure 8.11(a). Different cases, as numbered, are the outcome of this matrix. The traffic load of the systems in the simulation are configured in such way that all the cases are covered during the one simulation execution time as shown in the Figure 8.11(b).

For the rest of the simulation results it is configured as 1 Mbps, i.e., the traffic load of Sys1 starts with 1 Mbps and then increases to 2 Mbps after 12 s and so on as shown in the figure. The traffic load of Sys2 starts with 1 Mbps and then increases to 2 Mbps after 22 s and so on as shown in the figure. For both systems, Protocol Data Units (PDUs) of 375 bytes are considered.

In the IEEE 802.11 RCA configuration, the sensing period is set to 5 s and the sensing duration is set to 0.5 s and traffic estimation smoothing factor is set to 0.2.

8.4.3 Results and Evaluation

In the following the results for estimated traffic demand and resource allocation by two RCA-enabled IEEE 802.11 systems are evaluated in the first phase. In the second phase, the results for QoS measures like throughput, delay, and packet loss ratio are evaluated.

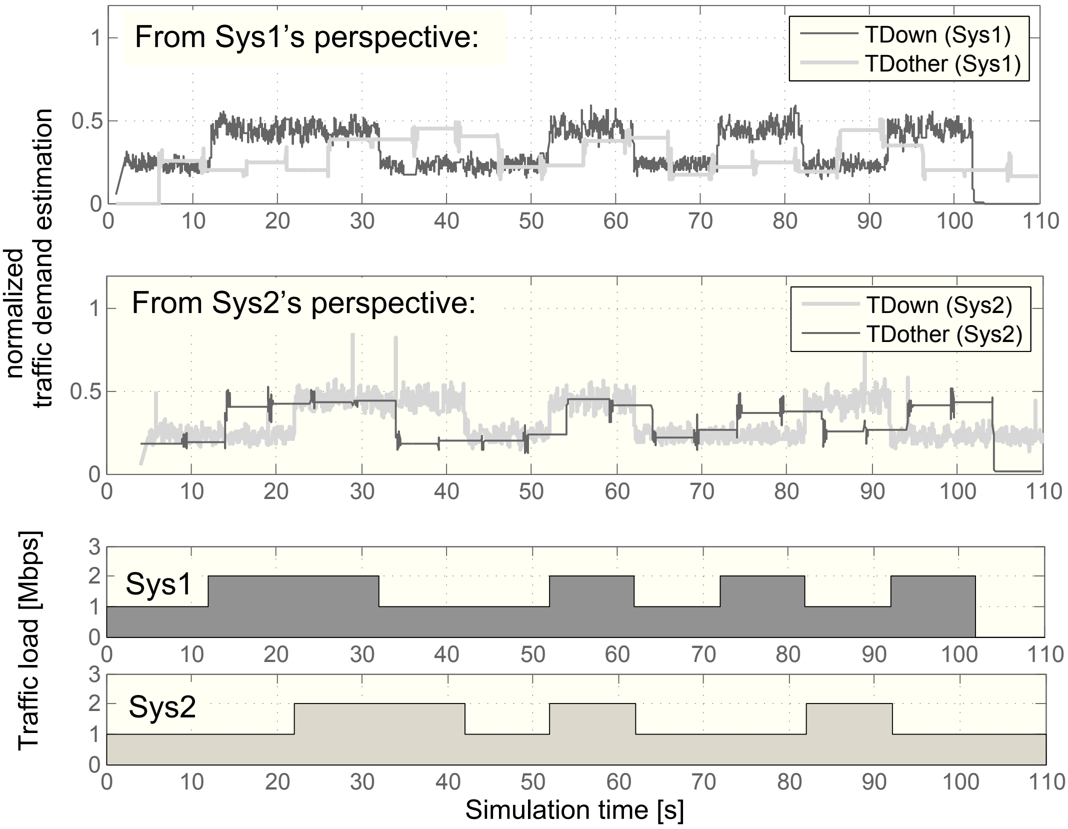


Figure 8.13: The estimated traffic demand by two RCA-enabled IEEE 802.11 systems against the simulation time

8.4.3.1 Traffic Demand Estimation and Resource Allocation

Figure 8.13 shows a prior result in the adaptation process of the RCA algorithm. The top two diagrams show the estimated traffic demand from the perspective of two systems. The top one shows the traffic demand estimation of Sys1's own system and the other system (Sys2) by dark and light gray lines respectively, estimated by the Sys1. The bottom one shows the traffic demand estimation of Sys2's own system and the other system (Sys1) by light and dark gray lines respectively, estimated by Sys2. As expected, the own traffic demand estimation by the systems along the simulation time is quite well matched with the traffic applied to the systems. The excellent part is that it takes only 20 to 30 iterations, which results in a delay between 200 to 300 ms, to estimate approximately equal to the actual traffic in case of traffic transition. The just mentioned fact is based on the observation on the result curve on the top two diagrams. For example, at the top diagram it is found that Sys1 takes 200 ms (at 12 s), 300 ms (at 32 s), 300 ms (at 52 s), 200 ms (at 62 s), 200 ms (at 72 s), 250 ms (at 82 s) and 200 ms (at 92 s) to estimate approximately equal to the actual traffic when traffic load is changed. The basic reason behind the fact is the considered smoothing factor of 0.05 in the exponential moving average based estimation model (as given by Equation 5.11). For the rest of the results analysis this delay is denoted as *real estimation delay*.

In the figure, the estimation of the others traffic demand along the simulation time is also matched quite well with the traffic applied to the other system. However, there is an additional delay observed between the actual transition of traffic load and its detection in the estimation, other than the real estimation delay of around 300 ms. The additional delay is due to the sensing period. The estimation process has to wait for the new samples to consider. So this additional delay can be estimated intuitively as follows. This delay generally is the time difference between the time of traffic transition and the starting time of the next sensing period, which suggests that this delay cannot be more than the sensing period. In other words, it will follow the sensing period distribution. In the figure, an additional delay of 4 s is observed. In the simulation setup, the first sensing starts at 7 s and then it repeats after each sensing period of 5 s. For the rest of the results analysis, this delay is denoted as *additional estimation delay*.

The top diagram in Figure 8.14 shows the estimated resource allocations (RA) along the simulation time by Sys1 for its own and the other system. The combined allocation is equal to the RCA_Interval as seen in the figure as well. Sys1 allocates the time duration to its own system according to its own estimated resource allocation shown in the figure and keep the rest of the RCA_Interval for Sys2. In other words, Sys1 sets its transmission starting point equal to the estimated Sys2's allocation, from its perspective. The similar process is also done in Sys2.

As described in the RCA method, the resource allocation is determined based on the traffic demands, the direct correlation is seen as well in both top diagrams in Figure 8.13 and Figure 8.14. The change in traffic estimation of either the own or the other system, triggers the change of the resource allocation, which is considered as a valuable outcome. This eventually means that the reconfiguration of the resource allocation and the reconfiguration of the starting point are matching the actual traffic dynamics, which is indeed the focus of the adaptation phase. The delay for the adaptation is directly correlated to the estimation delay discussed above for the own and other traffic demand. Comparing with actual traffic load, shown in the bottom of in the figure, few cases are discussed in the following. The starting of Sys2's transmission is considered as reference point.

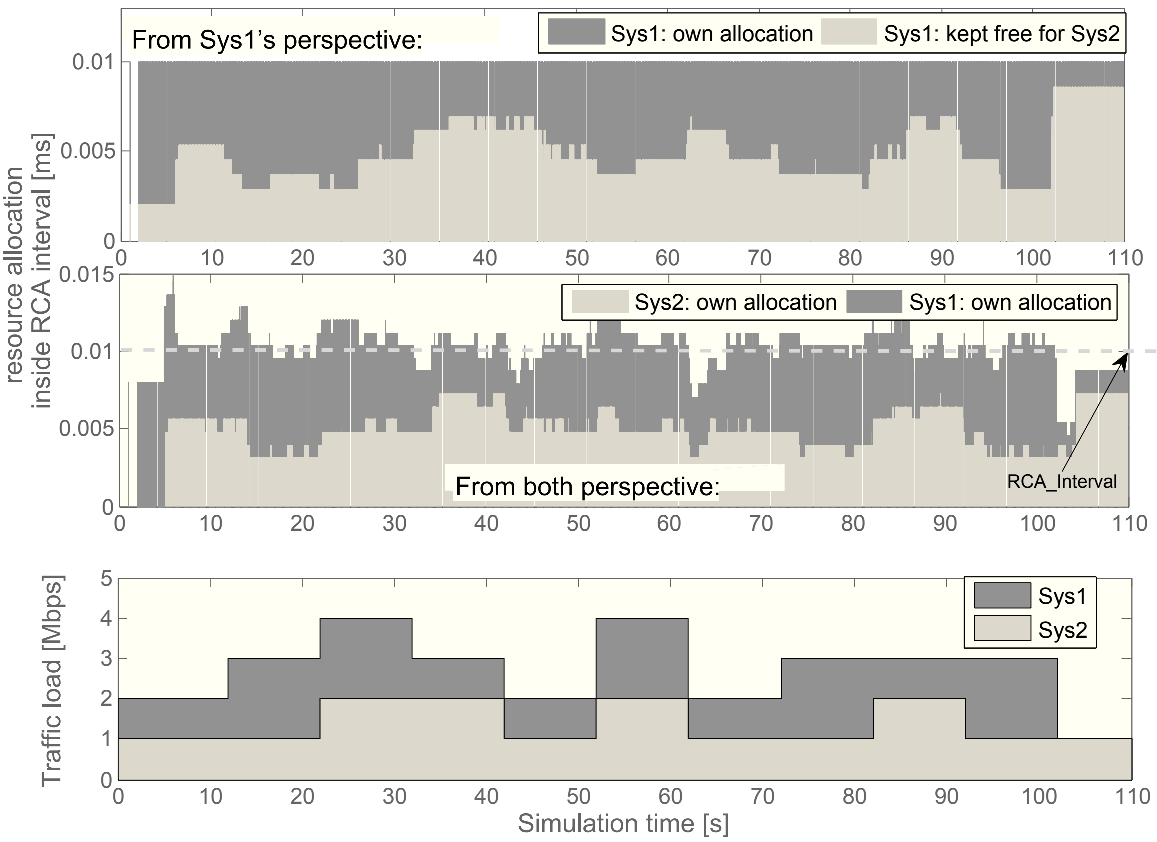


Figure 8.14: The resource allocation by two RCA-enabled IEEE 802.11 systems against the simulation time

- Case 1 at 12 s: When Sys1's traffic increases, its resource allocation increases proportionally after the real estimation delay of 0.2 s, and the estimated starting point for Sys1 becomes relatively closer.
- Case 2 at 22 s: The Sys1 senses Sys2's traffic increase in its next scheduled sensing at around 26 s (additional estimation delay of 4 s plus real estimation delay of 0.3 s). The newly estimated value triggers to reconfigure the starting point for the Sys1 relatively later (at around 4 ms) than the previous case (at around 2.5 ms) and to reallocate the resource, resulting in a decrease of resource allocation proportionally.
- Case 3 at 32 s: When Sys1's own traffic decreases, its resource allocation decreases proportionally with a real estimation delay of 0.3 s, and the estimated starting point for Sys1 becomes relatively even later (at around 6.5 ms) to the reference point.

The middle diagram of Figure 8.14 shows the own resource allocation from the individual system's point of view and these are the actual

RA. It shows that very often the aggregated allocation is more than the RCA_Interval. This phenomenon generally results in delay of the starting points due to carrier sensing characteristic unless special treatment, described in Section 9.4.4, is considered in the model.

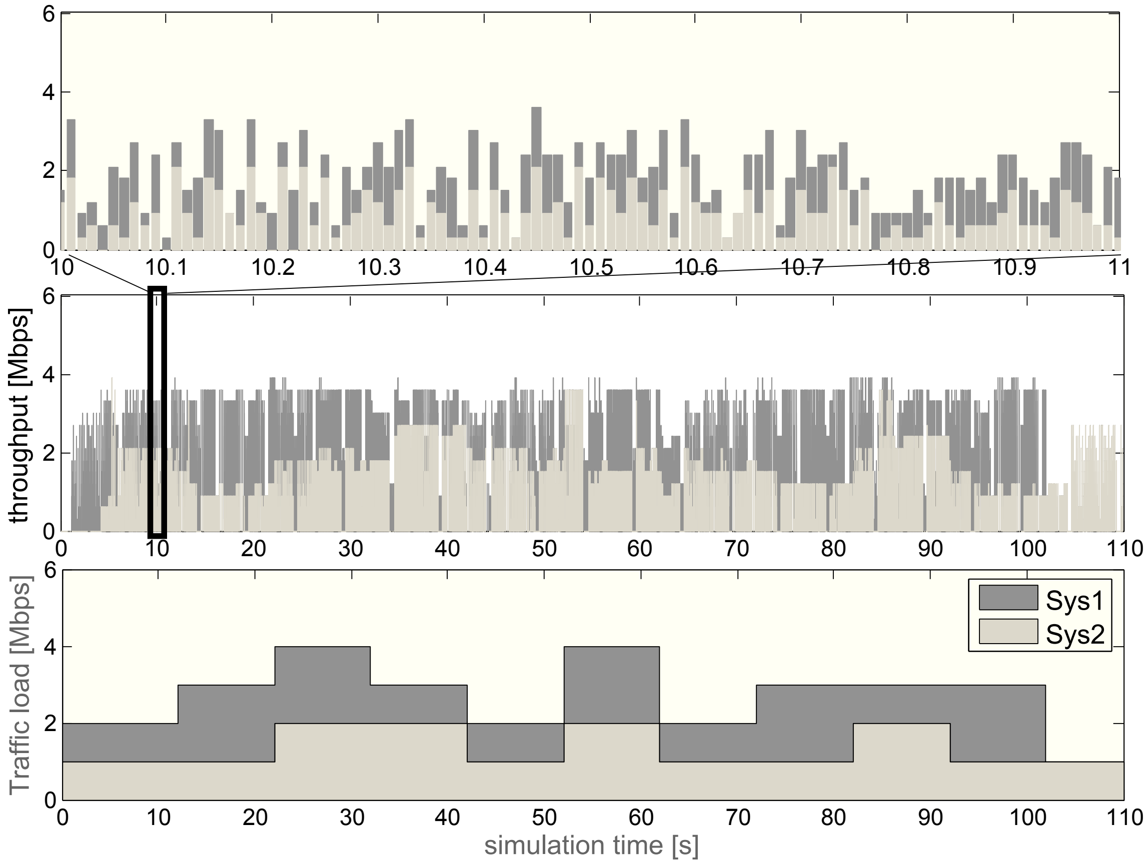


Figure 8.15: Achieved throughput timeseries (averaged over 10ms) measured on top of the MAC layer

8.4.3.2 Throughput and Delay

Figure 8.15 shows the achieved aggregated throughput against simulation time. The throughput is measured at the MAC layer and averaged over a 10 ms window. The impact of resource allocation is visible on the throughput.

Figure 8.16 shows the end-to-end delay of the packets. High delay peaks are seen in both delay curves after every 5 s. These are basically due to the packets which are waiting in the MAC buffer during the sensing duration when the own system was silent. The maximum delay peak is therefore equal

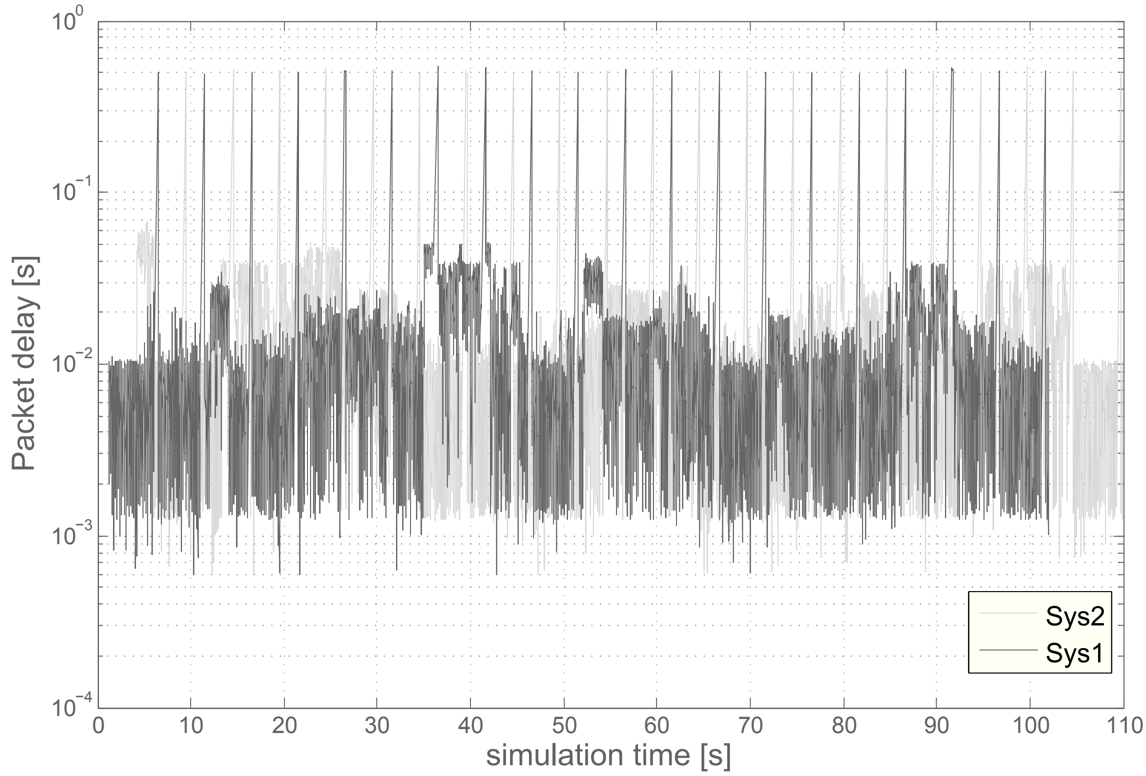


Figure 8.16: The end-to-end MAC delay timeseries

to the sensing duration of 0.5 s. Except for those delays, rest of the delays are not more than 7 ms depending on the traffic load scenarios.

For delay constrained traffic like VoIP, these high delays, resulting from sensing durations, are not acceptable. In such a case, an application of a QoS-aware buffer management (QBM) technique in the MAC buffer is a good solution, because QBM implements a strategy according to the traffic type and its QoS requirement. For example, for VoIP traffic, which has a maximum delay limit, QBM applies a strategy so that the packets inside the buffer will be dropped if they reach a predefined age threshold. As a result, the MAC buffer drops the packets which are waiting inside the buffer for more than a predefined age threshold, when the station stops its transmission due to sensing purpose. This approach reduces the impact of sensing on delays experienced by the VoIP application with a cost of packet loss, which is acceptable to some extent.

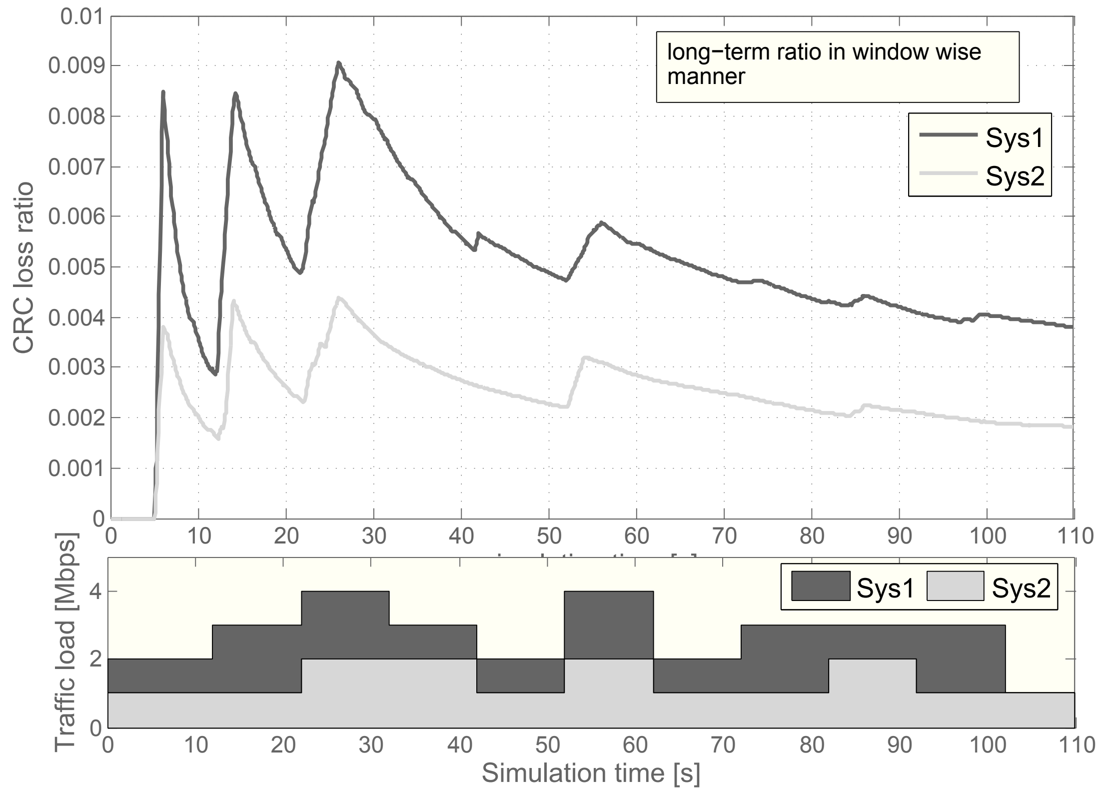


Figure 8.17: The CRC loss ratio (defined in Eq. 8.5)

8.4.3.3 Packet Loss Ratio

The packet loss ratio can be calculated per packet, i.e. whenever a packet comes, the packet loss rate is calculated as a long-term ratio of total measured lost/dropped packets to the total amount of packets including the most recently arrived packet's status.

Packet loss ratio can also be calculated per window. When it is calculated according to the following formula it is denoted as instantaneous or very short term loss ratio.

$$plr(k) = \frac{N_d(k)}{N_t(k)} \tag{8.4}$$

where, $N_d(k)$ is the measured number of packets dropped and $N_t(k)$ is the measured total number of packet input during the k-th measurement window which is the time interval $[k-1,k)$.[1] However, one disadvantage with

[1] It is derived from $[(k-1)T,kT)$, where T is the time for each measurement window.

this calculation could be when there is no input during this time window, because that could be interpreted as no packet loss without giving the details that there is no packet input.

The packet loss ratio which is calculated here is the long-term ratio of total measured lost/dropped packets to the total amount of packets per window basis. The loss ratio after the k-th measurement window

$$plr(k) = \frac{\sum_{j=1}^{k} N_d(j)}{\sum_{j=1}^{k} N_t(j)} \tag{8.5}$$

where, $N_d(j)$ is the measured number of packet dropped and $N_t(j)$ is the measured total number of packet input during the time interval $[j-1,j)$.

In case of considering the latest M windows, the loss ratio is as follows

$$plr(k) = \frac{\sum_{i=0}^{M-1} N_d(k-i)}{\sum_{i=0}^{M-1} N_t(k-i)}. \tag{8.6}$$

When M=1, it is the very short time loss ratio.

Figure 8.17 shows the CRC loss ratio according to Equation 8.5 against simulation time. The similar curve pattern, however in different magnitude scale, is seen. The loss ratio which is less than 1 % for both systems is acceptable for real time applications like VoIP.

8.5 Extension for Partially Overlapping Scenarios

In this section, the typical problems in the case of partially overlapping scenarios and a solution mechanism are discussed. Later, the shortcomings of the solution mechanism are highlighted, followed by a novel RCA based solution extended with cooperative spectrum sensing.

8.5.1 Hidden and Exposed Node Problem

In the case of a partially overlapping WLAN scenarios, not all the stations are inside the carrier sense ranges (Section 2.4) of each other. In such a scenario, the well-known *hidden node problem* and *exposed node problem* can occur as shown in Figure 8.18. The lowest data rate is assumed for all networks. In the scenarios, AP1 is within the transmission and carrier sense range of STA1.1 and AP2, while outside the transmission and carrier sense range of STA2.1, and AP2 is within the transmission and carrier sense range of STA2.1 and AP1, while outside the transmission and carrier sense range of STA1.1.

In the hidden node problem (top figure), AP2 is not able to detect the ongoing transmission of STA1.1 to AP1 by carrier sensing, and consequently,

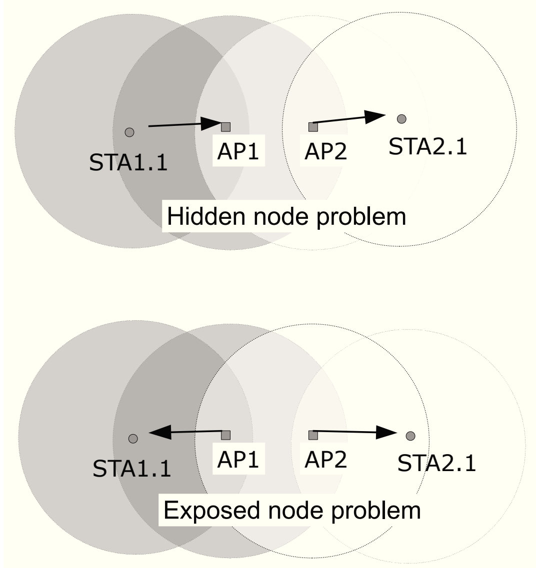


Figure 8.18: Partially overlapping scenario: *hidden node problem* and *exposed node problem*

it can start transmissions to STA2.1 resulting in interference to AP1's reception. Here, AP2 appears as a hidden node to STA1.1.

In the exposed node problem (bottom figure), AP2 detects the ongoing transmission of AP1 to STA1.1 by carrier sensing, and consequently, it is prevented to transmit to STA2.1, as it concludes that it will interfere with the neighbor's transmission. Here, two transmitters are exposed to each other, however, as the two receivers are outside of each other's range, two simultaneous transmissions can be successful without interference.

8.5.2 RTS/CTS Mechanism

The Ready-To-Send (RTS)/Clear-To-Send (CTS) mechanism is introduced into the WLAN channel access procedure to handle the above mentioned two problems [63]. Figure 8.19 shows the channel access procedure using the RTS/CTS mechanism. According to the mechanism, the problems are solved as follows.

- Hidden node solution: STA1.1 sends RTS to AP1 and in turn, AP1 sends CTS. AP2 detects CTS, but not the corresponding RTS, which helps it to identify itself as a hidden node and prevents itself from transmitting.
- Exposed node solution: AP1 sends RTS to STA1.1 and in turn, STA1.1 sends CTS. AP2 detects the RTS but not the consequent CTS, which

helps it to identify itself as exposed node and permits itself to transmit STA2.1.

What is important to see in Figure 8.19 is that introducing RTS/CTS already supports the spectrum sharing in homogeneous scenarios, where both systems can decode each other's frames. However, the general drawback of this scheme is a huge overhead in case of short frames (e.g. VoIP traffic) exchange and no Quality of Service (QoS) assurance.

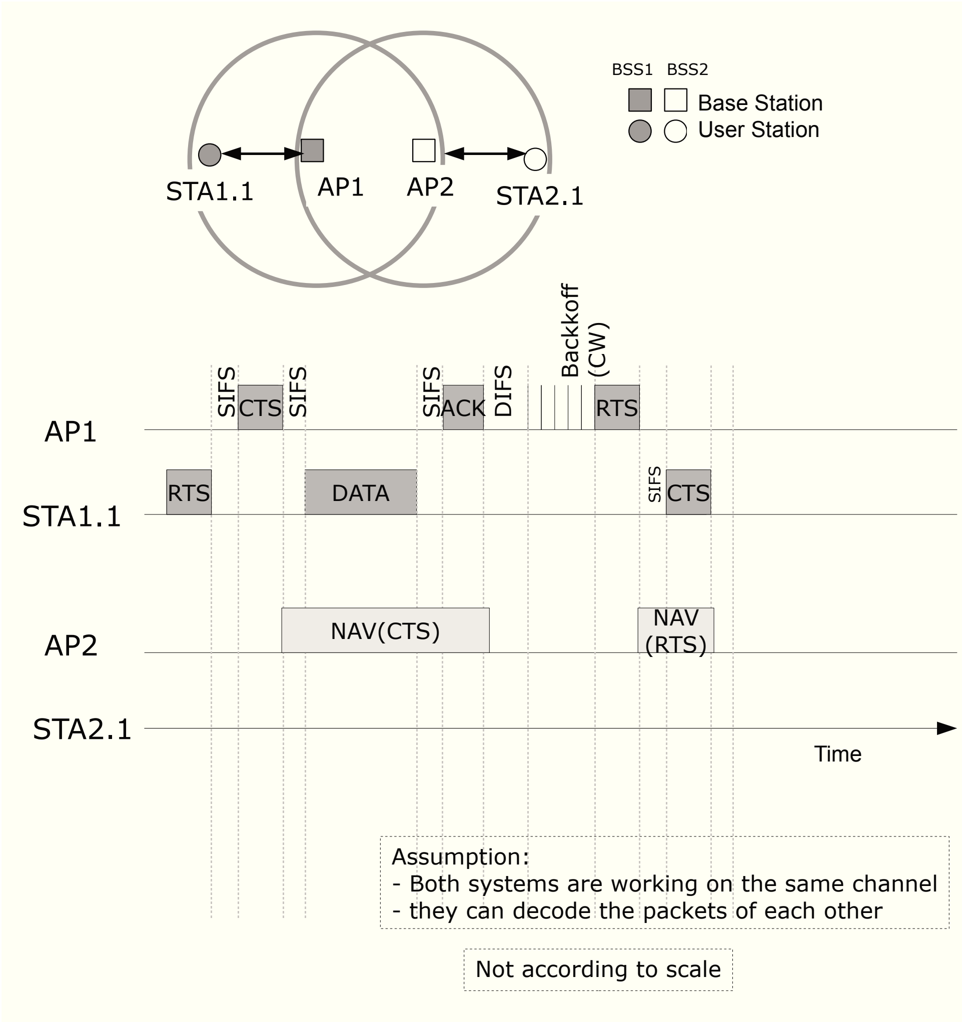


Figure 8.19: Timing diagram for channel access by collocated IEEE 802.11 systems using the RTS/CTS mechanism

8.5.3 Shortcomings of the RTS/CTS Mechanism in the Context of Coexisting Networks

Due to the lack of system level time synchronization between the coexisting systems, i.e. proper rules between the systems that specify at what time which system will access the channel, the following problems still exist despite the RTS/CTS solution, resulting in QoS degradation. The problems are also shown in Figure 8.20.

- STA1.1 sends RTS to AP1 and in turn, AP1 sends CTS, which prevents AP2 from transmitting as described above in the hidden node solution. However, STA2.1 is still hidden to system 1 and can transmit RTS resulting in a collision with CTS at AP2. STA2.1 sends again its RTS after a timeout interval, and in turn, AP2 sends CTS, which can collide with data frame from STA1.1 to AP1 at AP1 [31].
- Based on the exposed node solution as described above, the exposed node AP2 starts a communication with RTS, and in turn, STA2.1 sends CTS. However, CTS collides with an ongoing data transmission from AP1 to STA1.1 at AP2, resulting in a retransmission of RTS. The retransmitted RTS can have a collision with ACK from STA1.1 to AP1, resulting in retransmission of RTS from AP2 and the whole DATA sequence from AP1.

8.5.4 RCA with Cooperative Spectrum Sensing

A wireless network following the IEEE 802.11e HCCA method is exempt from the hidden node problem by its embedded feature that stations transmit only when polled. Moreover, when a node receives a CF-Poll frame, it updates the NAV according to the duration field of the CF-Poll frame. This phenomenon helps to avoid the hidden node problem (Figure 8.18) in the coexistence scenario, provided that both systems do not send the Beacon frames or the CF-Poll frames simultaneously. The RCA method is introduced to reduce such simultaneous transmissions.

The mentioned RCA method has two key characteristics: traffic demand estimation and assignment of the Beacon frame starting time. They are calculated based on the outcome of the channel measurement. Considering the positions of APs which affect the channel measurement, two cases are identified as shown in Figure 8.21 to be discussed further in the partially overlapping scenario.

It is apparent that in both cases systems cannot fully monitor the channel occupation of the other systems, however case 2 is more severe. So there are

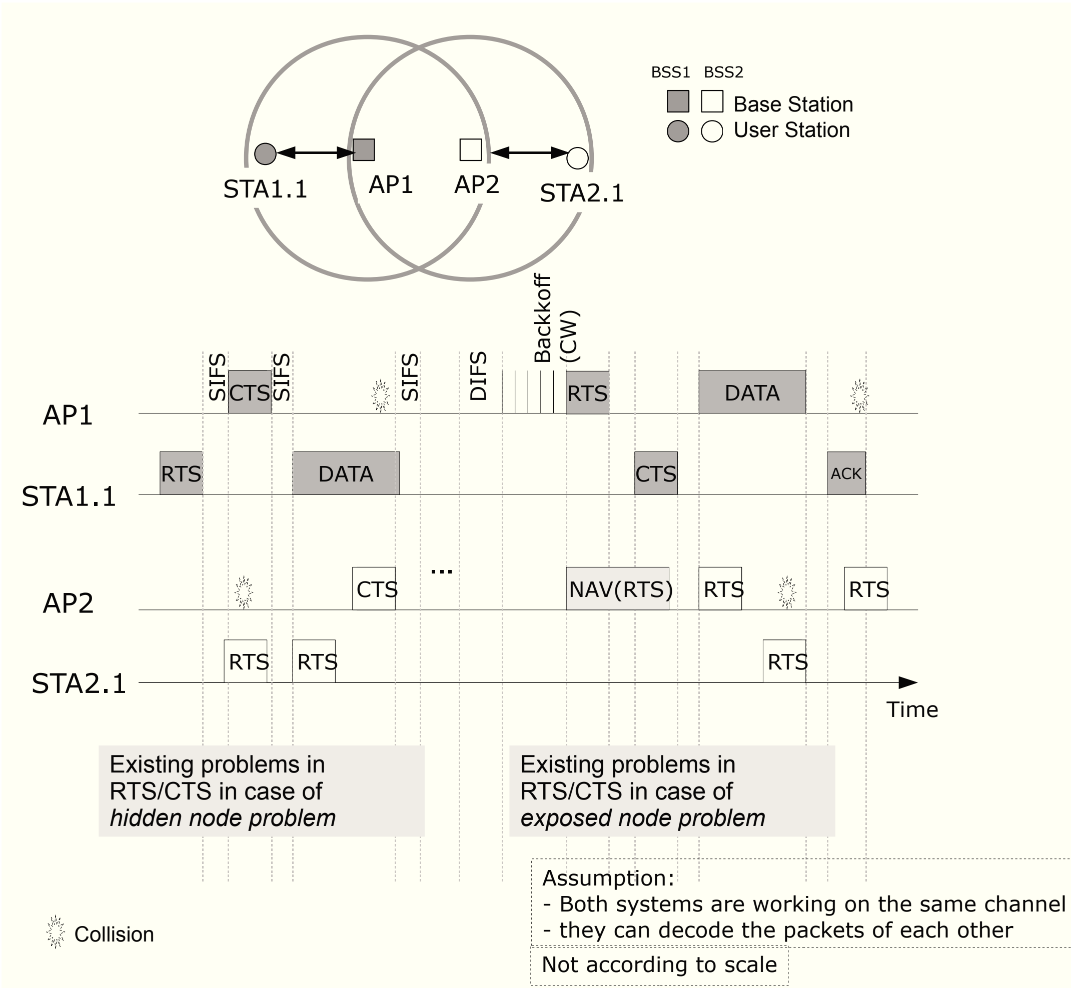


Figure 8.20: Timing diagram for channel access by collocated IEEE 802.11 systems using the RTS/CTS mechanism: existing problems

possibilities that a system can underestimate the traffic demand of the other systems resulting in an early starting offset.

Case 1: Two APs are in each other's carrier sense range. In this case, one system can monitor the downlink traffic of the other system completely and a certain amount of the uplink traffic, which depends on the mutual coverage ratio.

Case 2: Two APs are outside of each others's carrier sense range. However, the AP can hear some of the stations of the other system. In this case, one system can monitor only a certain amount of the uplink traffic of the other system. Moreover, the APs cannot detect each other's Beacon frames if the transmission power is the same.

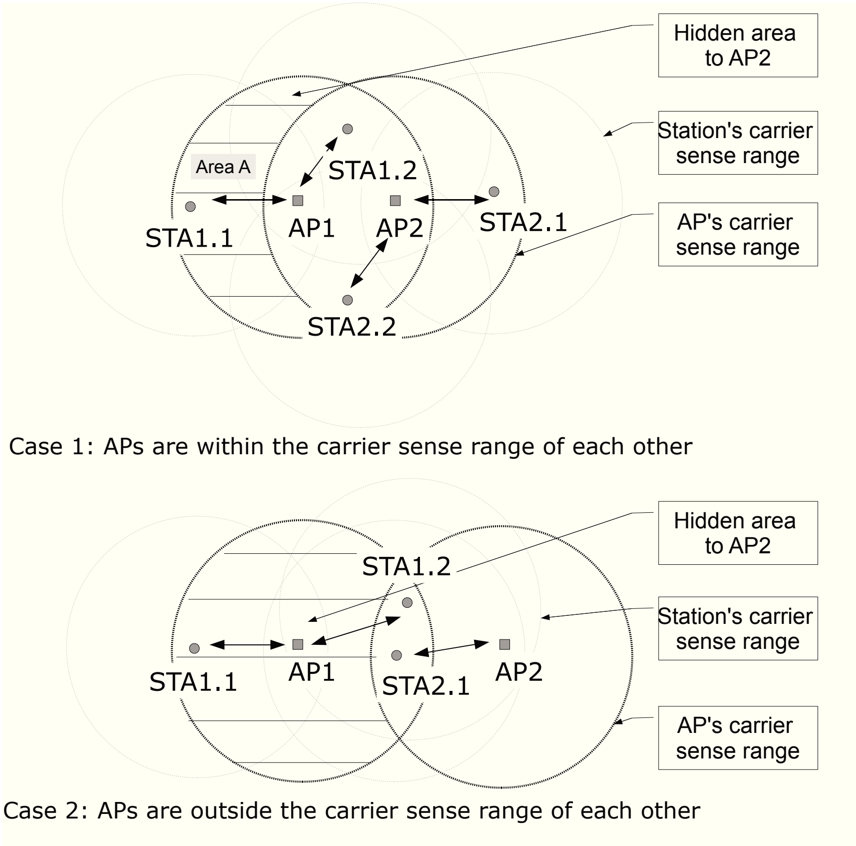


Figure 8.21: Two different partially overlapping scenarios: APs are within and outside the carrier sense range of each other

Considering the above unavoidable circumstances which appear in a partially overlapping coexistence scenario, the following extensions in the RCA method is proposed.

8.5.4.1 Cooperative Spectrum Sensing

The concept of cooperative spectrum sensing for cognitive radio has been proposed in [33, 81] in the context of detecting the primary users when multipath and shadowing are in concern. In the spectrum sharing context of this thesis, the system exploits a similar method to acquire the complete knowledge of spectrum occupation in case of hidden nodes around it in conjunction with multipath and shadowing, which is described as follows. Up to now, the measurement functionality is located in the AP, which can be denoted as individual spectrum sensing. In this extended proposal, the distributed mobile stations are also facilitated with the measurement functionality to exploit the spatial diversity in the measurements. Sensing is extended for (centralized) cooperative operation with the AP as the central identity. The whole process of sensing follows the steps described below.

1. AP sends a signal to all stations to individually perform local measurements of the channel occupation on a specified channel and time duration.
2. All stations measure the channel and report their measurement results to the AP. Which kind of results will be sent and how much preprocessing will be done on the local measurement samples on local stations are the key questions to be considered.
3. AP combines the local measurement results by appropriate data fusion rules and makes proper use of the results to estimate the traffic demand of the other system, and to estimate the relative locations of the stations which belong to the other system. The knowledge of the station locations can improve the performance of resource scheduling.

The signaling to request and report measurements is an another aspect in the method to be considered. In this purpose, Radio Measurement Request and Radio Measurement Report frames are used, which are provided in IEEE 802.11k, which is now part of the IEEE 802.11-2007 [63] standard. The Measurement Request frame consists of a Measurement Request element where for example the measurement type can be declared. In the RCA method the following signaling sequence is followed. At the starting of the next measurement, the AP sets the quiet element of the Beacon frames with a duration equal to the sensing duration and with an offset. For the measurement request, two options can be followed. 1. AP sends a separate Radio Measurement Request frame to the stations as a multicast frame (classical approach) just after a Beacon frame, or 2. Measurement Request element is added to the Beacon frame (a new proposal) which is eventually broadcasted. For the measurement report, the stations send the Radio Measurement Report frames in the next RCA_Interval cycle with a priority over Data frames. In this case, the AP can integrate an algorithm to check whether it receives the Radio Measurement Report frames or not.

The achieved outcome of the cooperative spectrum sensing can be utilized to schedule the transmissions of the own system with the knowledge of the neighbors and their channel occupation activity model.

8.5.4.2 CTS-to-Self

In the standard [63], to protect the data transmission to the AP in response to the CF-Poll the following is provided. The polled station can send a 'CTS-to-Self' frame with the receiving STA address (RA) containing its own MAC address and the duration equal to the CF-Poll's duration. This helps to update the NAV of the stations located in the hidden area. This method is integrated in the proposed solution in such a way that this will be triggered when a) the synchronization of the beacon starting points fails, or b) the synchronization of the scheduling fails, or c) random access (DCF) based stations are located in the hidden area. Degradation of performance metrics can used to identify such a situation by the AP. Situation c) can also be identified by the sensing method.

8.6 Extension for more than Two Networks

The adaptation of the generic RCA method (Section 6.3.1) in the coexistence scenario of two IEEE 802.11 systems has been introduced in Section 8.3. In this section, the RCA method is extended for the coexistence scenario of more than two IEEE 802.11 systems. In order to so, the following two procedures are required:

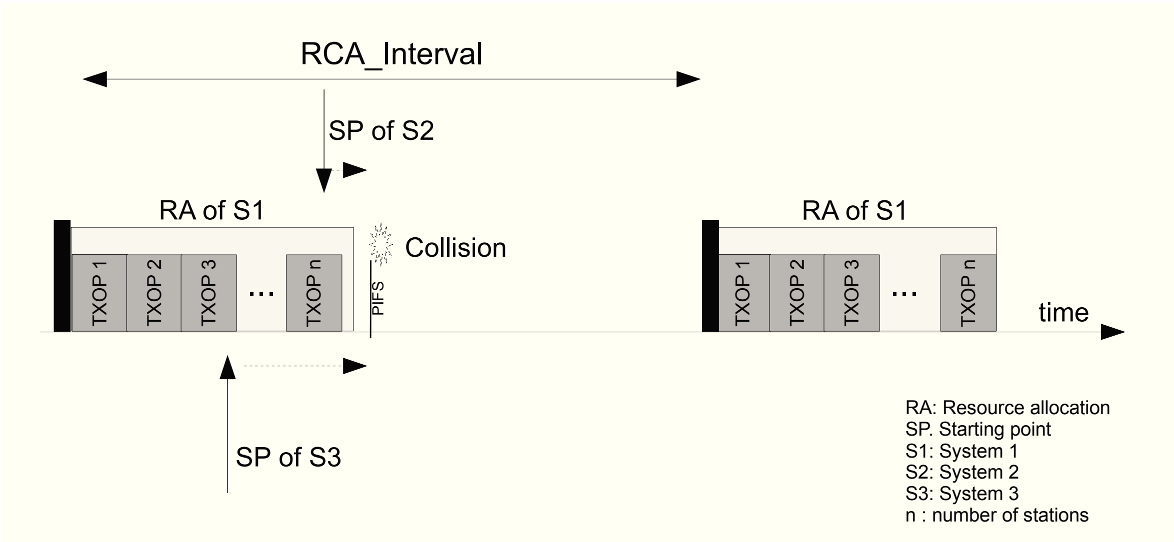


Figure 8.22: Collision due to delay in two system's beacon starting points

1. Schedule the transmissions of the systems' Beacon frames according to a sequence, so that the systems can utilize the resource sequentially, obviously with the consideration of traffic demand estimations. The concept of the virtual system ID (VSID) is proposed to support the sequential access and described in Section 8.6.1.
2. Handle the following event. Two or more systems' Beacon frames (system's starting point) have to be delayed if the channel is occupied.

This event could occur due to the estimation errors in the starting point (SP) and/or resource allocation (RA) as described in Section 6.3.2.2. Figure 8.22 shows such an event. In such a case, at the end of the channel busy all waiting systems start sending the Beacons just after the channel becomes idle, which results in collisions. The application of system level backoff is proposed to reduce such collisions and described in Section 8.6.2.

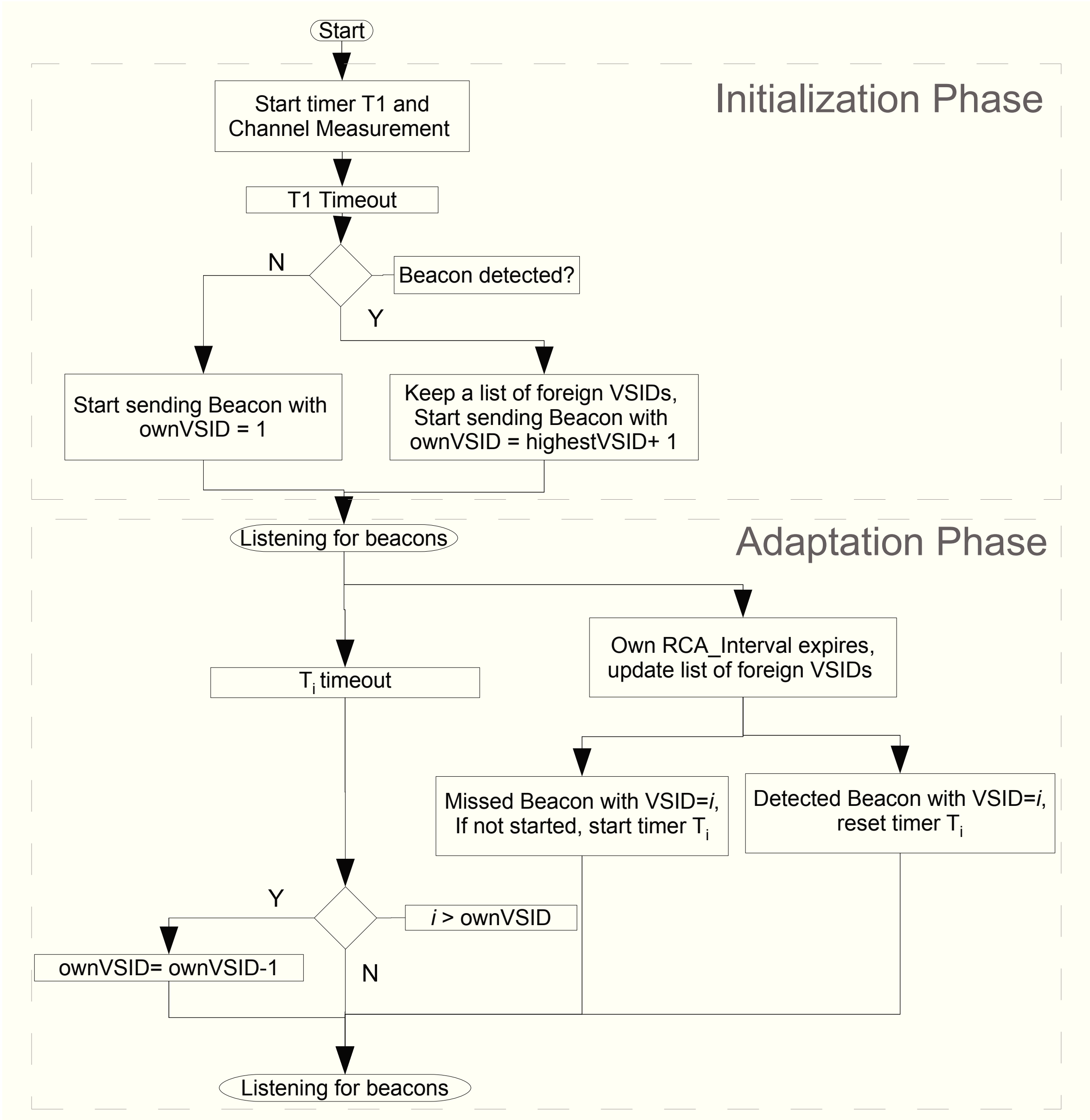


Figure 8.23: Flowchart of maintaining Virtual System ID (VSID) for synchronization

8.6.1 Virtual System ID (VSID)

To support the sequencing, the concept of a virtual system ID (VSID) is introduced besides the BSSID. The systems assign themselves VSIDs at the starting of their operation. For this purpose, an extra information element field, called VSID, is added in the Beacon frame body. The systems acquire the knowledge of each others' VSID from the broadcasted Beacon frames. The VSID of a system is required to be changed, if another system stops its operation, which is handled in the adaptation phase. A complete flowchart from the perspective of a system is shown in Figure 8.23, which should be integrated with the adaptive RCA method described in Section 6.3.2.

Initialization Phase: Before starting the operation in the channel, the system does channel measurements to estimate the traffic demand of the other systems operating in the surrounding, as discussed in Section 6.3.2.1. After the channel measurement, the system assigns its VSID to '1' if no Beacon is detected (i.e. it is the first system), otherwise to '1+highestVSID', where highestVSID is the highest number of the VSID it has detected. In this phase, the system acquires a list of the current VSIDs. With the help of the assigned VSID, the system is able to determine its starting point in the resource allocation process as discussed in Section 6.3.2.1.

Adaptation Phase: After completing the initialization phase, a system reaches to the adaptation state where it generally listens for the Beacon frames. After each of its own RCA_Interval, it checks whether it receives all the Beacon frames from the systems in its VSID list, and also adds the newly added system's VSID (if any) to that list. If the Beacon frame from VSID=i is missed, then a corresponding timer T_i is set at the start of the next RCA_Interval. In the next RCA_Interval, if the Beacon frame with VSID=i is received then it resets the timer T_i. The same process is followed for all Beacon frames from the other systems in its VSID list. At the timeout of the corresponding timer T_i (i.e, if the Beacon frame is still missing, it is realized that the corresponding system with VSID=i has gone offline), the system lowers its own VSID by 1 only if the ownVSID is greater than the missing Beacon's VSID=i. In the following an example scenario with time diagram is provided for better overview. Figure 8.24 shows the different executed states of the method from the perspective of System 2 and System k in a coexistence scenario of n systems. The method is executed independently in all n systems. When the system with VSID=2 (System 2) and the system with VSID=k (System k) sense that the Beacon frame with VSID=1 is missing, they set their respective timers T_1 at their corresponding start of the next RCA_Interval. It is assumed here that the timer value is three times the RCA_Interval. When both systems on their

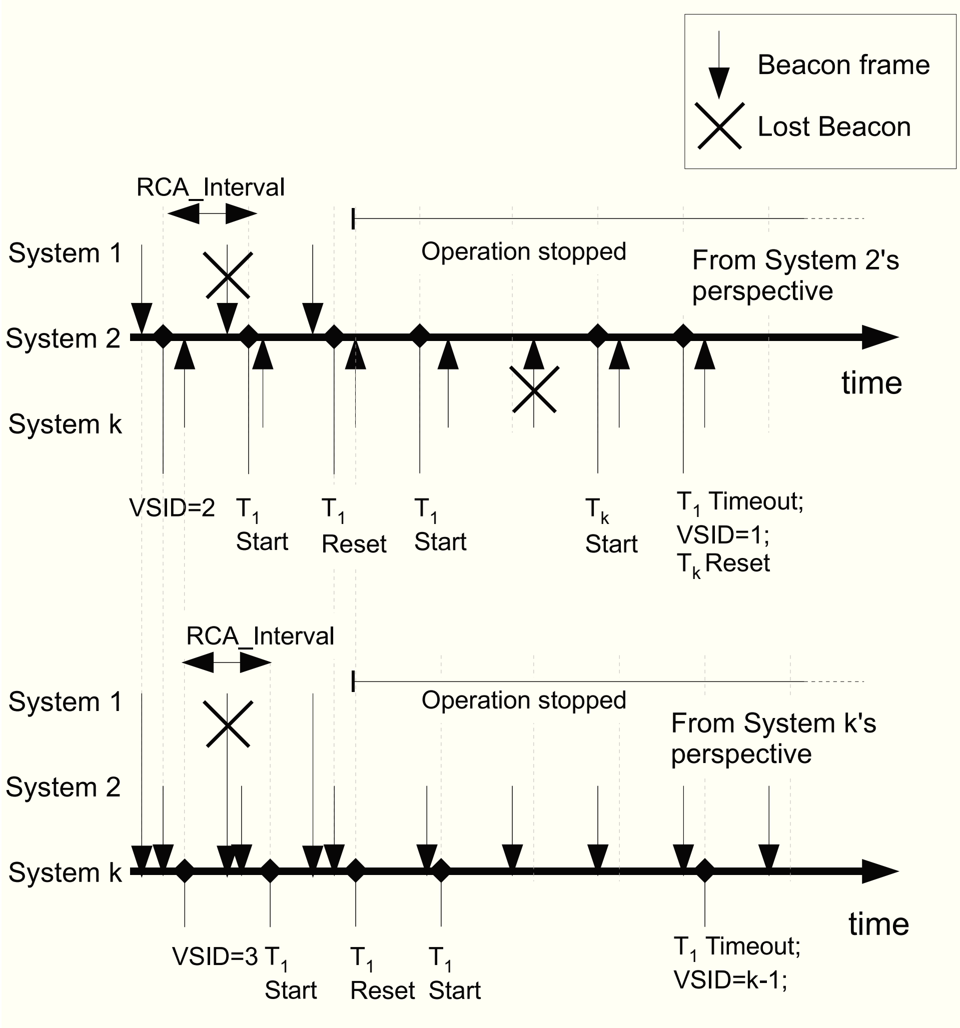


Figure 8.24: Timing diagram of adapting Virtual System ID (VSID) for synchronization

next RCA_Intervals receive the Beacon frame with VSID=1, they reset the timers T_1. When the Beacon frame with VSID=1 is not detected for a long period, the timers T_1 do eventually timeout, and systems change their corresponding VSIDs, i.e., the system with VSID=2 changes its VSID to 1 and the system with VSID=k changes its VSID to $k-1$.

This extension supports the proper synchronization of transmission starting points of the systems in coexisting scenarios. When the system operates in RCA mode, inserting the VSID field in the Data frames even increases the reliability of the above mentioned method in comparison to inserting the VSID field only in the Beacon frames.

8.6.2 Backoff in System Level

It is mentioned in the IEEE 802.11-2007 standard [63] in Section 9.9.2 that the Hybrid Coordinator (HC), which is the AP in this thesis, may perform a random backoff procedure similar to the one mentioned in DCF (Section 9.2.4 in [63]) when the frame exchange sequence is interrupted. However, it is left open how to detect the interference and based on what decision to perform a backoff. In this extended proposal, denoted as 'a random backoff at the system level', the random backoff concept is applied over the RCA method with a modification based on context requirement and with providing the base for detecting the interference and the decision criteria. The requirement is to reduce the collision events between the Beacon frames from different systems as shown in Figure 8.22.

If an AP senses that its starting beacon is going to be delayed due to channel busy state, it generates a random backoff period (quantified by the number of backoff slots) for an additional deferral time before transmitting. The system level random backoff keeps the features like exponential increase of the contention window (CW) and CW freezing when the channel becomes busy, controlled by the parameters RCA_CWmin and RCA_CWmax. However, two new features of the proposal are as follows.

1. The value of the parameters RCA_CWmin and RCA_CWmax could be adaptable based on the number of coexistence systems to reduce the waste of airtime.

2. To reduce the effect of the beacon delay to other systems and also to the next RCA_Interval, the allocated resource allocation (RA) of the system is reduced by the amount of total delay. This will also reduce the effect of this random delay property on the channel measurement by the RCA method.

Note that this random backoff has no interconnection with the station level random backoff (which is described in the DCF method) inside the protocol stack.

8.7 Extension for the Coexistence with Legacy 802.11 System

The concept proposed here is to generate idle periods intentionally by a system to provide opportunity to others. This is considered as a cooperative concept. In this case, most of the features of Legacy 802.11 standard are kept: Idle periods are generated in an IEEE 802.11 system by declaring the Contention Free Period (CFP) in the IEEE 802.11 superframe, how-

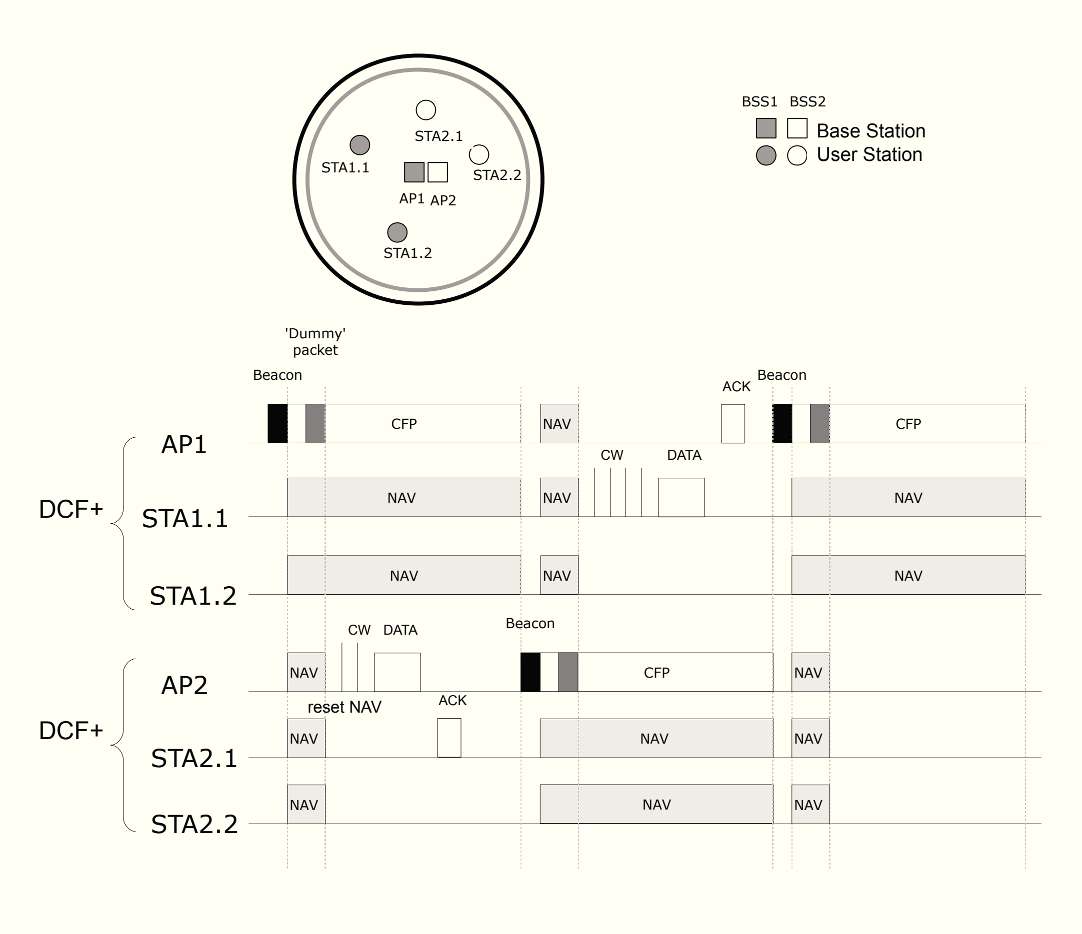


Figure 8.25: Timing diagram for channel access by collocated IEEE 802.11 DCF+ systems using PCF and CFP

ever, not scheduling own transmissions on that CFP duration. By making a CFP, a system allocates its own channel access to the CP and creates the opportunity in the form of idle periods for the other systems. When the other system cannot decode the Beacon frame, for example another legacy IEEE 802.11 system which is operating in the adjacent channel (say partially overlapping channel), then the other system can exploit the idle durations. However, when both systems, which are operating in the same spectrum, can decode the Beacon, they adjust their NAV accordingly[2] as shown in Figure 2.9, the concept does not work as expected. The reason is

[2]It is mentioned in the IEEE 802.11-2007 standard [63] in Section 9.3.2 that *all STAs (any device that contains an IEEE 802.11-conforming MAC and PHY interface i.e. AP and stations) that receives Beacon frames containing a CF Parameter Set information element, including STAs not associated with the BSS, set their NAVs to the CFPMaxDuration value at the nominal start time of each CFP.*

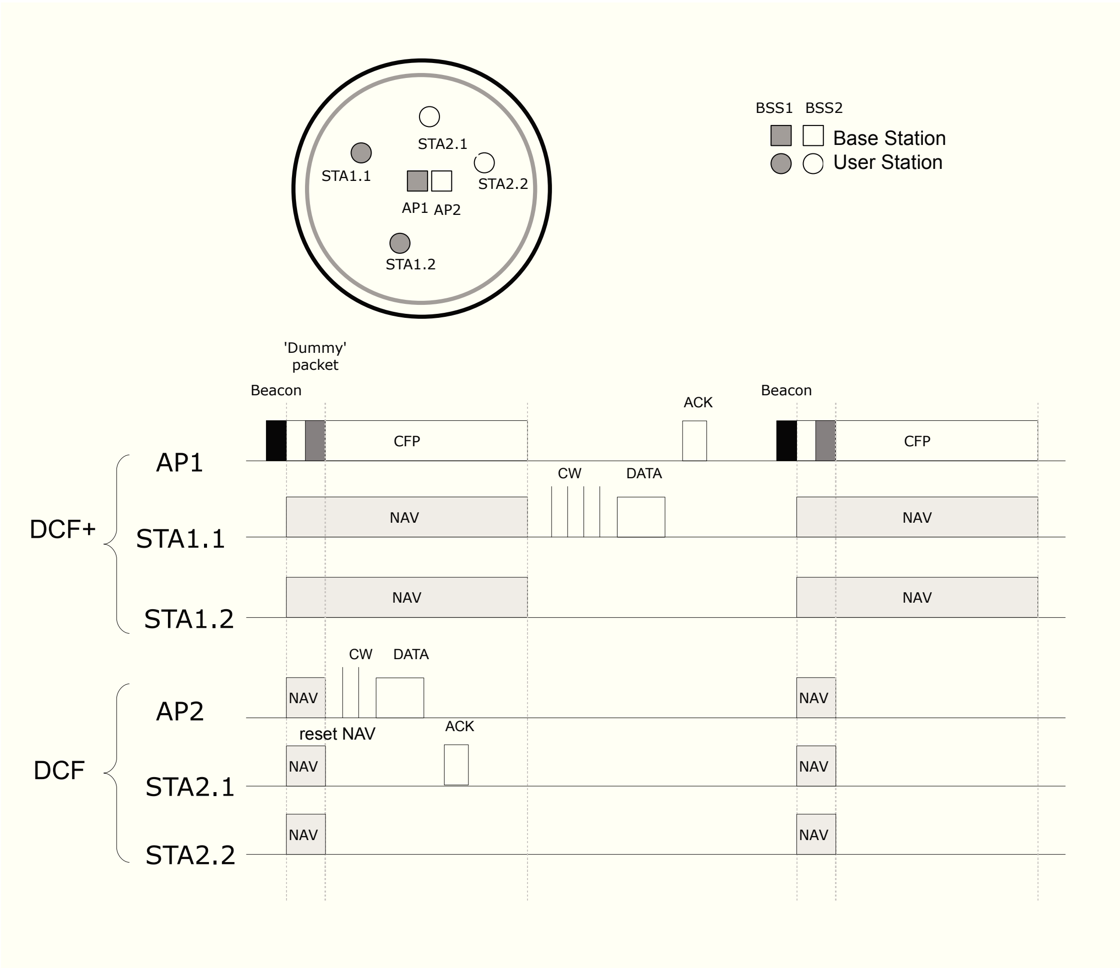


Figure 8.26: Timing diagram for channel access by collocated IEEE 802.11 DCF+ and DCF systems using PCF and CFP

that System 2 also stops transmission when System 1 stops its transmission. Note that in the figure the networks under BSS1 and BSS2 are considered as System 1 and System 2 respectively. This problem is similar to the *exposed node* problem. What is required in this case is to make System 2 reset the NAV. A protocol extension for the own system is proposed which solves the problem, described as follows. The system sends a *dummy* packet just after the Beacon with duration field equal to zero (0), with a flag on the packet coupled with BSSID. So stations under the own system will not update the NAV, however stations from the other system will reset NAV to zero as default. As the protocol is proposed to be enhanced, it is referred from now on as *DCF+*.

Based on the scenario, where the second system is DCF+ or legacy, two cases are considered as described in the following.

1. DCF+ vs. DCF+: The channel access concept in this case is shown in Figure 8.25. The AP from one system tries to cluster the accesses of the DCF stations in a limited time duration (CP) inside the superframe. By using the CFP concept of the PCF, the AP does not give access to the DCF stations associated to it (i.e. inside its BSS) in the CFP. So, other stations inside the other system exploit idle time durations for their frame transmissions. The same method is followed by the AP of the other system. Both systems have to synchronize the beacon starting points and the CFPs.

2. DCF+ vs. DCF: The channel access concept in this case is shown in Figure 8.26. Here, the DCF+ system is coexisting with the legacy DCF system. The DCF+ system provides opportunity to the DCF system as described before. What differs is that the rest of the time (i.e, in the CP duration of the DCF+ system) both systems will access the channel. Prioritizing the DCF+ system with an objective of fair sharing is expected to open a promising window of spectrum sharing. To provide priority to the frames of the DCF+ system, the same algorithm like in IEEE 802.11e [61, 17] can be followed, where different traffic access categories are prioritized. Shorter Interframe space and smaller contention window size are two examples in this context to enable priority.

8.8 Conclusion

The proposed generic spectrum sharing RCA method is adapted to the IEEE 802.11e based system, which follows the HCF controlled channel access (HCCA), by means of MAC scheduling. Performance indicators like throughput and end-to-end delay are investigated considering the VoIP applications. With increasing the RCA_Interval, more VoIP stations can be supported, however with a penalty of increased delay. Lowering the RCA_Interval supports the QoS requirement in many cases. In the second step, the adaptive RCA method is introduced in both IEEE 802.11 systems. The adaptiveness and cooperative behavior of the method is evaluated for dynamic traffic scenarios with their promising impact on the performance indicators. Proportional fair spectrum sharing is observed to support the QoS, with optimizing the aggregated performance. The RCA method is extended for the following two coexistence scenarios: partially overlapping scenarios and coexistence of more than two systems. The conceptual model of spectrum sharing in case of legacy IEEE 802.11 based systems is provided.

CHAPTER 9

SPECTRUM SHARING BETWEEN IEEE 802.11 AND IEEE 802.16 SYSTEMS

Due to the high cost of licensed bands, there is an option of operating in unlicensed bands for IEEE 802.16 based WiMAX systems. However, a new competitor in unlicensed bands is a huge concern as hints are given in the previous chapters considering the context of interference and spectral efficiency degradation. Therefore, spectrum sharing between coexisting competing heterogeneous wireless systems like IEEE 802.11 and IEEE 802.16 is an upcoming challenge. To understand the characteristics of interference in such a heterogeneous scenario, an analysis of possible interference is presented and the performance of the legacy systems is evaluated. The proposed concept mentioned in Chapter 6 is then adapted for the heterogeneous coexisting scenario consisting of the IEEE 802.16 and IEEE 802.11e based systems. In this case, the 802.11e Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA) is deployed to provide rules for airtime sharing in the IEEE 802.11e based system. Simulation results are presented showing that the proposed algorithm provides excellent improvement of system performance in the context of capacity and channel utilization compared to the case without applying any spectrum sharing method. The concepts for extending the RCA method in the case of partially overlapping scenario and a scenario of more than two systems are provided.

The chapter begins with state of the art related to the spectrum sharing between heterogeneous networks in Section 9.1. Section 9.2 provides an analysis on mutual interference which occurs in a coexistence scenario between the IEEE 802.11 DCF based system and the IEEE 802.16 system. The implementation and the performance evaluation of the proposed RCA method are done in two steps. In the first step, the adaptation and the performance of the RCA method in a heterogeneous scenario are evaluated and discussed in Section 9.3, considering the steady traffic load for a relatively larger time scale. Secondly, the adaptation and the performance of the adaptive RCA method are evaluated, discussed in Section 9.4. The extensions of the RCA method are described in Section 9.5, followed by a conclusion in Section 9.6.

9.1 State of the Art

In [90] the coexistence of HiperLAN/2 [74] systems is evaluated. Scheduling policies creating Silent Periods as transmission opportunities for other systems are introduced. Results are derived by simulation. A similar coexistence scheme is presented in [83] and [84]. In [83] a scheme is presented and evaluated analytically on how this idle period can be exploited. The scheme, presented for the spectrum sharing between two IEEE 802.16 systems, is as follows. One system fills the uplink (UL) and the downlink (DL) subframes in a traditional manner (Section 2.15), i.e., from the starting points of respective subframes. The second system fills the subframes in reverse time order, i.e, from the end points of respective subframes. A scheme that reschedules data and allows multiple systems to coexist by shifting their frame starting point is described and analyzed in [84].

In [36], a concept of using a busy tone signal for protecting 802.16 transmission in heterogeneous coexistence scenario is presented, but not evaluated.

In [35], spectrum sharing between heterogeneous wireless systems by means of *channel access scheduling* is provided. Interleaving the channel access among multiple systems in a TDMA fashion is the core concept of channel access scheduling. This is a proactive approach. Two heterogeneous wireless systems coexistence scenarios, GPRS/WiMAX and GPRS/WiFi, have been studied and simulated in the mentioned paper. The performance results of the simulations justify channel access scheduling as a feasible solution towards spectrum sharing.

Reactive spectrum sharing algorithms for coexistence between IEEE 802.11b and IEEE 802.16a networks in the same unlicensed band are given in [73]. Reactive schemes utilize three available degrees of freedom in frequency, power and time, and react to observations in these domains to avoid interference. The performance results of the simulations show the reactive algorithms can significantly reduce mutual interference resulting in improved spectrum efficiency and improved throughput in single cell and multiple cells scenarios

9.1.1 IEEE 802.16h

In the IEEE 802.16h [68] standard, released in July, 2010, several methods have been proposed for the coexistence of the IEEE 802.16 system in the unlicensed bands. It distinguishes between the coordinated and the uncoordinated coexistence. In the following the coexistence methods are described briefly according to [68].

Uncoordinated coexistence with specific spectrum users (SSUs): It is often termed as Dynamic Frequency Selection (DFS), which is mandated by tight regulatory requirements. In this case, the DFS shall be implemented according to the specification and procedure provided in [68].

Uncoordinated coexistence with non-specific spectrum users (non-SSUs): Compared to the SSU case, in this case the requirements are relaxed, for example, it is not mandated that the operating channel need to be vacated at once or at all; rather to reduce the interference would be enough. One realization of uncoordinated coexistence with non-SSUs, like other IEEE 802.16 systems or non-IEEE 802.16 systems (e.g. IEEE 802.11 systems), is termed as Dynamic Channel Selection (DCS). The DCS is proposed to use as means to find a least interfered (less occupied) channel at system startup and even during the normal operation. The channel measurement and channel switch procedures and related signalling are specified in the DCS. With uncoordinated operation no explicit messages are exchanged. A system has to sense the medium at the beginning of the frame. If the channel is busy the system is not allowed to perform any transmissions for the whole frame.

Coordinated coexistence method: In case of all IEEE 802.16 non-SSUs, a frame synchronization mechanism with a 4-frame (referred as coordinated coexistence frame, CX-Frame) structure is specified. This is considered as coordinated coexistence allowing multiple systems to negotiate their resource usage and described for maximum 3 fully or partially overlapping systems. The CX-frame is composed of Master, Slave and Shared subframes where the DL and the UL are scheduled and the optional Common subframe, where only the DL is scheduled. In the specification, a Coordinated Coexistence Contention-Based Protocol (CX-CBP) is provided to handle the bursty system. In CX-CBP, CX-Frame is divided into two parts: CXSBI (Coordinated Coexistence Schedule-Based Interval) for scheduled operation (the first two frames) and Coordinated Coexistence Contention-Based Protocol (CX-CBP) for bursty operation (the last two frames). One of the features of CX-CBP is listen-before-talk.

The RCA method described in this thesis is a generic concept which can be adapted for both coordinated and uncoordinated systems. In fact, the main idea behind the RCA method is to provide a sort of virtual coordination to the uncoordinated systems during the channel access. In that sense, RCA method is fully adaptable/compatible to the coordinated coexistence method provided in the IEEE 802.16h standard.

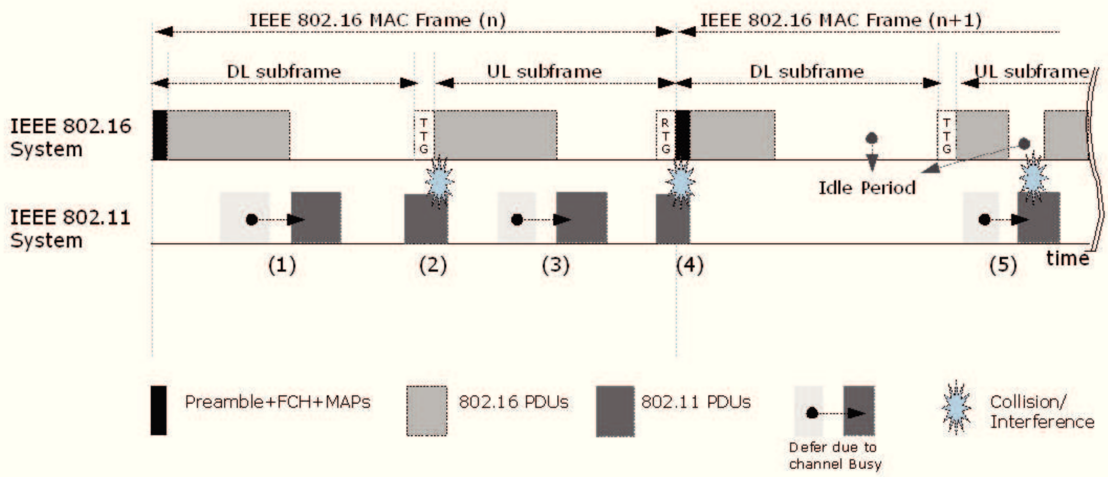


Figure 9.1: Timing diagram for channel access by collocated IEEE 802.11 and 802.16 systems; possible interference and collision events

9.2 Interference in Heterogeneous Scenarios

In this section, an analysis is presented which shows the interference and collision events that occur when IEEE 802.11 and IEEE 802.16 systems are collocated and operate in the same channel, for example in the 5 GHz ISM band. It is assumed that all stations are within mutual interference range. Figure 9.1 shows the events which occur during the channel access of IEEE 802.16 and legacy IEEE 802.11 DCF systems. The upper part of the figure shows the IEEE 802.16 channel access which follows the rules mentioned in section 2.2.4.4 and shown in Figure 2.15. The lower part of the figure shows the IEEE 802.11 channel access which follows the rules mentioned in section 2.1.4.3 and shown in Figure 2.8.

According to the frame structure of the IEEE 802.16 system shown in Figure 2.15 and Figure 2.16, there are three possible locations inside the frame where idle periods appear: at the end of the downlink subframe, the end of the uplink subframe and during the Random Access (RA) phase. The last one basically is merged with one of the former two, based on its location as shown in Figure 2.16. Some major events including collision events are identified in Figure 9.1 and numbered for further reference and explanations as follows. Note that events like (4) and (5) are also described in [36].

1. When the channel is busy due to transmissions of the IEEE 802.16 system, IEEE 802.11 station's channel access is deferred up to the time point where the channel becomes idle. In this point of time the IEEE 802.11 system can take control of the channel according to rule (b) mentioned in section 2.1.4.3.
2. When the channel is idle and a MAC layer Service Data Unit (MSDU) is available from a higher layer, the IEEE 802.11 station starts the frame exchange according to rule (a) mentioned in section 2.1.4.3. As in the case of the IEEE 802.16 system, channel access is centrally scheduled, it starts its uplink subframe and occupies the channel if an MSDU is available. As an IEEE 802.16 station is not bound to channel sensing before transmission like in the case of IEEE 802.11, the transmission attempt is not deferred if the channel is already being used by the IEEE 802.11 system. This results in interference, and the probability of losing interfered packets in both systems is very high.
3. The same as (1) happens during the uplink subframe of 802.16.
4. The same as (2) can happen when the next 802.16 frame starts. It is even more critical because in this case, the preamble, FCH and MAP of the 802.16 frame can be lost. This would eventually trigger the method of adapting the DL and UL synchronization.
5. According to [36], when a subscriber station does not have any data to be transmitted though it is scheduled to do so and the UL MAP is successfully transmitted, this could generate an idle period. This creates the possibility that the 802.11 system can take over the control of the channel following the rule (b) which would cause interference to following 802.16 PDUs.

It is important to note that the IEEE 802.11 DCF based system can take over the control if required when the idle period duration is equal or more than the Distributed Interframe Space (DIFS), depending on its backoff state. This characteristic of the IEEE 802.11 DCF channel access method, which is sometimes denoted as 'selfish' behavior, is one of the main problems in the context of collocated wireless networks, when the other system is following tightly scheduled medium access control like Time Division Multiple Access (TDMA) and Time Division Duplex (TDD) as in IEEE 802.16. In such a case, the the interference events, as discussed above, occur in a significant amount. This results in quantifiable performance degradation of the systems which could be extracted in the absence of such a scenario. However, the coexistence performance can be improved by:

- Protecting the starting time of the scheduled frame exchange duration of IEEE 802.16 [36]. Some percentage of capacity will be lost to send a blocking signal which depends on the busy signal duration. The author of this thesis believes that the busy signal duration can be adapted to the estimated maximum length of 802.11 frames, based on measurements. It is also recommended in [36] to use a blocking signal to circumvent interference events like (5). However, according to the IEEE 802.16-2004 standard [60] on page 450, the UL burst will be padded when there is no packet to transmit according to the standard padding mechanism, mentioned in the standard itself, if required. The author of this thesis believes that this padding already facilitates the 'blocking concept' of the idle periods created in such cases. However, the idea of a blocking signal would still be helpful where an UL burst is lost due to bad channel conditions.
- Applying the Listen-Before-Talk (LBT) mechanism in the case of the IEEE 802.16 system: In the IEEE 802.16h [68] standard the LBT concept is applied before the beginning of the superframe and if the channel is found busy, no transmission will take place in the succeeding frame. This enables the systems to reduce the number of collisions, however, there is a challenge to keep the QoS values like delay and jitter within the required levels.
- Making the channel access of the IEEE 802.11 more regular like the IEEE 802.16 and adapting the periodicity, service starting point, and service period length of both systems: This is the main focus of this work and introduced in the following.

9.3 RCA as an Algorithm

Figure 9.2 shows the Regular Channel Access (RCA) method in the case of collocated IEEE 802.11 and IEEE 802.16 systems. Here, *RCA_Interval* is adjusted equal to the 802.16 frame length. During the initialization phase the duration of the IEEE 802.16 frame length is measured. The 802.16 system schedules downlink (DL) and uplink (UL) subframes at the beginning of the frame (*RCA_Interval*) in such a way that there is expected to be only a Transmit Transition Gap (TTG) duration gap between downlink and uplink. In such a case, transmissions during the downlink and uplink subframes can be viewed logically as one continuous busy period. Note that

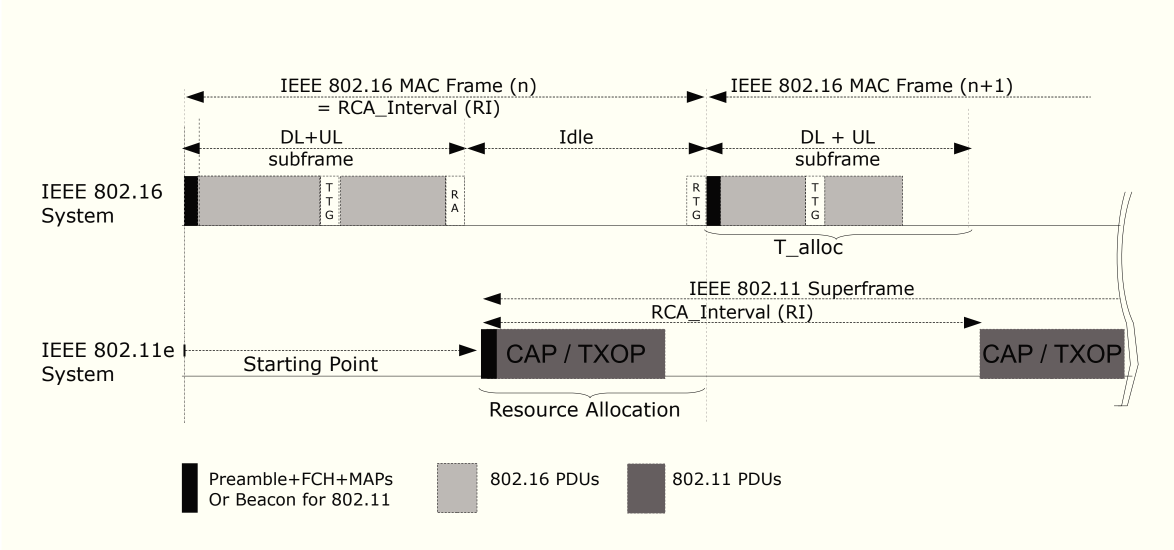


Figure 9.2: Timing diagram for channel access by collocated IEEE 802.11 and 802.16 systems with Regular Channel Access (RCA) method

the DL burst will be padded when there is no packet to transmit in the allocated time duration, according to the standard padding mechanism. The TTG is shorter than the DCF Interframe Space (DIFS). The rest of the airtime in the superframe is kept as idle period for other systems. The air time (resource) allocation for IEEE 802.16 (DL+UL) transmissions inside the IEEE 802.16 frame can be dynamically adjusted considering the traffic load of the own system and others, using equation (6.1) and (6.2).

To enable RCA in WLAN, an 802.11e based system, like wireless multimedia extension is considered. By introducing a MAC scheduler in the Hybrid Coordinator (HC) of the 802.11 system, a regular channel occupation and provision of idle periods is possible as shown in the lower part of Figure 9.2. The basic functions are as follows: The interval between the start of two successive channel occupations by the 802.11 system is realized as *RCA_Interval* which is configured to be equal to the 802.16 frame length. The required air time allocation for 802.11 transmissions inside the *RCA_Interval* is calculated considering the equation (6.1) and (6.2). To fill up the idle period left by the 802.16 system, the 802.11e system starts scheduling its PDUs with an offset from the beginning of 802.16's frame start. The offset is calculated to

$$SP_{own} = RA_{others} \tag{9.1}$$

By this proposed approach, the coexisting systems are coordinated and synchronized to share the same spectrum 'indirectly' by the help of ap-

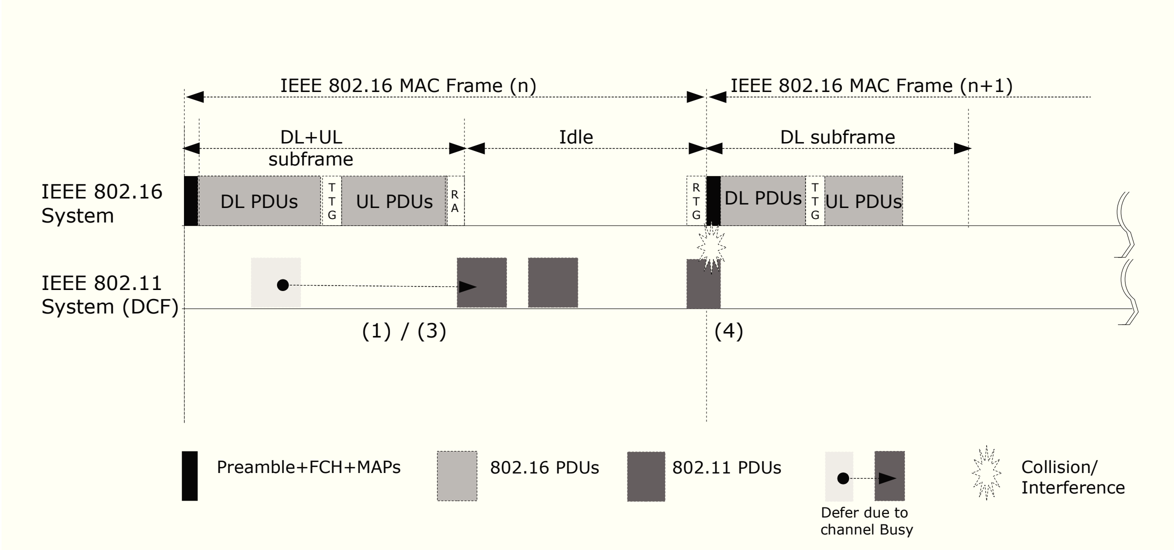


Figure 9.3: Timing diagram for channel access by collocated IEEE 802.11 and 802.16 system with Regular Channel Access (RCA) method in 802.16

plying the regular channel occupation on the one hand and by the use of measurement techniques, discussed in Chapter 5, on the other hand.

Figure 9.3 shows the possible interference and collision events in the timing diagram for an intermediate solution case where the RCA enabled 802.16 system and a 802.11 DCF based system are in coexistence. Mainly events like (1), (3) and (4) occur.

In the following, evaluation results of 802.11 and 802.16 system performance in the coexistence scenario are shown.

The evaluation has been done in two steps. In the first step, the static resource allocation applied to the RCA method and performance of the systems in the coexisting scenario is evaluated. In this case, the Steady State Phase of traffic demand is assumed. In the second step, adaptive resource allocation based on measurements and estimation, which is described as aRCA, is applied to the IEEE 802.11 based system and the results for the Key Performance Indicators are evaluated.

9.3.1 Simulation Model

Four different system models are introduced to evaluate the coexistence scenarios.

- Legacy 802.11 system: All stations (AP and STA) inside the IEEE 802.11 network/system are following the DCF channel access method (Section 2.1.4.3).

- Legacy 802.16 system: The BS and SS stations inside the IEEE 802.16 system are following the TDMA/TDD (Section 2.15) channel access method. The downlink and uplink subframes compose the frame (according to their ratio of requirement, e.g, 50 %:50 %).

- RCA enabled 802.11 system: The Stations (AP and STA) are following the model described in 8.3. All the stations follow the HCCA so that stations transmit (uplink) only when they are polled by their AP. Regular channel occupation is created by grouping the downlink and uplink transmissions in time domain inside the superframe.

- RCA enabled 802.16 system: In this case, the BS and SS stations inside the IEEE 802.16 system are also following the TDMA/TDD channel access method. However, the downlink and uplink subframes are grouped together to create a 'busy subframe' and some space of the frame kept free/idle to create an 'idle subframe'. An example of the frame composition can be downlink:uplink:idle = 35 %:15 %:50 %. So, the basic differences against the legacy IEEE 802.16 system are combined downlink and uplink (DL+UL), and additional idle duration in each frame. In the simulation, the uplink (UL) subframe is switched off to model a continuous busy period at the beginning of the 802.16 frame. It approximately models the actual intention of 'DL+UL' at the beginning of the 802.16 frame as discussed in Section 9.3.

9.3.2 Simulation Setup

To understand the characteristics of the effects of interference and collisions in the systems, a scenario with one Base station and one Subscriber Station for the 802.16 system and one Access Point and one station for the 802.11 system is considered. This also resembles the apartment scenario mentioned before, where other orthogonal frequency channels in the unlicensed band are occupied by other systems. The impact of more stations is discussed in the end of Section 9.3.3. The system parameters are listed in Table 9.1. Both systems are using the most robust modulation scheme of binary phase shift keying (BPSK) with a coding rate of 1/2, which can provide 6 Mbit/s of Data rate at the physical layer. This is considered during simulation to show the fundamental operation of the algorithm. Each Simulation is run for 500 s model time. In each simulation run, the static offered traffic for both systems during the span of simulation duration is considered.

Table 9.1: System parameters

Common	Carrier Frequency	5.470 GHz
	MCS	BPSK 1/2
	Bandwidth	20 MHz
802.16	Frame length	10 ms (720 Symbols)
	1 Symbol duration	1/72 ms
	Preamble+FCH	3 Symbols
	MAP	4 Symbols
	DL subframe	355 Symbols
	TTG	2 Symbols
	UL subframe	328 Symbols
	Random Access	26 Symbols
	RTG	2 Symbols
802.11	Slot Duration	9 μs
	SIFS	16 μs
	PIFS	25 μs
	DIFS	36 μs
	CWMin	15
	CWMax	1023
	ACK Duration	44 μs
802.11e	RCA_Interval	10 ms
	QoS CF-Poll Duration	56 μs
	QoS Null Duration	56 μs

9.3.3 Results and Evaluation

Throughput and delay results are evaluated as performance metrics for three cases.

1. Case1: Legacy 802.11 and 802.16 systems.
2. Case2: Legacy 802.11 and RCA enabled 802.16 systems
3. Case3: RCA enabled 802.11 and 802.16 systems.

9.3.3.1 Throughput Evaluation

In this context, throughput measured on top of the MAC layer is considered.

Case1: Legacy 802.11 and 802.16 systems

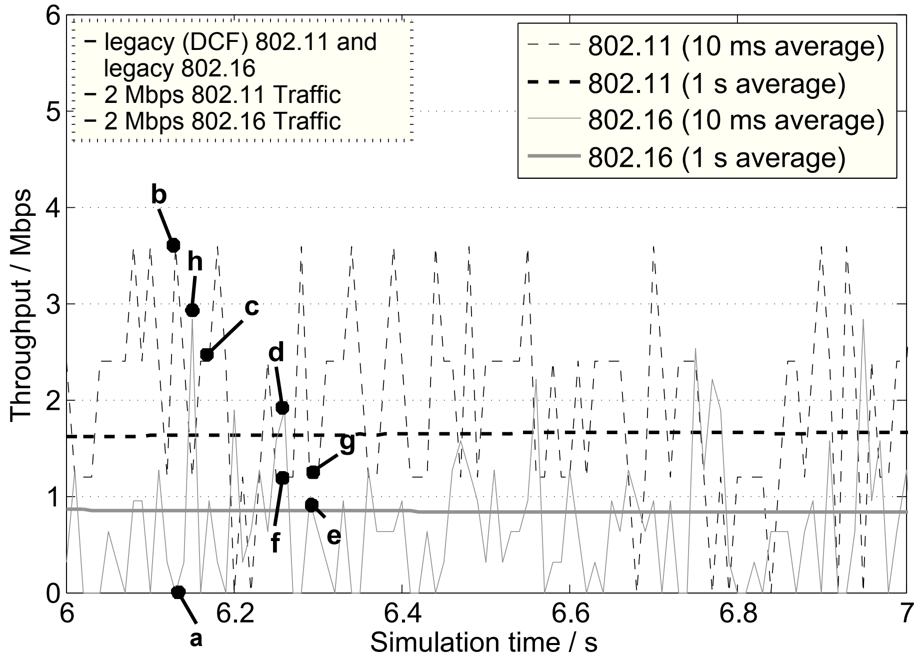


Figure 9.4: Throughput of legacy 802.11 and 802.16 against time

Figure 9.4 shows the throughput averaged over 10 ms in the model time interval between 6 s to 7 s. The throughput averaged over 1 s is also shown. Note that the throughput of 802.16 in the figure is the summation of downlink and uplink throughput. Here, 2 Mbps (1 Mbps DL + 1 Mbps UL) traffic load and Protocol Data Units (PDUs) of 375 bytes in the case of the 802.16 system and 2 Mbps traffic load and PDUs of 1480 bytes in the case of the 802.11 system are configured as offered traffic load. PDU interarrival times follow an exponential distribution. The 802.16 system uses a periodic frame of 10 ms length as shown in Figure 2.15.

IEEE 802.11 follows DCF, so it does not access the channel when it senses it busy. Each simultaneous transmission causes data loss. When all uplink and downlink PDUs of 802.16 collide with 802.11 PDUs, this results in zero throughput (points (a) in the figure) for 802.16. The rest of the frame airtime, if any is left, is occupied by 802.11 for retransmission of the lost PDUs first and more PDUs depending on traffic load secondly; resulting in throughput like (b) or (c) for 802.11. Throughput like (d) or (e) for 802.16

and (f) or (g) for 802.11 correspond to the situation when some PDUs in either downlink or uplink are not lost in the case of 802.16. Points like (h) correspond to the situation when both downlink and uplink are not lost. Due to the Poisson traffic source, different random events are observed. However, the main noticeable observation is the long time average which clearly shows the huge difference between the offered and received traffic for both systems. This is due to the high number of collisions.

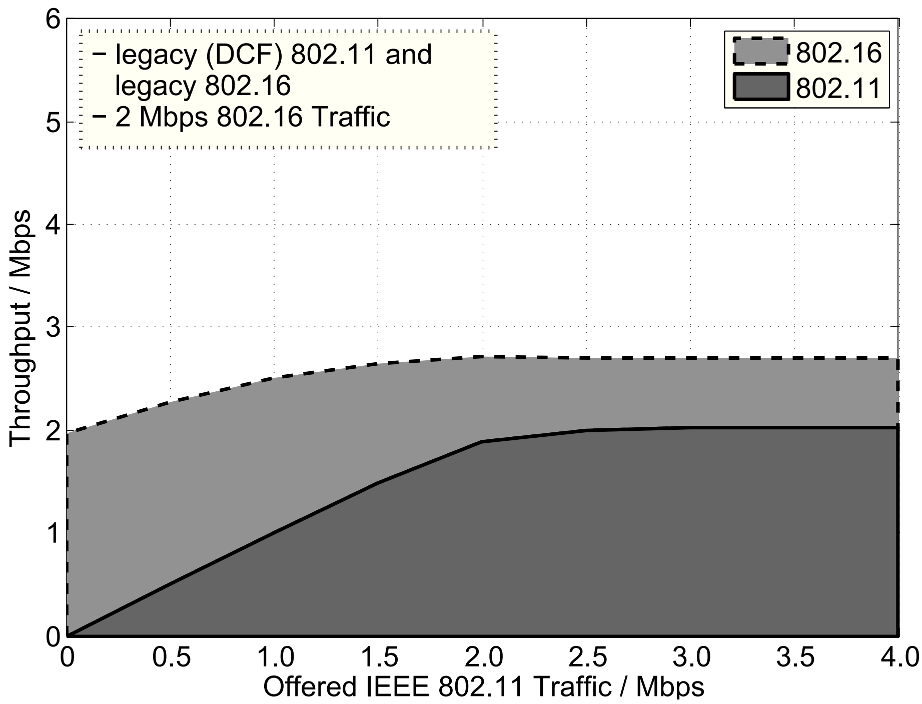


Figure 9.5: Mean throughput of both systems in Case1 against 802.11 traffic

Figure 9.5 shows the mean throughput over offered 802.11 traffic. A stacked graph is used showing the throughput of each system as well as the total throughput of both systems. The 802.16 uplink and downlink throughputs are decreasing significantly with increasing 802.11 traffic up to 2 Mbps; because it increases the probability of collision events like (2) and (4) mentioned in 9.2 and shown in Figure 9.1. However, the 802.11 throughput is not affected as lost packets are retransmitted in the idle time period inside the current frame. For offered IEEE 802.11 traffic of more than 2 Mbps, the 802.11 throughput reaches saturation. The trend of the curves of 802.11 and 802.16 shows one of the characteristics of 802.11 which is 'selfishness' during channel access. This is harmful for other systems in the context of coexistence. Overall, it has been found that around 2.5 Mbps aggregated throughput can be achieved, in other words, 40 % of the channel capacity can be utilized.

These throughputs can be improved by physically joining the downlink and uplink of the 802.16 system together as discussed in 9.3 and verified in the next results.

Case2: Legacy 802.11 and RCA enabled 802.16 systems

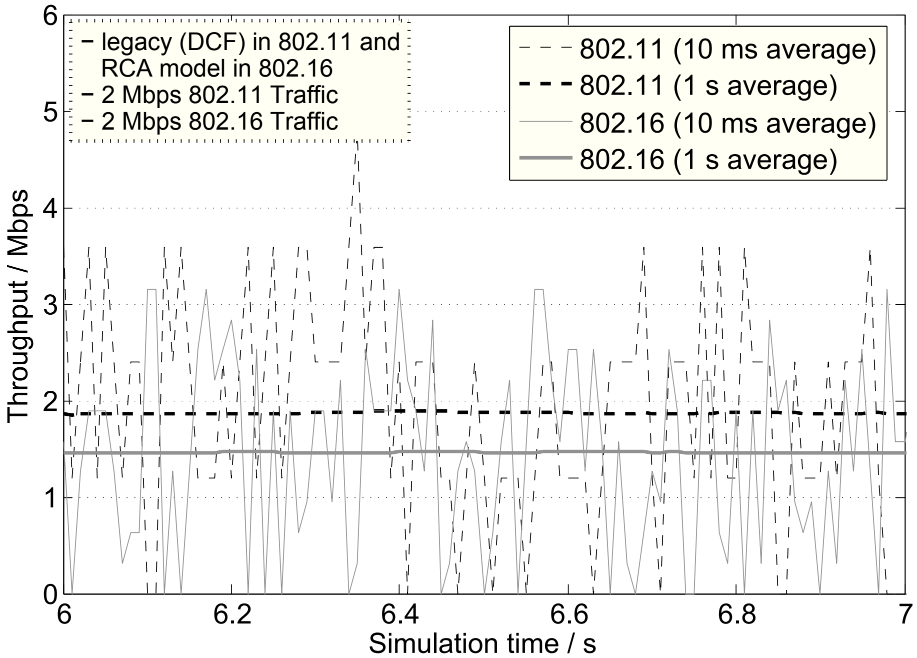


Figure 9.6: Throughput of both systems in Case2 against time

Figure 9.6 shows the same kind of performance metric like before; however, in this case, only downlink traffic is configured in the 802.16 system equal to the sum of downlink and uplink (2Mbps) in Case1. The 1 s average shows clearly that the difference between the offered and received traffic is reduced and throughput is increased for both systems; significantly for 802.16. The reason is that the number of collisions is reduced as the number of events like (3) mentioned in 9.2 and shown in Figure 9.1 are avoided.

Figure 9.7 shows the individual and overall system throughput against offered 802.11 traffic. As expected, the impact of interference is less severe if only downlink traffic is present. In this case, the channel is idle for about half of the time. At low loads of 1 Mbps and 2 Mbps, no data loss occurs in the IEEE 802.11 system. A trend of decreasing 802.16 throughput like in Case1 is observed, but the level of throughput is higher than in Case1

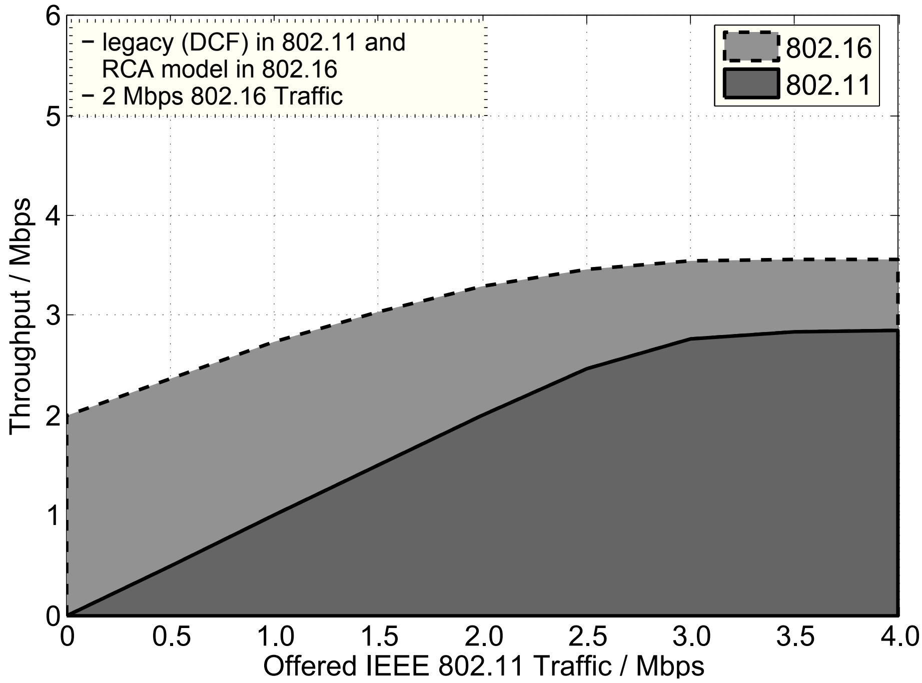


Figure 9.7: Mean throughput of both systems in Case2 against 802.11 traffic

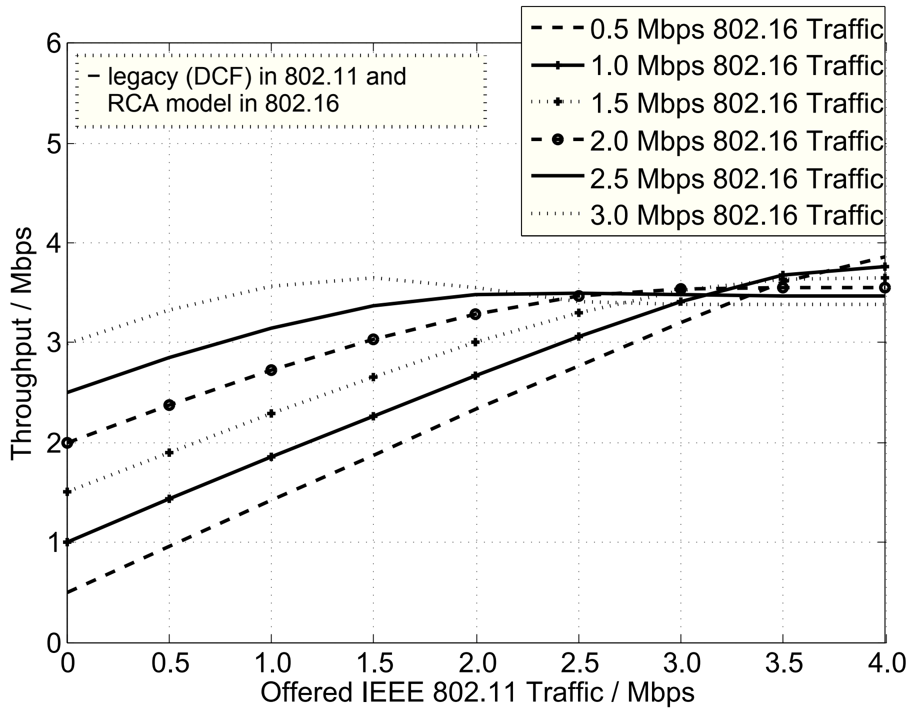


Figure 9.8: Overall mean throughput of both systems in Case2

as the number of collisions between the systems is less. The overall channel utilization is improved up to 60 % which resembles better throughput than Case1. The downlink only results give a hint towards the achievable performance if the 802.16 downlink and uplink traffic flows are scheduled directly after each other in the beginning of the superframe or the uplink subframe is filled from the back as presented in [84]. It can be concluded from these results that such a modified scheduling is able to increase the overall and system wide throughput performance. We can consider this as a model of regular channel access in an 802.16 system. In this figure, 802.16 offered traffic is fixed. To see the impact of offered 802.16 traffic in a coexistence scenario, Figure 9.8 is depicted. Increasing the offered load of both systems results in more collisions and overheads. As shown in the figure, the maximum achievable overall throughput which is around 3.5 Mbps is even degraded when overall offered traffic increases.

From the above results it is found that unrestricted and uncoordinated channel access of 802.11 severely degrades the performance.

Case3: RCA enabled 802.11 and 802.16 systems

Initial simulation results verify the benefit of regular channel access. In the simulated scenario, only the downlink is active for the 802.16 system, which as discussed above, models the scheduling of downlink and uplink directly after each other. The IEEE 802.11 system uses RCA with an *RCA_Interval* of 10 ms (which is the superframe length of 802.16).

The results in Figure 9.9 show individual and overall throughput against offered 802.11 traffic when the 802.16 offered traffic is 2 Mbps. In this case, the airtime is equally divided between the systems. In this RCA case, the 802.11 system utilizes the idle periods by shifting its starting time and limiting its own channel occupation to fit into those idle periods. This process decreases interference, resulting in lower probability of losing packets, which eventually increases the throughput performance of the 802.16 system. Due to fixed allocation of airtime, the 802.11 system does not interfere at all. The 802.11 throughput goes to saturation at less offered load due to fixed allocation, however better fairness between systems is achieved.

Figure 9.10 shows the overall throughput. Here the airtime in the superframe is equally divided between the systems. Due to the fixed capacity allocation of 50 %, the 802.11 throughput does not vary much for different 802.16 offered loads and the 802.16 throughput is almost equal to the 802.16 traffic up to 3 Mbps. The dark line in the figure shows the coexistence performance when both systems have equal traffic load and airtime is allocated accordingly. The maximum achievable throughput is almost 5.5 Mbps which shows that proper sharing can improve the spectrum utilization up to 90 percent. The same is true for differing traffic demands of the systems.

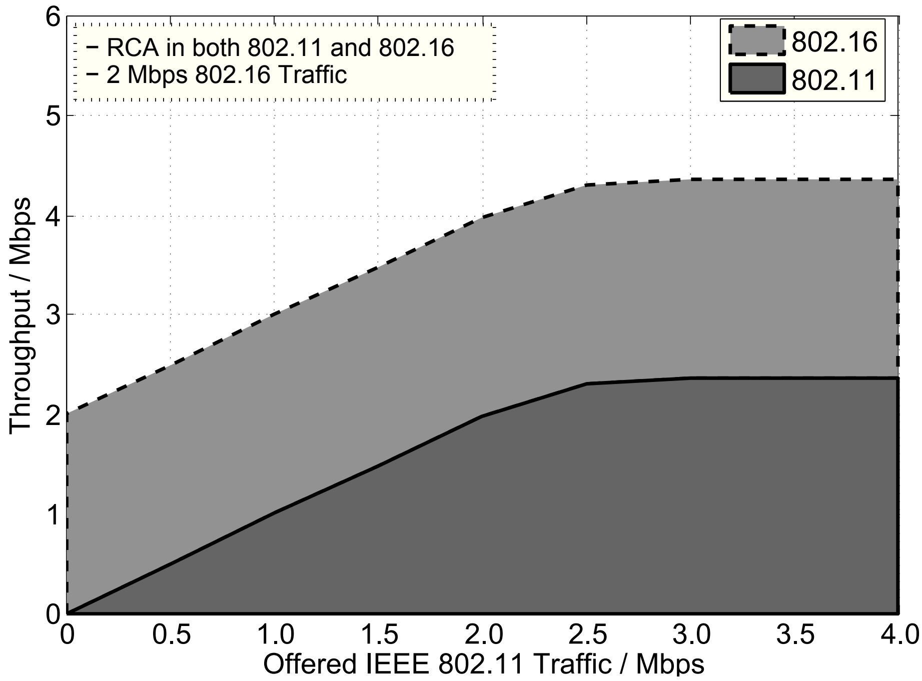


Figure 9.9: Mean throughput of both systems in Case3 against 802.11 traffic

9.3.3.2 Delay Evaluation

The end-to-end MAC delay is generally defined as the summation of delay components like queuing delay, channel access delay, transmission delay and retransmission delay (if Automatic Repeat Request (ARQ) applies), propagation delay and processing delay. The last two delay components are not considered (set to zero) in the following delay evaluation due to the same reasons discussed in 8.3.3.

Figure 9.11 shows the mean delays experienced by the 802.11 and 802.16 systems in considered Cases from 1 to 3. Delays are shown against the 802.11 offered traffic and for 2 Mbps 802.16 offered traffic. Applying the ARQ in the MAC layer for the 802.16 system is optional according to the 802.16 standard [60]. Retransmission delays are not counted here for 802.16 as ARQ is not applied. The 802.16 delays almost remain constant with increasing 802.11 offered traffic.

The 802.11 system has ARQ in the MAC layer. Due to the random access of the 802.11 system in Case1 and Case2, it has been found that the higher the 802.11 traffic, the higher is the collision rate resulting in higher retransmission delays. As stated before, the collision rate is higher in Case1 than Case2 and that increases the retransmission delays and queueing delays in Case1 compared to Case2. The delays in Case3 are experienced mainly due

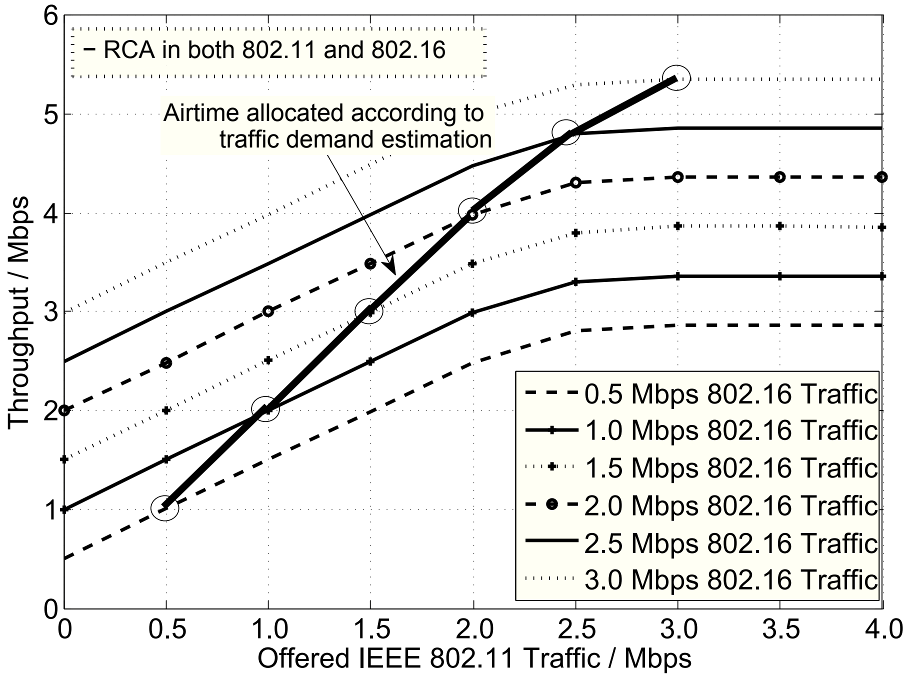


Figure 9.10: Overall mean throughput of both systems in Case3

to queueing and access delays. Due to the Poisson traffic, in some points of simulation time, more packets are generated than the expected mean and queued in the buffer. Those queued packets are served in a later subsequent RCA_Interval which leads to higher delays. This phenomenon is more visible with increased 802.11 offered traffic.

Figure 9.12 shows the mean delays against the offered traffic of both systems for Case2 and Case3. In Case2, mean 802.11 delays are increased with increasing the offered traffic of both systems due to the reason mentioned above. When the overall traffic exceeds the channel capacity, the upper limit of mean delay is reached. This is due to limited buffer size, however taking into account the buffer loss. In Case3, mean 802.11 delays, however, do not vary significantly with 802.16 offered traffic load. This is due to the following reasons: During the simulation configuration, systems are allocated fixed resources (airtime) and operation points of the 802.11 system shifted accordingly: the 802.16 system does not interfere with the 802.11 system and according to the simulation configuration, systems have fixed resource allocation. The 802.16 system experienced the higher mean delay with increased 802.11 traffic for both cases.

The delay results could be improved on the one hand by allocating the re-

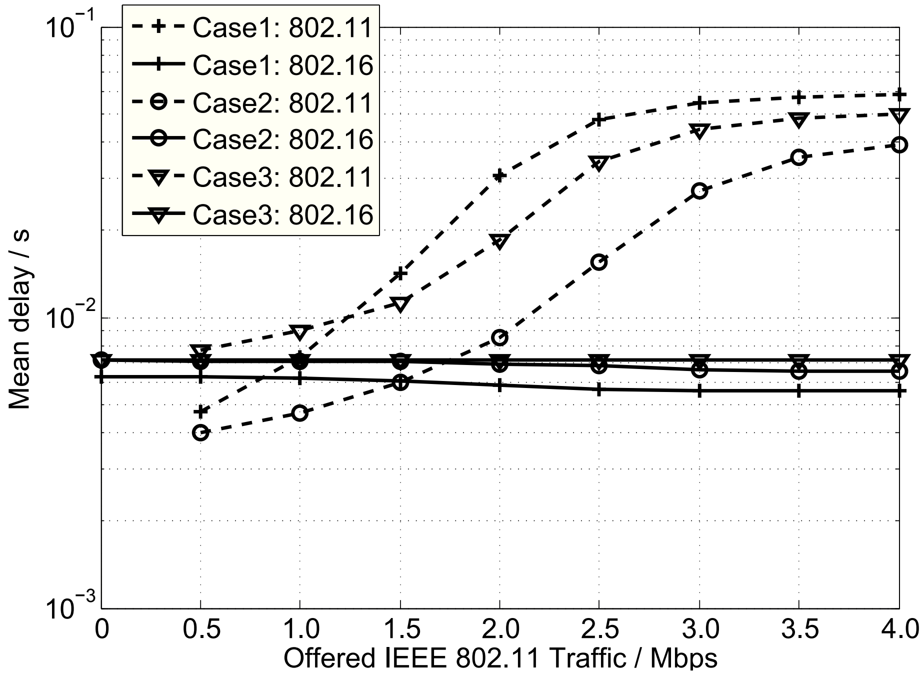


Figure 9.11: Mean delays experienced by both systems in Case 1-3 with 2 Mbps 802.16 Traffic

source (i.e. the airtime in the RCA_Interval) according to the traffic demand of the systems and on the other hand by applying buffer management, specially QoS-aware buffer management (QBM) according to the application requirement as discussed in Section 8.4.3.2.

When more stations are appeared in the systems, the following results can be anticipated based on above results.

In case 1 and case 2, where a legacy IEEE 802.11 system is one of the coexisting partner more collisions are possible due to events like (2) and (4) mentioned in 9.2 and shown in Figure 9.1, resulting in relatively lower throughput and higher delay compared to the single station scenario. In case 3, where RCA enabled systems are considered, performance would not vary significantly unless the aggregated traffic load goes beyond the systems' capacity. In RCA, collisions are avoided inherently according to the design by means of resource allocation. anyway by means of pre resource allocation. Due to multiple stations there would be slight signaling overheads.

9.4 Adaptive RCA

In this case, the adaptive RCA method where the system is able to readjust its RCA parameters (resource allocation and starting point) in varying

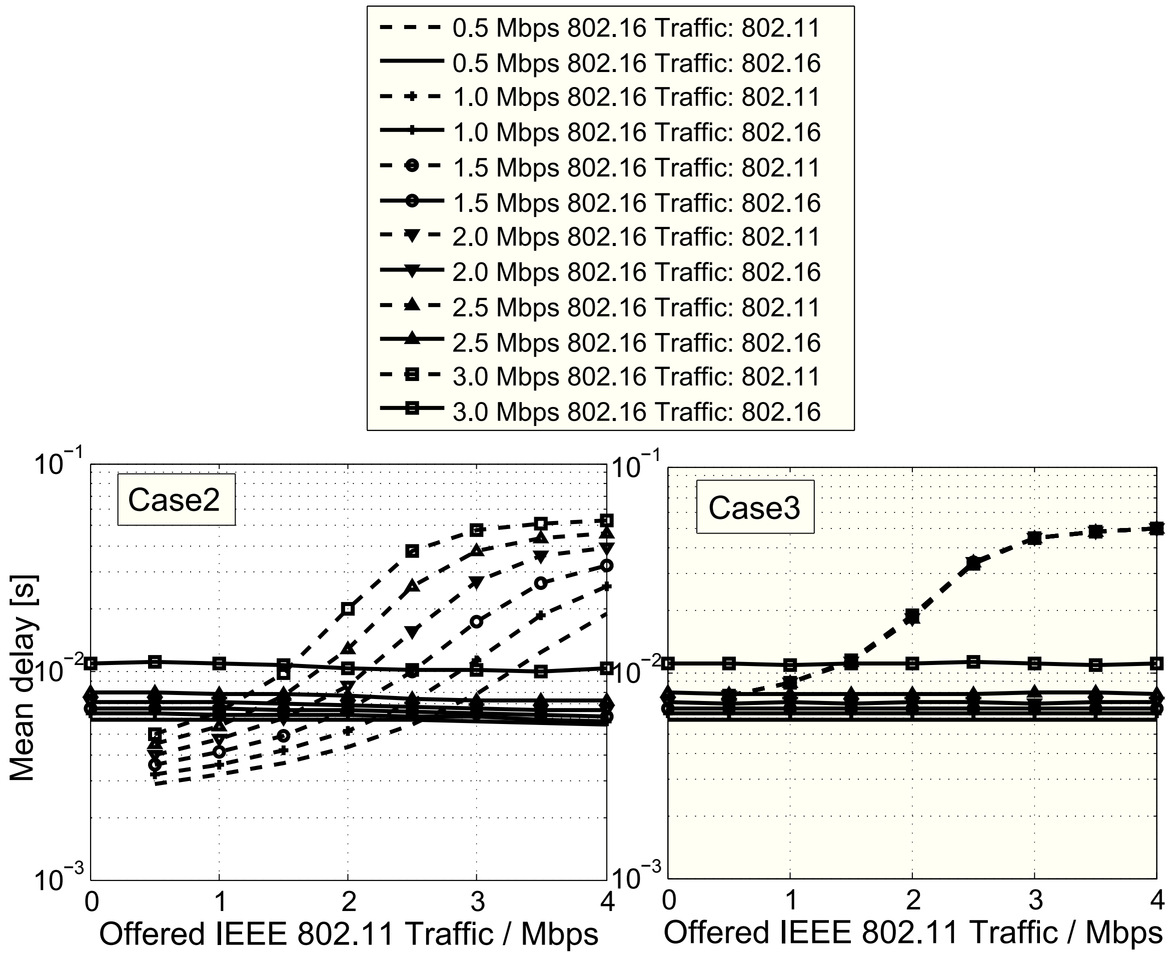


Figure 9.12: Mean delays experienced by both systems in Case 2 and 3 against offered traffic

conditions is applied to the IEEE 802.11 system.

9.4.1 Simulation Model

Two different system models are introduced to evaluate the coexisting scenarios.

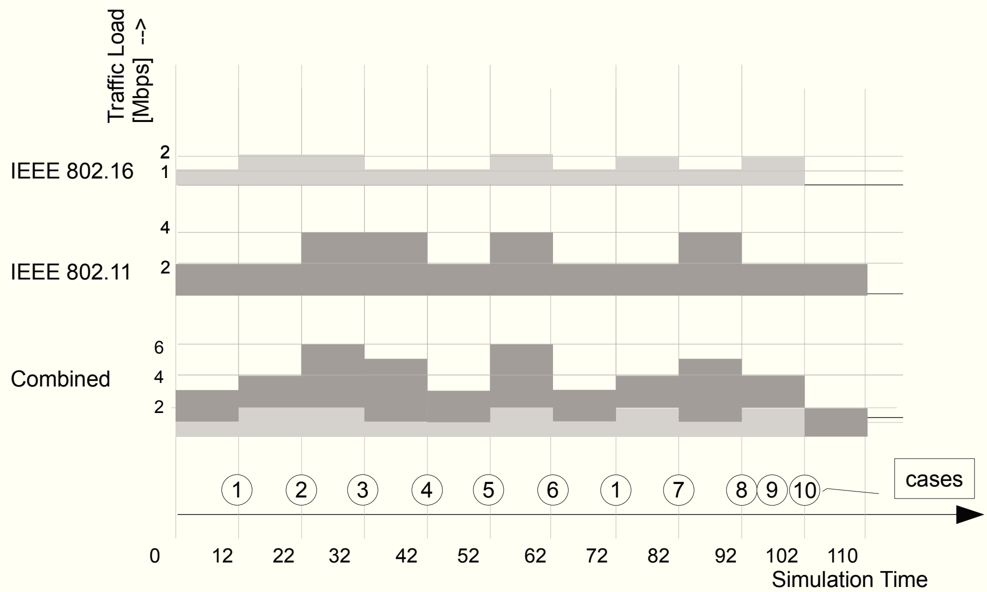
- Adaptive RCA enabled 802.11 system: The Stations (AP and STA) are following the model described in Section 8.4.1.1.
- RCA enabled 802.16 system: In this case, the uplink (UL) subframe

is switched off to model a continuous busy period at the beginning of the 802.16 frame. It approximately models the actual intention of 'DL+UL' at the beginning of the 802.16 frame as discussed in Section 9.3.

IEEE 802.16	Increase	√				√		√			
	Decrease			√			√		√		√*
	Does not change		√		√					√	
IEEE 802.11	Increase		√			√			√		
	Decrease				√		√				
	Does not change	√		√				√		√	√
Cases:		1	2	3	4	5	6	7	8	9	10

(a) Scenario: cases

* IEEE 802.16 traffic load decreases to near zero



(b) Traffic load scenario for validation

Figure 9.13: Simulation Scenario for Adaptive RCA validation

9.4.2 Simulation Setup

Similar traffic load scenario (see Section 8.4.2) is applied for validating the adaptive behavior of the aRCA method with the traffic dynamics. The different cases shown in Figure 9.13(a) is considered here as well and a traffic load dynamic scenario is developed as shown in Figure 9.13(b).

For the rest of the simulation results it is configured as 1 Mbps, i.e., the traffic load of IEEE 802.16 starts with 1 Mbps and then increases to 2 Mbps after 12 s and so on, as shown in the figure. The traffic load of IEEE 802.11 starts with 2 Mbps and then increases to 4 Mbps after 22 s and so on, as shown in the figure. For both IEEE 802.11 and IEEE 802.16 systems, Protocol Data Units (PDUs) of 375 bytes are considered. In the IEEE 802.11 RCA configuration, the sensing period is set to 5 s, the sensing duration is set to 0.5 s and traffic estimation smoothing factor is set to 0.05.

9.4.3 Results and Evaluation

In the following the results for estimated traffic demand and resource allocation are evaluated in the first phase. In the second phase, the results for QoS measures like throughput, delay, and packet loss ratio are evaluated.

9.4.3.1 Traffic Demand Estimation and Resource Allocation

Figure 9.14 shows two significant prior results to the performance indicators in the adaptation process of the RCA algorithm. The bottom diagram showing the applied traffic load is illustrated for reference. The top diagram shows the estimated traffic demand of one's own system (IEEE 802.11) and of the other system (IEEE 802.16) by dark and light gray lines respectively, estimated by the IEEE 802.11 system. As expected, the own traffic demand estimation along the simulation time is quite well matched with the traffic applied to the system. The excellent part is that it takes only 20 to 30 iterations, which results in a *real estimation delay* between 200 to 300 ms, to estimate approximately equal to the actual traffic in case of traffic transition.

In the figure, the estimation of the others traffic demand along the simulation time is also matched with the traffic applied to the other system quite well. However, there is an *additional estimation delay* of approximately 4 s observed between the actual change of traffic load and its estimation.

The middle diagram in Figure 9.14 shows the resource allocations along the simulation time estimated by the own system for its own and the other system. The combined allocation should be equal to the RCA_Interval as seen in the figure as well. In the figure the transmission starting point for the IEEE 802.16 system coincides with 0 ms in the y-axis. Considering the starting point model as Equation 9.1, the transmission of the IEEE 802.11 system starts where the resource allocation for the IEEE 802.16 system

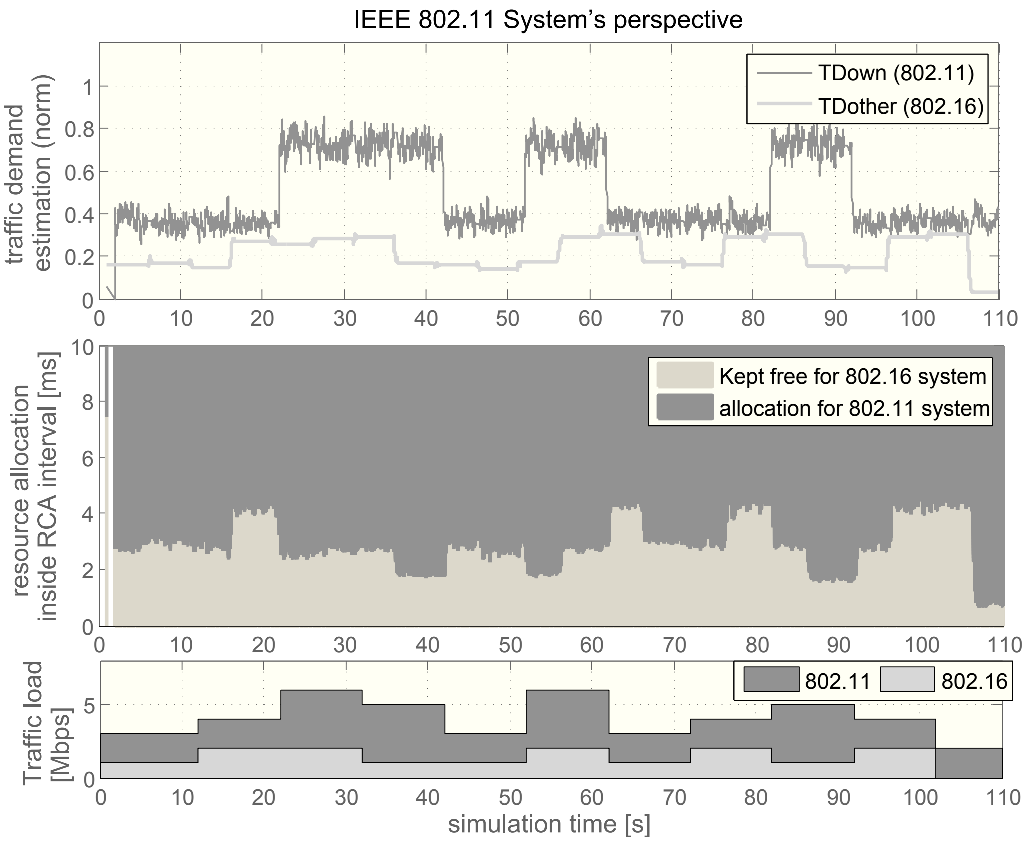


Figure 9.14: The estimated traffic demand and the resource allocation against simulation time

ends.

The IEEE 802.11 system does the following:

- sets its transmission starting point equal to the estimated 802.16 allocation,
- allocates the time duration to its own system according to the 802.11 allocation shown in the figure and
- keeps the rest of its RCA_Interval (802.11's perspective) free for the 802.16 system.

As described in the RCA method, the resource allocation is determined based on the traffic demands, the direct correlation is seen as well in both the top and the middle figures. Comparing with Figure 9.13, few cases are discussed in the following. The starting of IEEE 802.16's transmission is considered as reference point.

- Case 1 at 12 s: The IEEE 802.11 system senses IEEE 802.16's traffic increase in its next scheduled sensing at around 16 s (additional estimation delay of 4 s plus real estimation delay of 0.3 s). The newly estimated value triggers to reconfigure the starting point for the IEEE 802.11 system relatively later (at around 4 ms) than the previous case (at around 2.5 ms) and to reallocate the resource, resulting in a decrease of resource allocation proportionally.
- Case 2 at 22 s: When IEEE 802.11's traffic increases, IEEE 802.11's resource allocation increases proportionally after the real estimation delay of 0.2 s, and the estimated starting point for the 802.11 system becomes relatively closer (at around 2.5 ms).
- Case 3 at 32 s: When IEEE 802.16's traffic decreases, IEEE 802.11's resource allocation increases proportionally in its next scheduled sensing, and the estimated starting point for the 802.11 system becomes relatively even closer (at around 2 ms) to the reference point.
- Case 4 at 42 s: When the IEEE 802.11 traffic decreases, IEEE 802.11 resource allocation decreases proportionally with an estimation delay of 0.3 s.
- Case 5 at 52 s: Proportional increase and then decrease in IEEE 802.11's resource allocation between 4 s is observed.

Similar effects are observed in the other cases.

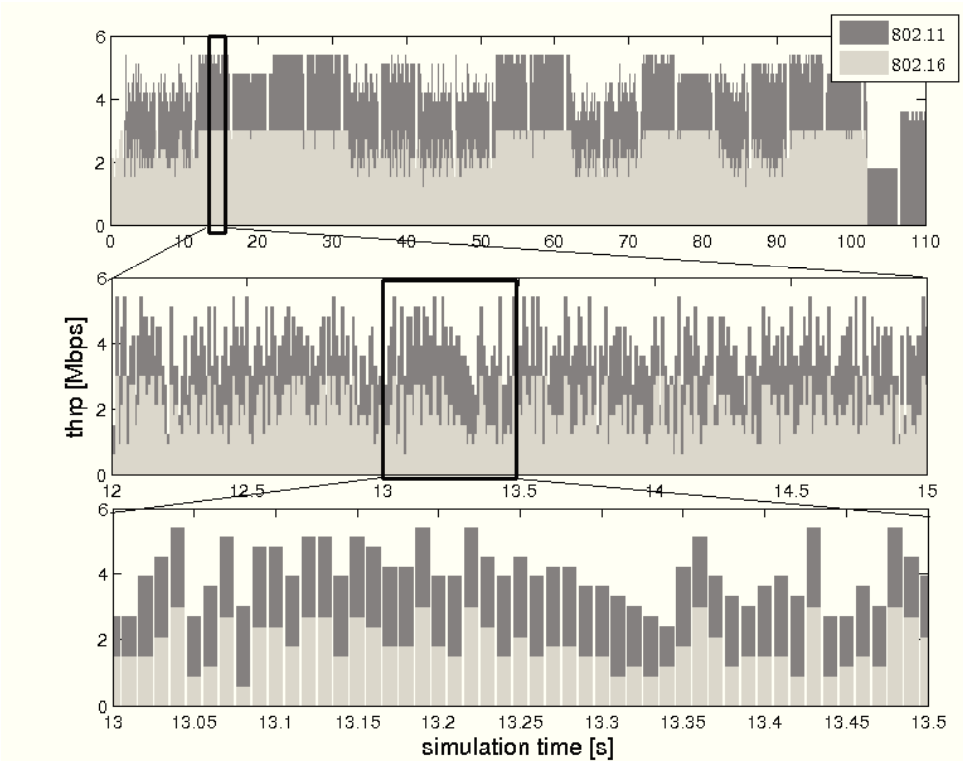


Figure 9.15: Achieved throughput timeseries (averaged over 10ms) measured on top of the MAC layer

9.4.3.2 Throughput, Delay and Packet Loss Ratio

In the following the performance indicators: throughput, delay and packet loss are evaluated. Packet loss due to interference is discussed here.

Figure 9.15 shows the achieved aggregated throughput against simulation time. The throughput is measured at the MAC layer and averaged over a 10 ms window (which is seen in the diagram with a smaller scale). The impact of resource allocation is quite visible on the throughput. For example, at medium mean aggregated load of 4 Mbps, approximately the same amount of throughout is achieved.

Figure 9.16 shows the end-to-end delays of the packets. High delay peaks are seen in the IEEE 802.11 delay curve after every 5 s. These are basically due to the packets which are waiting the MAC buffer during the sensing duration when the own system was silent. The maximum delay peak is therefore equal to the sensing duration of 0.5 s. Except for those delays,

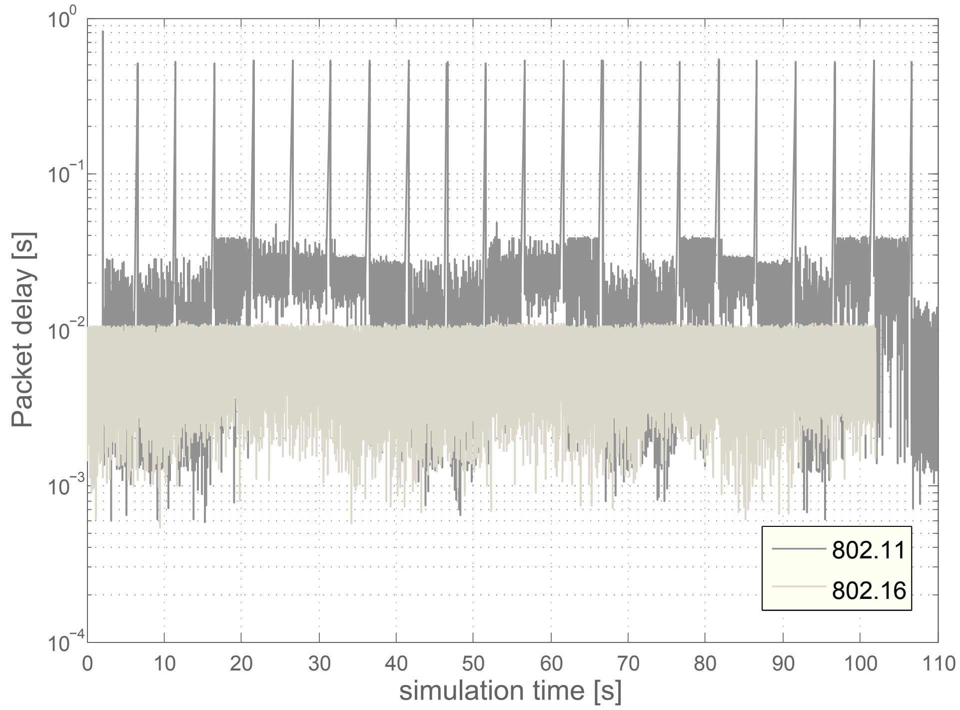


Figure 9.16: The end-to-end MAC delay timeseries

the rest of the delays are not more than 50 ms, which is very good for supporting QoS oriented applications. As seen in the figure, the delays are increased with increase of traffic load as noticed before. IEEE 802.16 packets are experiencing delays of not more than 10 ms, which corresponds to the IEEE 802.16 frame duration. At 102 s, when IEEE 802.16's traffic decreases almost to zero, the IEEE 802.11 packets are experiencing significantly lower delays as expected after the sensing period has finished.

Figure 9.17 shows the CRC loss ratio (calculated according to Equation 8.5) against simulation time. Any point in the curve means the ratio of the lost packets to the total packets up to that simulation time point. The curves follow a similar pattern, because the interference from any system has a mutual effect. The magnitude of the curves are different because the total numbers of packets transmitted by each system are different due to

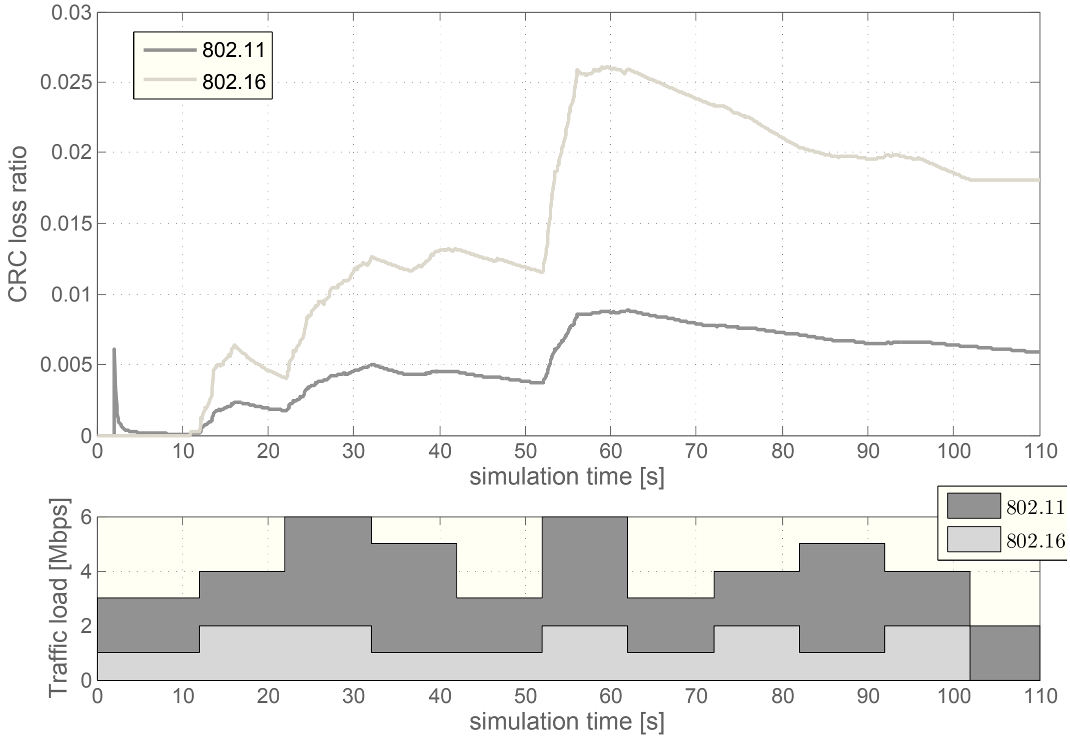


Figure 9.17: The CRC loss ratio (defined in Equation 8.5)

different traffic load. This phenomenon can be explained by the following example. Assume that mean traffic loads of the IEEE 802.11 and the IEEE 802.16 system are $TL_{.11}$ and $TL_{.16}$ Mbps, where $TL_{.11} > TL_{.16}$ and respective mean packet lengths $PL_{.11}$ and $PL_{.16}$, where $PL_{.11} = PL_{.16} = PL$ (according to simulation configuration); that means, the systems transmit $\frac{TL_{.11}}{PL}$ and $\frac{TL_{.16}}{PL}$ packets per second respectively. Now if X number of packets are experienced CRC loss due to mutual interference in each system, then the CRC loss ratios are $\frac{X*PL}{TL_{.11}}$ and $\frac{X*PL}{TL_{.16}}$, where $\frac{X*PL}{TL_{.11}} < \frac{X*PL}{TL_{.16}}$.

The following event, denoted as (A) and shown in Figure 9.18 for further reference, is identified as the reason for packet collision resulting in CRC loss.

(A) The end point of the IEEE 802.16 ($EP_{.16}$) busy period could shift later than estimated ($\hat{EP}_{.16}$). In this situation, the estimated starting point of the IEEE 802.11 system ($\hat{SP}_{.11}$) is delayed due to carrier sensing, resulting in the situation where the end part of the estimated resource allocation of the IEEE 802.11 system ($\hat{RA}_{.11}$) coincides with the start part of the next IEEE 802.16 frame transmission. The possibility of collisions depends on

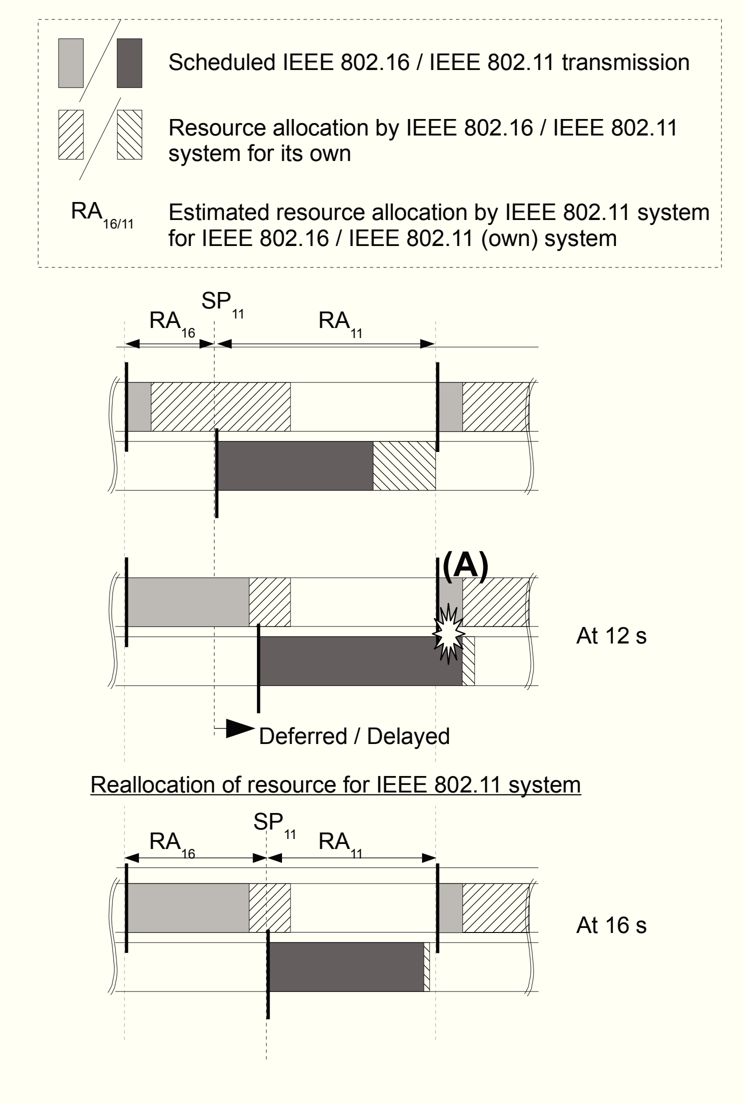


Figure 9.18: The consequences of resource allocation in the adaptive RCA method

the actual packet transmission on the RA period. For example, if there is a high number of packets in the queue of the 802.11 system, then collisions are observed among the last MSDU frames in the 802.11's allocation and the starting MSDU frames in the subsequent 802.16's allocation.

As seen in the curves, in the beginning at the low load, there is almost no loss.

- Case 1 at 12 s: With the starting of medium load due to the increase in IEEE 802.16 load, the loss ratio also starts increasing up to when the resource allocation and the starting point are reconfigured in IEEE 802.11. The reason is described in (A).

- Case 2 at 22 s: The traffic load increases in IEEE 802.11's own system, the aggregated load goes to saturation. With the starting of case 2, the loss ratio also starts increasing, though the resource allocation is updated proportionally and it is continued up to when the traffic load of IEEE 802.16 decreases. Due to the saturation traffic, events like (A) occurs very often.
- Case 3 at 32 s: The traffic load decreases in the IEEE 802.16 system, resulting in less (A) events up to the next significant reconfiguration of the resource allocation and the starting point. At this point, (A) events reappear up to next Case 4.
- Case 4 at 42 s: At low load condition, there is almost no loss.
- Case 5 at 52 s: The magnitude of (A)'s occurrence is much higher at the beginning when reconfiguration of RA and SP of IEEE 802.11 is mainly based on its own traffic demand. Later the magnitude decreases when IEEE 802.16's traffic demand is sensed and taken into account.
- Case 6 at 62 s: Same as Case 4.
- Case 1 at 72 s: The impact on the long-term ratio is less compared to Case 1 at 12 s.
- Case 7 at 82 s: The occurrence of (A)'s is lesser at the beginning when reconfiguration of RA and SP of IEEE 802.11 is mainly based on its own traffic demand, though IEEE 802.16 traffic load is decreased. Later it increases when IEEE 802.16's traffic demand is sensed and taken into account.
- Case 8 at 92 s: Collisions due to (A) events continue up to when IEEE 802.16's traffic demand is sensed and taken into account in the reconfiguration of RA and SP of IEEE 802.11.
- Case 9 at 97s: Very few collisions occur.
- Case 10 at 102 s: No collisions.

9.4.4 Enhancement of the Model

Three significant enhancements on the model are described below.

1. In the above, the traffic demand and resource allocation followed by the evaluation of performance indicators for aRCA is shown. In the above, the minimum allocation unit, which can also denoted as quantization, as mentioned in Section 6.3.2.2 is not considered. The top diagram of Figure 9.19 shows the impact of quantization for the same traffic load scenario. The bottom diagram, which is shown before,

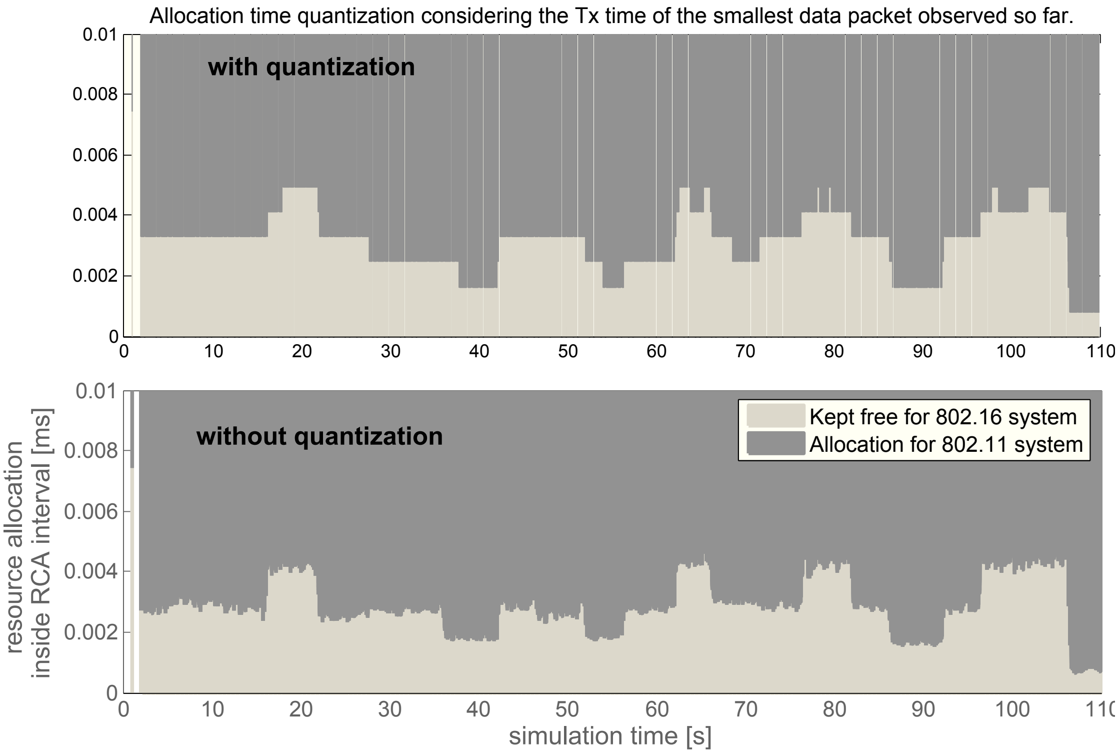


Figure 9.19: The resource allocation with and without quantization. Quantization based on RA_{own}^{step} defined in Equation. 6.7

is considered for comparison. The quantization approach is basically considered, on the one hand to reduce the frequency of reconfiguration of RA and SP, and on the other hand to make the reconfiguration effective.

2. The traffic demand estimation of IEEE 802.11 (own) system is based on the incoming bits in the MAC buffers as described in Section 5.6. In this case, packets are without any protocol (MAC and PHY) overhead. During the normalization process, there is also no signaling overhead considered, which is basically the first approximation model. In the following, these two overhead issues are considered in the model, on the one hand to make one's own traffic demand estimation, eventually the resource allocation, more appropriate and on the other hand, to make it similar to the traffic demand estimation of the IEEE 802.16 (other) system, where everything which generates busy periods is considered in the estimation.
3. The most significant of the three enhancements is the following. As

it is already seen in the evaluation, though less, but there are CRC losses in the previous model which are mainly due to the reason defined in (A). It shows that when the starting point of the IEEE 802.11 is delayed then there is a possibility of collision among the last MSDU frames in the 802.11's allocation and the starting MSDU frames in the subsequent 802.16's allocation. The solution to this problem is in fact already hidden inside the problem. In the model, the following enhancement is introduced. In case of delay on the starting point, realized as the delay of Beacon frames of IEEE 802.11 system, the estimated RA is reduced by the amount of delay.

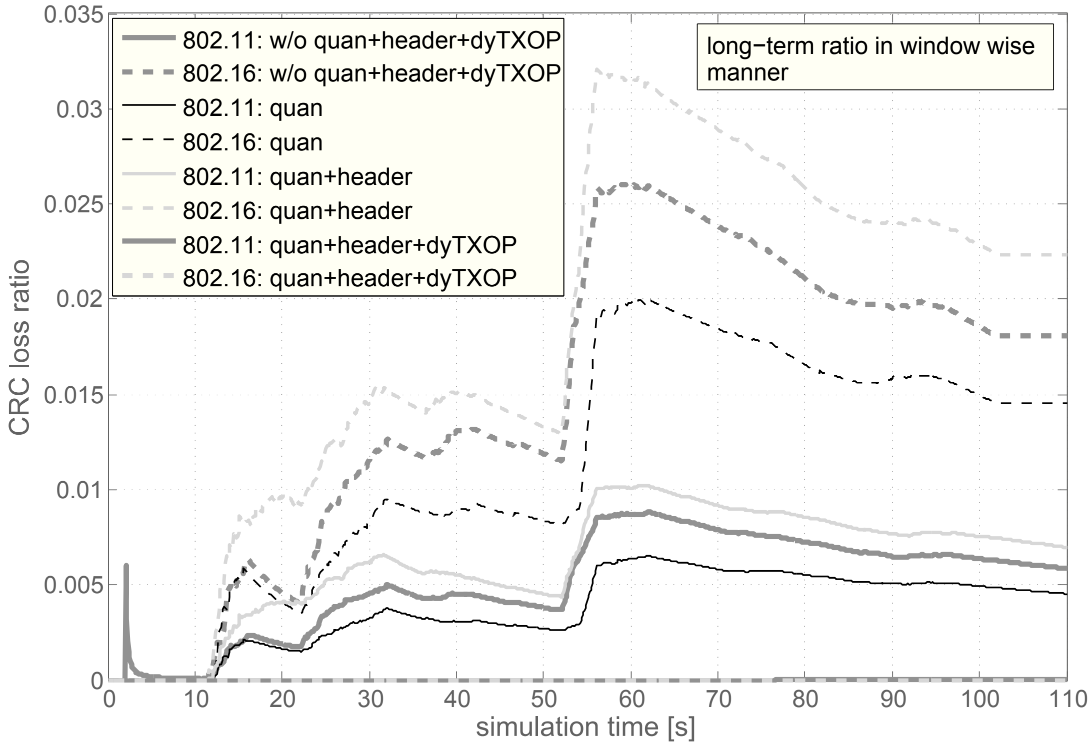


Figure 9.20: The CRC loss ratio with different simulation models

Figure 9.20 shows the CRC loss ratio for three enhancement models with the initial model, which is denoted as *w/o quan+header+dyTXOP*. All the model implementations are in the IEEE 802.11 system. With first enhancement of quantization the scale of loss ratio is lower due to the less occurrence of (A) events. With considering the headers in the estimation, a proportional increasing factor is added in the resource allocation, which results in more

CRC loss. Considering the third enhancement, CRC loss goes to almost zero. In this case, the RCA enabled 802.16 system is considered.

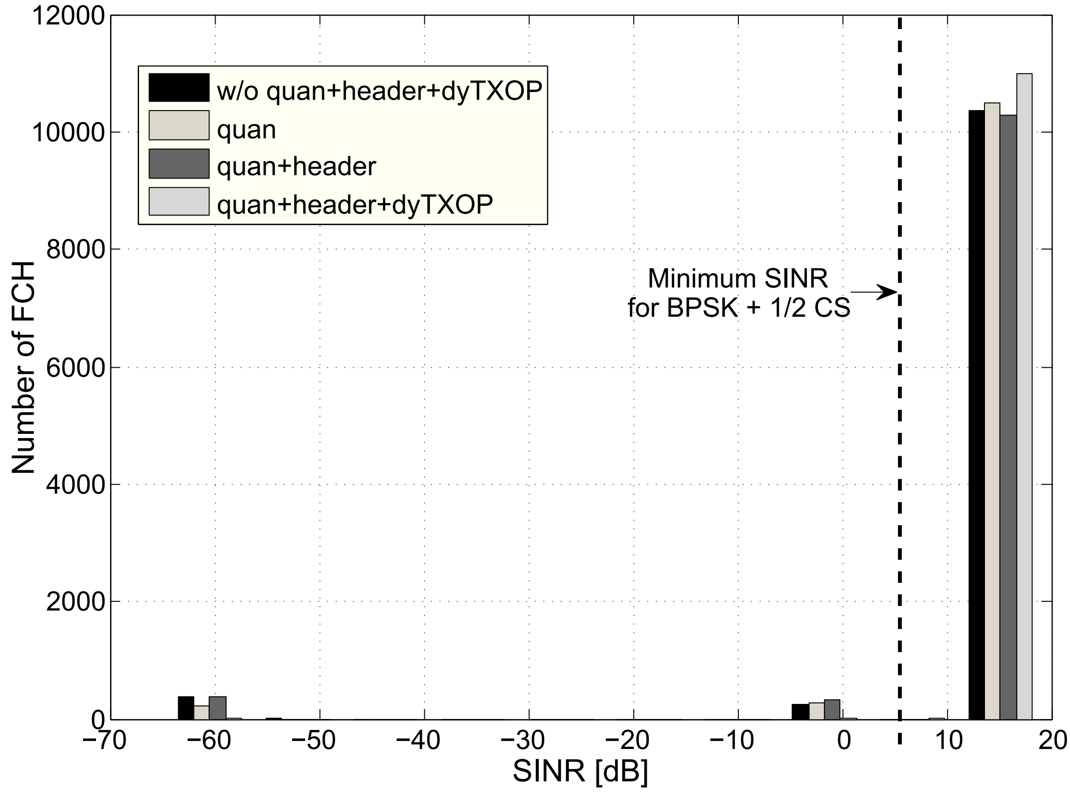


Figure 9.21: Histogram of the SINR values for the FCH in IEEE 802.16 system

Figure 9.21 shows the histogram of the SINR values for the frame control header (FCH), received at the subscriber stations of the IEEE 802.16 system. It is quite apparent from the figure that the number of FCHs with SINR less than the threshold, are actually considered as lost packets. The threshold is marked in the figure.

In the above, a substantial emphasis is given on the loss of FCH due to the following fact. If the FCH is lost, the IEEE 802.16 system has to apply an adaptation method (given hints on the IEEE 802.16 standard) which consumes adaptation time (without data transmission). From the author's knowledge, it would degrade the QoS in the IEEE 802.16 system, for example increase the end to end delays of data packets and decrease the throughput based on the buffer management.

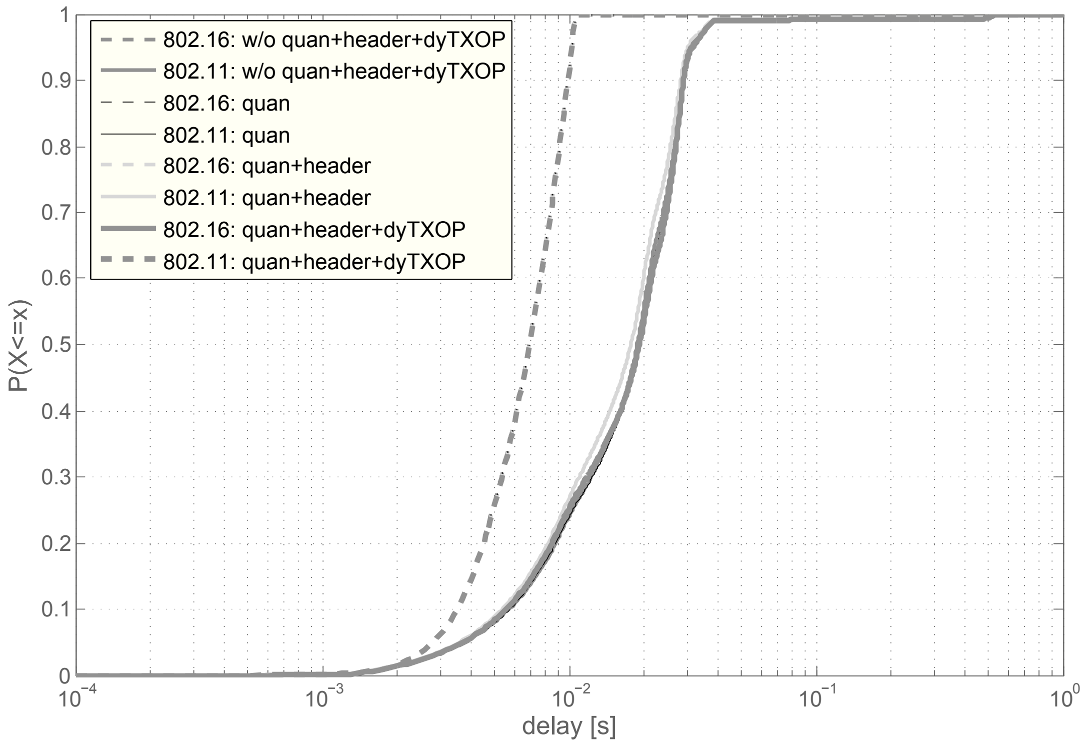


Figure 9.22: CDF of the end-to-end MAC delays with different simulation models

Figure 9.22 shows end to end delays for above mentioned cases. A significant difference is not visible.

In the following, a statistical evaluation method to find the confidence interval (CI) for the mean is given.

9.4.5 Statistical Evaluation: Confidence Level for Mean Throughput

To have the reliability over the achieved performance measures a statistical evaluation is performed. In the framework of this thesis, a number of independent simulation runs are considered for the statistical evaluation. Simulation runs are generally statistical experiments, different runs with different seeds. The mean from each simulation run is realized as a random variable. Let it be denoted as x_i, where $i = 1, 2, .., n$ and where n is the sample size. Note that the law of large numbers should be followed in each simulation run, so that the x_i are independent.

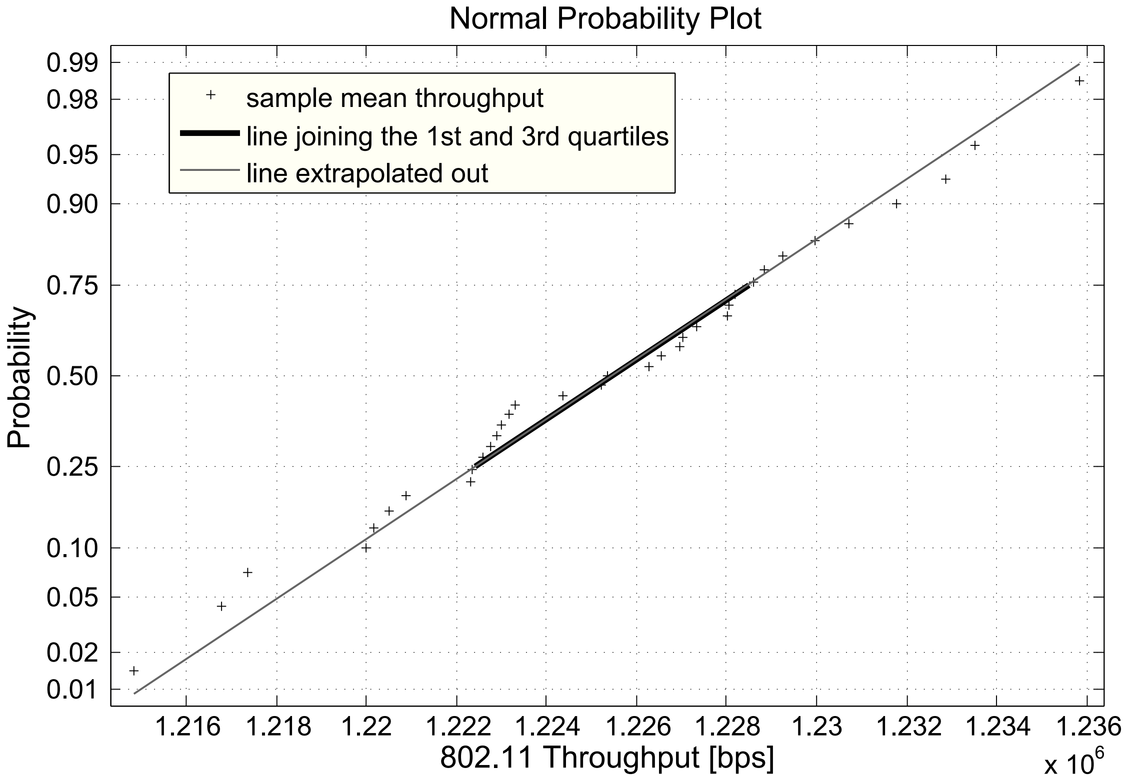


Figure 9.23: Normal probability plot of sample mean throughputs achieved in 35 independent simulation runs

There are different methods which are followed to calculate the confidence interval. The general policy is as follows.

If the variance σ^2 of the population is known, then the variance is used so that the following relation can be obtained.

$$\mu = \overline{x} \pm \frac{z_{\alpha/2}\sigma}{\sqrt{n}} \tag{9.2}$$

where $\overline{x}$ is the sample mean. z is determined from the normal distribution table. The two values in Equation 9.2 are called the confidence limits for the mean and the interval between them is called the confidence interval for the mean with known variance σ^2 and given confidence level $1 - \alpha$. A different interpretation is: the mean is between the confidence limits with a probability $1 - \alpha$ [41].

If the variance is not known, then the sample variance is calculated and used to find the confidence limits.

$$\mu = \overline{x} \pm \frac{zS}{\sqrt{n}} \tag{9.3}$$

In the above two cases, the sample size is considered to be sufficiently high, generally $n > 30$. It is considered that for $n > 30$, the x_i follow the normal distribution. If it is not large enough, then the student t distribution is used to calculate confidence limits.

In the context of this thesis, the confidence level for the mean of the IEEE 802.11 throughput with an unknown variance is calculated. Here, $n = 35$ is considered which supports that the means are normally distributed. However, in the following, three different methods are investigated. There are different methods or tests in mathematical statistics to decide whether samples follow a normal distribution.

1. Figure 9.23 shows a normal probability plot considering the sample throughput means achieved in 35 independent simulation runs. This is a graphical validation tool for a quick normality test. The MATLAB implementation is used here. According to the implementation, the cumulative relative frequencies of the samples are sketched onto the plot. It shows that the samples are approximately linearly fit to the line joining the first and third quartiles and its extrapolation. This concludes that the x_i can be considered as normally distributed.
2. The implementation of the Lilliefors test in MATLAB is also used to verify whether the sample means follow the normal distribution. The implementation is as follows: The default null hypothesis is that the sample in vector x comes from a distribution in the normal family, against the alternative that it does not come from a normal distribution. The test returns the logical value h = 1 if it rejects the null hypothesis at the 5 % significance level, and h = 0 if it cannot. The mean values considered here result in 0.
3. The right side of Figure 9.24 is also a kind of graphical concept to have an idea that the samples follow a normal distribution. The MATLAB function called `histfit` is applied in this case. It calculates and draws the histogram with superimposed fitted normal density based on the samples.

After having completed the normality test, the confidence interval is calculated according to Equation 9.3. The left diagram of Figure 9.24 shows the means from 35 simulation runs, the maximum, the minimum, the standard deviation and the 95 % confidence limits of the mean.

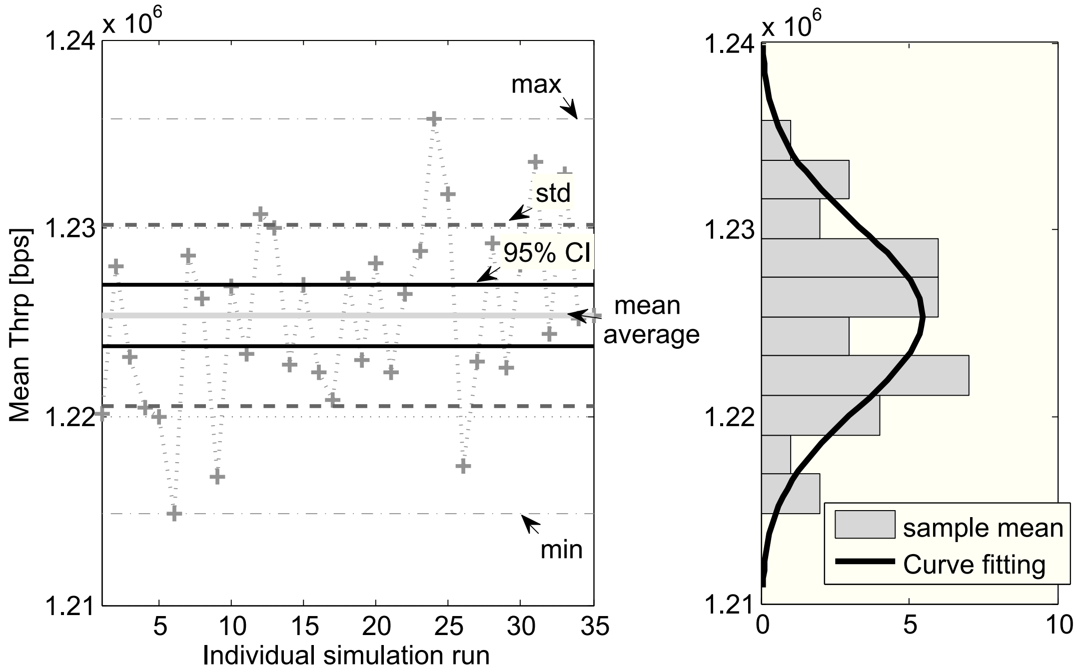


Figure 9.24: Statistical evaluation: confidence interval (left diagram) and normality test (right diagram)

9.4.6 Different Scheduling Approach

In [84], a different scheduling approach for the RCA enabled IEEE 802.16 system is given. Note that it is provided considering the homogeneous scenario consisting of IEEE 802.16 systems. During the scheduling, the major part of the DL phase is scheduled at the front part of the IEEE 802.16 frame whereas rest of the DL phase and UL phase are scheduled at the back part of the frame to keep a continuous idle period in the middle of the frame.

Figure 9.25 shows the timing diagram for channel access in the case of heterogeneous scenarios where the RCA enabled 802.16 system following the just mentioned scheduling approach and the RCA enabled 802.11 system follows the scheduling approach according to the design considered in this thesis (Section 9.3). It can be said from the figure that the estimation of the starting point for the IEEE 802.11 system is rather complex because, on the one hand, the reference point (the starting point of the back part

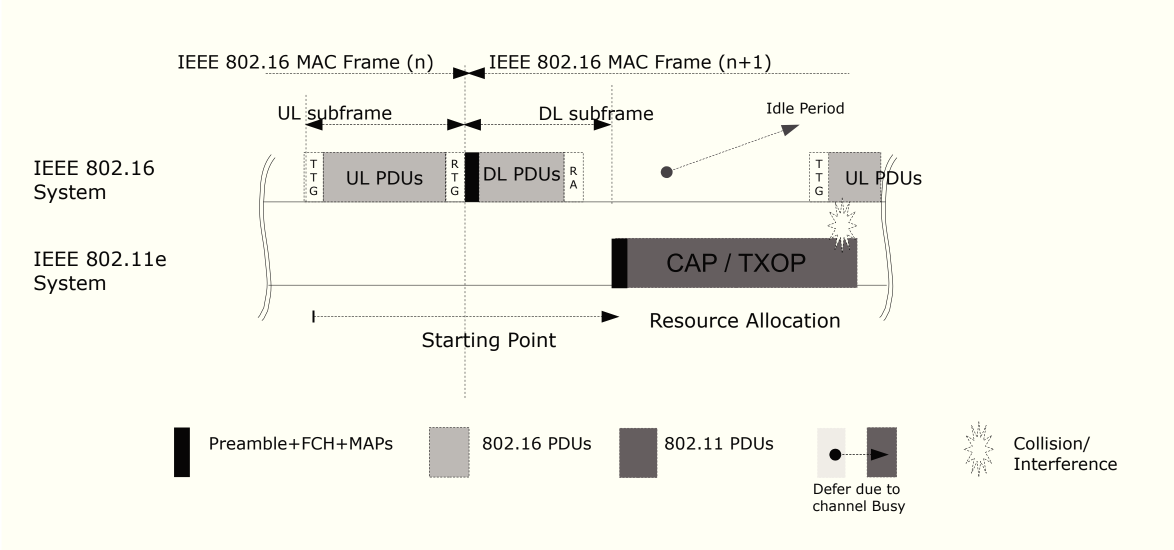


Figure 9.25: Timing diagram for channel access by collocated RCA enabled IEEE 802.11 and 802.16 system, where in the IEEE 802.16 system, the DL phase is scheduled at the front part and the UL phase at the back part of the IEEE 802.16 frame as mentioned in [84]

of the IEEE 802.16 frame) fluctuates and on the other hand, assuming that the IEEE 802.11 system is not capable to decode IEEE 802.16's frame starting. Moreover, there is a higher probability of occurring events like (A) as mentioned in Section 8.4.3.3, though the enhanced model *dyTXOP* is introduced in the IEEE 802.11 system. This is because the starting of the back part is hard to predict.

9.5 Extensions for Partially Overlapping and for more than Two Networks Scenarios

In this section, the typical problems in the case of partially overlapping scenarios are discussed. Later, a similar approach as proposed in Section 8.5.4, cooperative spectrum sensing is introduced.

9.5.1 Extensions for Partially Overlapping Scenario

In the case of a partially overlapping scenario, not all the stations are inside the carrier sense ranges of each other. In this scenario, the well-known *hidden node problem* will occur. From the IEEE 802.11 system's point of view two key cases are depicted in Figure 9.26.

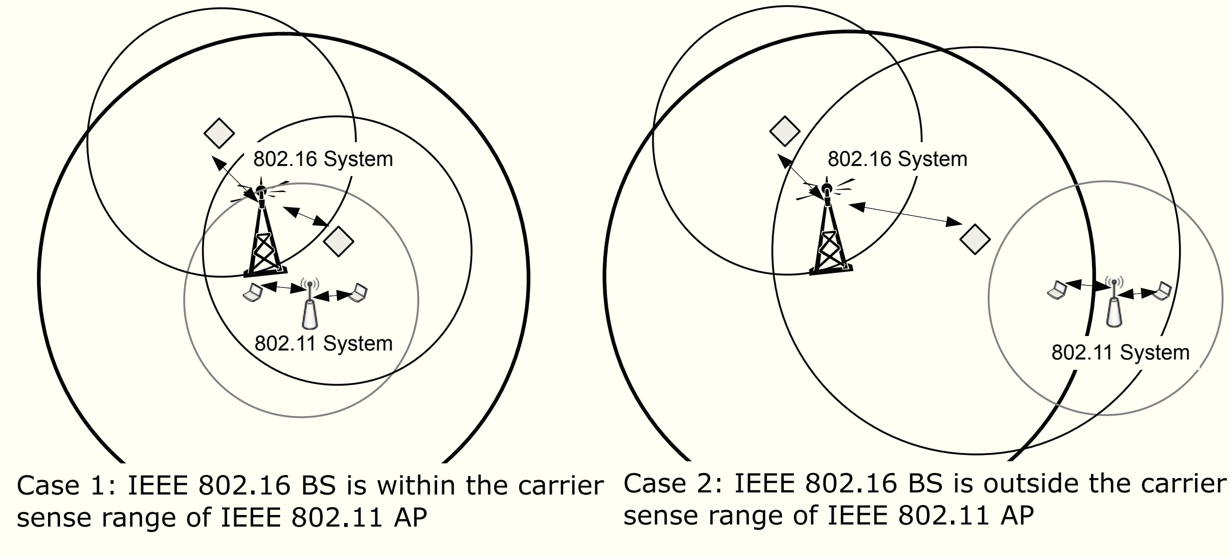


Figure 9.26: Two different partially overlapping scenarios: IEEE 802.16 SSs are within and outside the carrier sense range of IEEE 802.11 AP

- Case 1: In this case, the IEEE 802.11 AP can monitor the downlink traffic of the IEEE 802.16 system completely and a certain amount of the uplink traffic. This causes problems in the System Type Identification (STI) and the Traffic Demand Estimation (TDE) process by providing incomplete information.
- Case 2: In this case, the IEEE 802.11 AP can monitor only a certain amount of the uplink traffic of the IEEE 802.16 system. Moreover, both systems cannot detect each other's Beacon frames.

According to the proposal in Section 8.5.4, cooperative spectrum sensing can provide a better overview about spectrum utilization in the vicinity than individual sensing in the AP. The achieved outcome of the cooperative spectrum sensing can be utilized to schedule the transmissions of the own system with the knowledge of the neighbors and their spectrum utilization activity model. Based on the analysis and concept presented in this thesis, further research in this direction is possible.

From the IEEE 802.16 system's point of view two key cases are

- Case1: In this case, the IEEE 802.16 System is experienced interference due to the IEEE 802.11 system (left diagram of Figure 9.26).
- Case2: In this case, only the IEEE 802.16 System can interfere with the IEEE 802.11 system and not the other way round (right diagram of Figure 9.26).

In Section 15.1.3.2.1 of the IEEE 802.16h [68] standard, channel measurement in the operating stage is provided which is to some extent similar to cooperative spectrum sensing. The BS requests the SSs to measure the channel.

9.5.2 Extension for more than Two Systems

In the following, logical extensions of the RCA method in case of more than two coexisting (homogeneous and heterogeneous) systems are proposed

9.5.2.1 Homogeneous Scenario: More than Two IEEE 802.16 Systems

In the case of more than two uncoordinated IEEE 802.16 systems, the similar concept of the virtual system ID (VSID), as described in Sections 8.6.1, can be deployed in the system level to maintain their sequences during the channel allocation in the RCA_Interval.

9.5.2.2 Heterogeneous Scenario: More than One System of Each Type

In this case, the RCA_Interval is logically divided into two sub-intervals denoted as *dot16SubInterval* and *dot11SubInterval*. The IEEE 802.16 systems group their channel allocation inside a sub-interval, dot16SubInterval, of the RCA_Interval, and moreover, they adapts the virtual system ID (VSID) method to maintain their sequences inside the dot16SubInterval. The IEEE 802.11 systems also group their channel allocation inside dot11SubInterval, which is scheduled just after the dot16SubInterval inside the RCA_Interval. They also adapt similar VSID method to maintain their sequences inside the dot11SubInterval and a backoff method. Note that, the IEEE 802.11 and the IEEE 802.16 systems can only decode VSID from their own system types, not from other system type.

9.6 Conclusion

In this chapter, an analysis of possible interference that can occur in the heterogeneous coexistence scenario with the legacy IEEE 802.11 and the legacy IEEE 802.16 systems is identified and shown in timing diagram. Simulation results are evaluated considering such a scenario which resemble coexisting wireless networks in an apartment scenario. It shows only 40 % capacity could be utilized. The proposed generic spectrum sharing method, RCA is applied in a first step only on the 802.16 system and it shows the channel utilization is increased by up to 20 %. When both systems are following the method, the improvement is even higher and fairness between the systems is observed. In the second step, the adaptive RCA method is introduced in the IEEE 802.11 system. On the one hand, IEEE 802.11 system's adaptiveness is evaluated in case of dynamic traffic and on the other hand, its impact on the performance indicators is measured. Proportional fair spectrum sharing is observed to support the QoS, with optimizing the aggregated performance. The adaptive RCA model is enhanced, which even shows an excellent improvement in the CRC loss ratio. The conceptual extentions of the RCA method are proposed for the following two coexistence scenarios: partially overlapping scenarios and coexistence of more than two heterogeneous systems.

CHAPTER 10

CONCLUSIONS

This thesis is the outcome of systematic scientific research work from its initial stage of generating new concepts for spectrum sharing to its completion stage of evaluating the performance of the developed method in target coexisting scenarios. In this thesis, a generic spectrum sharing concept in wireless networks is proposed, with the desire to mitigate the interference proactively on the first hand and reactively on the second hand. Two existing wireless systems based on IEEE 802.11 and IEEE 802.16 wireless technologies are described and analyzed for modeling the concept. The spectrum sharing enabling techniques such as a RSS-based detection method, a pattern recognition based system identification method, statistical knowledge based traffic demand estimation methods are developed and integrated in the design method.

The chapter begins with the problem statement in Section 10.1. Then, the work presented in the thesis is summarized in Section 10.2, followed by a discussion of potential future research directions of this work in Section 10.3. The chapter ends with concluding thoughts as the final statements in Section 10.4.

10.1 Problem statement and solution concept

It is dangerous to put limits on wireless.[1] Exceptional engineering efforts have been made to develop and to apply cutting-edge wireless communication technologies for the benefit of human society. This is justified on the one hand, by the development of more and more new application concepts based on wireless communication and on the other hand, by the integration of the wireless radio interface into numerous devices to deploy these concepts. Moreover, the increase of voice and video traffic is tremendous in recent years and expected to increase even in higher magnitude in coming years. All these developments lead to an anticipated situation where a considerable amount of spectrum is required. Nevertheless, the total amount of spectrum is limited and most of the radio and micro wave frequencies

[1] Guglielmo Marconi, 1897 (invented the wireless telegraph)

are allocated by the spectrum regulators as licensed bands. It is already proven in some extent that the paradigm shift from licensed to unlicensed band can create more new capacity, with a special treatment to reduce the destructive mutual interference between the wireless systems applying the mature technology. The main challenge of unlicensed bands is to identify the interference sources, if there are any, on the first hand and then secondly to mitigate the interference in an intelligent and efficient way, so that all systems can coexist with fair spectrum sharing. This will eventually help to assure the QoS (e.g. throughput, delay, jitter, loss ratio, etc.) as well as Quality of user experience (QoE) considering the cost. For this reason, the development of the spectrum sharing methods from the conceptual state to the performance evaluation state is the focus of this thesis. A generic spectrum sharing concept, denoted as Regular Channel Access (RCA), is developed to mitigate the interference. A spectrum sensing framework is developed as an enabling technique for spectrum sharing which is tailored to identify the interference source and to estimate the interference. Inside the framework of this thesis, the IEEE 802.11 based WLAN system and the IEEE 802.16 based WMAN system are considered for mutual coexistence. The IEEE 802.11 based system creates a multi-billion industry out of its innovative operational method in the unlicensed band. The deployment of the IEEE 802.16 based system in the unlicensed band also has a promising financial advantage. The centralized channel access schemes are investigated from the perspective of both systems. The generic concept is adapted in the IEEE 802.11 system by tailoring the medium access control scheduling and very few extensions in the protocol standard as follows.

- A new usage layout of the QoS control subfields for the QoS Null frame is proposed.
- An extra information element field, called Virtual System ID (VSID), is added in the Beacon frame body.

10.2 Summary of Results

The thesis starts with giving a list of initiatives and the initiators as the drivers to spectrum sharing since they show many promising and valuable examples towards dynamic spectrum sharing. This is followed by the identification of enabling techniques towards spectrum sharing where the contributions of this thesis correspond to.

From the context of the problem identified in the thesis, a comprehensive scenario, denoted as a Metropolitan Scenario, is shown, which inspires to develop a scenario matrix and to study the big scenario in a systematic manner. The two real world scenarios from the context of wireless environments in the densely urban area are classified as 'apartment' and 'office' scenarios for this study.

The enabling techniques such as the sensing methods and the estimation methods to obtain the knowledge about the wireless environment are developed, which is considered as the a-priori requirement to the spectrum sharing methods. In this respect, a detailed study on the characteristics of channel occupation by the IEEE 802.11 and the IEEE 802.16 wireless systems is done, justified by the analysis on the channel occupation footprint from the simulation trace. Note that these two types of networks are selected for this study. Distinguishable patterns are observed in the footprint, which helps to formulate rules, provided in the thesis, for identifying the system and its type. Next, the estimation model for the traffic demand of the other systems based on channel occupation, and of one's own system based on the aggregated incoming traffic bits in the MAC queues are described. Two different traffic demand estimation methods, the exponential moving average (EMA) and the statistical distributions, are developed and evaluated. It is shown that the estimation error is becoming higher during the transient period when the traffic load changes. In the case of statistical distribution, the traffic demand estimation is done by estimating four different parameters (mean, 50-, 90-, 95-percentile). The outcome of these methods eventually helps configuring the spectrum sharing parameters like the resource allocation and the transmission starting point for the own system. Compared to the EMA based estimation, the distribution based estimation method is expected to be more reliable from the perspective of the resource allocation calculation, where QoS-aware x-percentile parameter value can be used; nevertheless with higher computational cost.

Considering the different access methods followed by the wireless networks, a generic spectrum sharing concept is hypothesized. Based on this hypothesis, a concrete and useful algorithm denoted as Regular Channel Access (RCA) is developed. One of the objectives of the RCA method is to reduce the impact of interference in the coexisting scenarios, which is justified for the steady traffic load in the coexisting networks for a relatively larger time duration (around 500 s). Later the algorithm is further enhanced to make it adaptive in the case of traffic dynamics in a smaller time scale (around 10 s). The sensing and estimation framework acts as a feedback element to the spectrum sharing method.

Before applying the algorithms to the MAC scheduling of the IEEE 802.11 based system, a mathematical model is provided to calculate the transmission times for the IEEE 802.11 frames, and the frame exchange durations for both the downlink and the uplink phases when the system follows the centralized HCF Controlled Channel Access (HCCA) mechanism. The results show the high impact of protocol and signaling overhead on the total transmission durations, especially for a smaller packet scenario which is a very common in case of VoIP traffic as well as for a higher PHY transmission rate scenario which is realized during the transmission on short ranges and good channel condition. The higher boundaries of normalized throughput in the case of standalone and coexisting scenarios are calculated by taking into account the frame exchange durations.

The real benefits of the Regular Channel Access are evident from the measures of the performance indicators. It is demonstrated that the collocated systems based on the legacy medium access protocol, without special treatment, experience events like interference as well as collisions due to which the performance of the systems degrades immensely which would not happen if the systems are operating alone. It is also demonstrated that this drawback can be overcome by the RCA method, on the one hand, by clear separation of the channel access in the time domain resulting in reduction of those events and on the other hand, by a proportional share of air time. The handling of dynamic features becomes apparent when the intelligent and cognitive cycle of *sense-analyse-decide-act* is embedded in the radio system by means of modeling the framework of spectrum sensing and the adaptive RCA. In such a case, the interference and collision events are mitigated, partially or completely based on the algorithms, resulting in promising improvement on the performance indicators.

It is a well known fact that the HCCA is suitable for applications like voice and video. Similar benefits in the RCA method, which is based on the HCCA, are achieved in case of collocated systems. In a HCCA enabled system, QoS-aware traffic scheduling, based on the user priority (UP) and/or traffic specification (TSPEC) parameter values for the requested MSDU, shows great merits to satisfy QoS requirement. Multi-layer scheduling, i.e., QoS-aware scheduling on top of the RCA (i.e., coexistence aware scheduling) would satisfy both requirements. In coexistence aware scheduling, the estimated resource allocation (RA) period would subdivide into several zones based on the reliability of transmission on those zones from the perspective of being interfered and collisions probability. Frames from different applications are then scheduled in the different zones based on their QoS requirement. For example, an application with lower delay bound (e.g. VoIP) is scheduled at the beginning of the RA period and application with lower loss ratio (e.g. FTP) is scheduled at the middle of the RA period.

10.3 Potential Future Work

In the following, further potentials are identified on the extension and evaluation of the spectrum sharing algorithm presented in this thesis. With respect to the application scenario, it would be useful to investigate a mixed application model and its treatment with a coexistence aware scheduling method, which can be realized as an added value to the RCA method, to provide the QoS assurance in the coexistence scenarios.

In the case of 802.11, the common idea, that higher throughput can be obtained by aggregating the smaller frames to make a larger frame for a common destination and sending the same information, is applicable. It reduces the air-time spent for overhead shown in Chapter 7.

With respect to the IEEE 802.16h system, the system performance evaluation of the heterogeneous coexistence scenario, where the other system is an IEEE 802.11 DCF based or RCA enabled IEEE 802.11 system, is required. Note that the IEEE 802.16h system is meant to operate in the unlicensed band and expected to include a listen-before-talk method. An RCA enabled IEEE 802.16h system is important to be investigated as well. Such a case is, in some extent, similar to the homogeneous scenario with two RCA enabled IEEE 802.11 systems.

It is quite interesting to evaluate the performance of the spectrum sharing concepts and algorithms described in Section 8.7, where the IEEE 802.11 DCF based WLAN system is considered. This algorithm assures the backward compatibility. The concept of the mathematical model provided in [79] and [39] can be extended to calculate the individual and aggregated throughputs of the coexisting systems in this purpose. The similar mathematical extension is also possible to calculate the legacy IEEE 802.11 system's throughput in case of a heterogeneous coexistence scenario with IEEE 802.16 system as described in Section 9.3.2 to compare against the simulation results provided.

With respect to the overlapping coverage scenario, this thesis evaluates the full overlapping case. Moreover, all the evaluations consider the channel model with only pathloss. It would be useful to evaluate the partially overlapping case as well as the scenarios with all the three channel model components: pathloss, shadowing and multipath applying the proposed RCA method with and without cooperative spectrum sensing.

Though the RCA method is evaluated for IEEE 802.11 and IEEE 802.16 based systems, it does not mean that the concept is limited to those two technologies. Principally, it could be extended for spectrum sharing between other technologies, for example, between IEEE 802.11 and IEEE 802.15 based networks in time domain or between OFDMA based IEEE 802.16

and LTE networks in time-frequency combined domain.

10.4 Final Statement

The outcome of the thesis demonstrates the clear benefit of the hypothesis and the design framework which are considered. This thesis is the basis for further research related to the design of spectrum sharing, where one or more than one of the following are considered: cooperative communication, cognition, adaptation, software updates and policy updates. The observations and the techniques used in the proposed RCA method will add a new potential to be further harnessed not only by the academia, but also by the standard bodies as well as the related parties. Adaptability of the generic rules for air time sharing by the different wireless systems in their MAC protocols increases the aggregated performance by mitigating the destructive mutual interference in the coexisting scenarios.

APPENDIX A

The IEEE Standards

A.1 The IEEE 802.16 Standards and Amendments

Figure A.1 provides a list of the IEEE 802.16 standards highlighting the area of focus and the current status.

In Progress(inP)/ Published(Pub)/ Supersed (S)/ Withdrawn(W)/ Merged (M)/ Current(C)	Final document	Doc type	description	Task group and activity
S	IEEE Std 802.16-2001	STD	Fixed Broadband Wireless Access (10–66 GHz)	TG1
S	IEEE Std 802.16.2-2001	STD	Recommended practice for coexistence	TG2
S	IEEE Std 802.16c-2002	A	System profiles for 10–66 GHz	Tgc
S	IEEE Std 802.16a-2003	A	Physical layer and MAC definitions for 2–11 GHz	TGa
W	IEEE Std 802.16b	A	License-exempt frequencies	TGb
M	IEEE Std 802.11d	A	Maintenance and System profiles for 2–11 GHz (Project merged into 802.16-2004)	TGd
S	IEEE Std 802.16-2004	STD	Air Interface for Fixed Broadband Wireless Access System (rollup of 802.16-2001, 802.16a, 802.16c and P802.16d)	TGd
M	IEEE Std 802.16.2a	A	Coexistence with 2–11 GHz and 23.5–43.5 GHz (Project merged into 802.16.2-2004)	TG
C	IEEE Std 802.16.2-2004	STD	Recommended practice for coexistence (Maintenance and rollup of 802.16.2-2001 and P802.16.2a	TG2
S	IEEE Std 802.16f-2005	A	Management Information Base (MIB) for 802.16-2004	TGf
S	IEEE Std 802.16-2004/Cor 1-2005	A	Corrections for fixed operations (co-published with 802.16e-2005)	TG*
S	IEEE Std 802.16e-2005	A	Combined Fixed and Mobile Operation in Licensed Bands	TGe
C	IEEE Std 802.16k-2007	A	Bridging of 802.16 (an amendment to IEEE 802.1D)	TGk
S	IEEE Std 802.16g-2007	A	Management Plane Procedures and Services	TGk
C	IEEE Std 802.16i	STD	Mobile Management Information Base (Project merged into 802.16-2009)	TGi
C	IEEE Std 802.16-2009	A	Air Interface for Fixed and Mobile Broadband Wireless Access System (It consolidates and obsoletes IEEE Standards 802.16-2004, 802.16e-2005 and 802.16-2004/Cor1-2005, 802.16f-2005, and 802.16g-2007)	TG*
C	IEEE Std 802.16j-2009	A	Multihop relay	TGj
C	IEEE Std 802.16h-2010	A	Improved Coexistence Mechanisms for License-Exempt Operation	TGh
InP	IEEE Std 802.16m	A	Advanced Air Interface with data rates of 100 Mbit/s mobile and 1 Gbit/s fixed. Also known as *Mobile WiMAX Release 2* or *WirelessMAN-Advanced*. Aiming at fulfilling the ITU-R IMT-Advanced requirements for 4G systems.	TGm
InP	IEEE Std 802.16n	A	Higher Reliability Networks	TGn
InP	IEEE Std 802.16p	A	Enhancements to Support Machine-to-Machine Applications	TGp

STD = Standard and/or Revision, RP = Recommended Practice, A/ COR = Amendment / Corrigendum, TG* = TG maintenance

Figure A.1: IEEE 802.16 standards [8]

A.2 The IEEE 802.16 MAC Frame Header

The specifications of the different fields located in the IEEE 802.16 MAC frame header are provided in Table A.1. In the table, *n/a* stands for not applicable and *var* stands for variable.

Table A.1: Different fields of generic MAC header and bandwidth request header

Field	Details	GMH		BRH	
		Length (bits)	Field Value	Length (bits)	Field Value
HT	Header type	1	0	1	1
EC	Encryption control (0: payload not encrypted, 1: payload encrypted)	1	1	1	0
Type	Type	6	n/a	3	n/a
BR	Bandwidth request (the SS requests in the number of bytes of uplink bandwidth for a given CID)	n/a	n/a	19	var
ESF	Extended subheader field (0: ES not present, 1: ES present)	1	var	n/a	n/a
CI	CRC indicator (0: CRC not included, 1: CRC included)	1	var	n/a	n/a
EKS	Encryption key sequence	2	var	n/a	n/a
Rsv	Reserved	1	n/a	n/a	n/a
LEN	MPDU length in bytes, including the header and CRC, if present	11	var	n/a	n/a
CID	Connection identifier of the connection on which the MPDU will be sent	16	var	16	var
HCS	Header check sequence	8	var	8	var
Total		48		48	

A.3 The IEEE 802.11 Standards and Amendments

Figure A.2 provides a list of the IEEE 802.11 standards highlighting the area of focus and the current status.

In Progress(inP)/ Published(Pub)/ Supersed (S)/ Withdrawn(W)	Final document	Doc type	description	Task group and activity	PHY/MAC/higher layer
S	IEEE Std 802.11-1997	STD	IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification - 1,2 Mbps, 2.4 GHz, MAC: CSMA/CA, contention based and free service, PHY: FHSS, DSSS, Infrared	MAC/PHY	P+M
S	IEEE Std 802.11-1999	STD	Supersed IEEE 802.11-1997	MAC/PHY	P+M
S	IEEE Std 802.11-1999 (R2003)	STD	Supersed IEEE 802.11-1999	WG	P+M
Pub	IEEE Std 802.11a-1999 (Amendment 1)	A	Higher Speed PHY Extension in the 5GHz Band, 54 Mbit/s, PHY: OFDM	TGa	P
Pub	IEEE Std 802.11b-1999 (Amendment 2)	A	Higher Speed PHY Extension in the 2.4 GHz Band, 5.5 and 11 Mbps, PHY: DSSS	TGb	P
Pub	IEEE Std 802.11c-1998	A	Bridge operation procedures; included in the IEEE 802.1D standard	TGc	H
Pub	IEEE Std 802.11d-2001 (Amendment 3)	A	Operation in Additional Regulatory Domains, International (country-to-country) roaming extensions	TGd	H
Pub	IEEE Std 802.11e-2005 (Amendment 8)	A	MAC Enhancements (QoS), including packet bursting	TGe	M
W	IEEE Std 802.11F-2003	RP	Inter-Access Point Protocol (2003), Withdrawn February 2006	TGF	H
Pub	IEEE Std 802.11g-2003 (Amendment 4)	A	Further Higher Data Rate Extension in the 2.4 GHz Band, 54 Mbit/s (backwards compatible with b)	TGg	P
Pub	IEEE Std 802.11h-2003 (Amendment 5)	A	Spectrum and Transmit Power Management Extensions in the 5 GHz Band in Europe	TGh	M
Pub	IEEE Std 802.11i-2004 (Amendment 6)	A	MAC Security Enhancements	TGi	M
Pub	IEEE Std 802.11j-2003 (Amendment 7)	A	4.9 GHz-5 GHz Operation in Japan	TGj	H
Pub	IEEE Std 802.11k-2008	A	Radio Resource Measurement,	TGk	M
Pub	IEEE Std 802.11n-xxxx	A	Higher throughput improvements using MIMO	TGn	P+M
Pub	IEEE Std 802.11p-xxxx	A	WAVE—Wireless Access for the Vehicular Environment	TGp	P?+M
Pub	IEEE Std 802.11r-2008	A	Fast Roaming, Fast Basic Service Set (BSS) Transition	TGr	M
InP	IEEE Std 802.11s-xxxx	A	Mesh Networking, Extended Service Set (ESS) by Wireless Distributed System (WDS)	TGs	M
Cancelled	IEEE Std 802.11.2	RP	Wireless Performance Prediction (WPP)—test methods and metrics Recommendation	TGT	M
InP	IEEE Std 802.11u-xxxx	A	InterWorking with External Networks: goal: to allow a common approach to interwork IEEE 802.11 access networks to external networks in a generic and standardized manner	TGu	M
InP	IEEE Std 802.11v-xxxx	A	Wireless Network Management	TGv	M
Pub	IEEE Std 802.11w-xxxx	A	Protected Management Frames	TGw	
Pub	IEEE Std 802.11y-2008	A	650-3700 MHz Operation in USA	TGy	
InP	IEEE Std 802.11z-xxxx	A	Extensions to Direct Link Setup	TGz	
Pub	IEEE Std 802.11-2007	STD	A new release of the standard that includes amendments a, b, d, e, g, h, i & j.	TGma	P+M+H
InP	IEEE Std 802.11aa-xxxx	A	Video Transport Streams	TGaa	
InP	IEEE Std 802.11ac-xxxx	A	Very High Throughput <6GHz	TGac	
InP	IEEE Std 802.11ad-xxxx	A	Very High Throughput 60GHz	TGad	
InP	IEEE Std 802.11ae-xxxx	A	QoS Manangement	TGae	
InP	IEEE Std 802.11af-xxxx	A	TV Whitespace	TGaf	
InP	IEEE Std 802.11-xxxx	STD	802.11 Accumulated Maintenance Changes	TGmb	

STD = Standard and/or Revision, RP = Recommended Practice, A/ COR = Amendment / Corrigendum

Figure A.2: IEEE 802.11 standards [7]

A.4 The IEEE 1900.x Standards

In the following, the working groups related to the IEEE 1900.x standards are briefly discussed.

- **IEEE 1900.1 Working Group:** This WG is working on terminology and concepts for next generation radio systems and spectrum management to develop a standard which provides technically precise definitions and explanations of key concepts. The standard is published as IEEE 1900.1 standard [65]. The standard provides detailed explanations on next generation radio systems and spectrum management technologies from different perspectives, and also describes how these technologies interrelate.
- **IEEE 1900.2 Working Group:** This WG is working on providing a comprehensive guideline for interference and coexistence analysis and already has published the IEEE 1900.2 standard [64]. This standard provides technical guidelines for analyzing the potential for coexistence or in contrast interference between radio systems operating in the same frequency band or between different frequency bands.
- **IEEE 1900.3 Working Group:** dissolved.
- **IEEE 1900.4 Working Group:** This WG has published the IEEE 1900.4 standard [67] on architectural building blocks for optimized radio resource usage in heterogeneous wireless access networks. The standard defines the building blocks comprising (i) network resource managers, (ii) device resource managers, and (iii) the information to be exchanged between the building blocks, for enabling coordinated network-device distributed decision making that will aid in the optimization of radio resource usage, including spectrum access control, in heterogeneous wireless access networks.
- **IEEE 1900.5 Working Group:** This WG is working on defining a set of policy languages, and their relation to policy architectures, for managing the features of cognitive radios for dynamic spectrum access applications. The initial work concentrates on standardizing the features necessary for a policy language to be bound to one or more policy architectures to specify and orchestrate the functionality and behavior of cognitive radio features for dynamic spectrum access applications; future additional tasks will build on this foundation to standardize how this is done in greater detail, paying special attention to interoperability concerns.
- **IEEE 1900.6 Working Group:** This WG is working on defining the

logical interface and supporting data structures used for information exchange between spectrum sensors and their clients in radio communication systems, in an abstract level without constraining the sensing technology, client design, or data link between sensor and client.

APPENDIX B

Simulation Platform openWNS

In this appendix, a comprehensive overview of the simulation platform, open Wireless Network Simulator (openWNS) is provided. The results presented in Chapter 5, 8 and 9 are produced by extending this simulation tool. The main structure and components are shown in Figure 6.7.

B.1 Simulation Core

The core part of the simulator provides the basic functionalities required for the discrete event stochastic simulation, as described briefly in the following.

B.1.1 Event Scheduler

The event scheduler has a two dimensional data structure, where in one dimension, each specific simulation time is stored, and in the other dimension, the number of events that are queued for each specific simulation time are stored. Function and Bind libraries from Boost C++ [2] are used to model the event scheduler.

B.1.2 Random Number Generator and Distributions

The random number (RN) generator used in the openWNS simulator is based on the Mersenne twister pseudo-random number generator. In this context, one of the implementations of Mersenne twister generator, called `mt19937` by the Boost Random library is used. `mt19937` is chosen by considering the quality, performance and memory requirement. The cycle length for `mt19937` is $2^{19937}-1$, determining high quality. The performance is determined by the speed of RNs generation, which means the number of RN generation per unit CPU time or in the other way, the CPU time taken for each RN generation. `mt19937` is tested as a fast generator as given in [14]. The approximate memory requirement for `mt19937` is 625 * sizeof(`uint32_t`). `uint32_t` is an unsigned int that requires 32 bits of memory space.

The Boost random library is used in openWNS, on the one hand for having several distributions like Bernoulli, Cauchy, Exponential, Normal, Log-Normal and Uniform, and on the other hand, it has its own implementation for Poisson, Ricean, Pareto, Erlang and Binomial distributions [42].

B.1.3 Statistical Evaluation

The Statistical evaluation method in the simulation is generally divided into two parts: one part is the measurement source which is meant for collecting the measurement values and providing the timestamps and context information for the respective values. Another part is the evaluation framework, whose tasks are to sort the measurements based on context on the one hand, online evaluation according to the evaluation type, on the other hand.

The measurement source is considered as the probing location in the simulator, which can be defined in the model with the definition of the context. The context is included to facilitate the evaluation later. The context of a measurement is used as the additional information which helps sorting the measurement based on the context. For example, a scenario consisting of 10 IEEE 802.11 stations is assumed. Delay measurements in the MAC layer consist of all delays experienced by all the stations. Here, during the measurement source modeling, the context definition is provided to add the station id (e.g., MAC-ID). This helps later during the evaluation to sort the delays according to the station id. The evaluation framework is created during the configuration time in the configuration setup where sorting criteria, evaluation characteristics (like settling time) and evaluation type are defined. It is worth mentioning that different evaluation models exist in openWNS like *PDF* and *Moments*. PDF can be used to get the results for the distribution function, the complementary distribution function, and the probability function of a given random x-sequence. Moments can be used for simple statistical evaluation like mean, variance, skewness etc.

B.1.4 Configuration

The configuration of simulation scenarios is done by the object oriented Python programming language [12]. The features like composition, inheritance and polymorphism of the object oriented programming language show their advantages during the configuration of simulation scenarios. Functional composition of a node from multiple layers, functional composition of a layer from multiple functional modules (functional unit) are widely used in openWNS. Inheritance and polymorphism is generally used during creating a special kind of station by inheriting the general features from a basic one and by adding the special features exploiting the polymorphism. For example, an IEEE 802.11 basic transceiver is defined, and from this basic transceiver, access points and user stations are derived which have special features, like the AP has to sent Beacon frames and stations have to scan for Beacon frames. Scenarios are composed of several nodes, which are configured by control structures like for-loop, etc. Each simulation module, for example cyclic redundancy check (CRC), Error Model, etc., has a default configuration and is subject to parameterization.

B.2 Simulation Framework

As the name suggests, the simulation framework provides the fundamental building structure for the simulator. An idea similar to software design patterns [50] can be identified in the forming of the simulation framework. It provides the facility to reuse simulation models in different extents, where models are suitable and fit the concept. This makes the process of development of protocol layers and simulation models much easier. In this direction, the simulation protocol building block and its common interfaces are defined and described in the following. This building block is denoted as 'Functional Unit (FU)'; a group of interconnected FUs builds a Functional Unit Network (FUN), realized as forming a protocol stack in the node-component model.

B.2.1 Node Model: Functional Unit Network

The node-component model as shown in Figure 6.7 is followed in openWNS, where each station is defined as a node. The node is composed of components, which are analogous to protocol layers like the OSI/ISO reference model, for example as shown in Figure 2.3. In the simulation framework, those components are defined as simulation modules. Some of the specific simulation modules are described in Section B.3.

In openWNS, the basic data unit that is transmitted among the FUs is called compound. The compound is similar to a protocol data unit (PDU) [82]. In the OSI concept of 'service provider- service user model', a data unit transmitted among the OSI layers is defined as PDU for given layer, which is composed of service data unit (SDU) from the upper layer and protocol control information (PCI). This PDU is then considered as SDU for next lower layer. During the flow from lower to higher layer, the PCI parts are extracted and the remaining parts are passed to the next higher layer. Analogously, the data unit transmitted among FUs, the compound, is modified in FUs by adding control information on outgoing compounds and reinterpreting the added control information for incoming compounds. This control information is called *commands*. For example, the Preamble

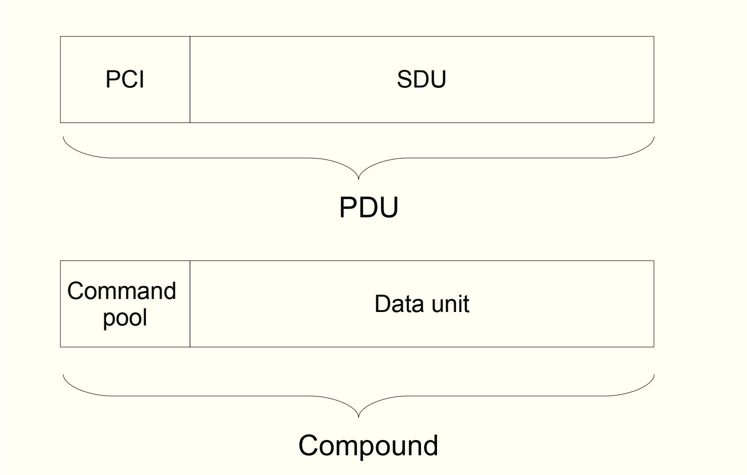


Figure B.1: Protocol data unit and compound concepts [47]

Generator FU in WLAN adds the frame ID of the upcoming frame to which the preamble belongs to as control information. Commands added by one FU in one FUN can be interpreted and used by other FUs either within same FUN or in the peer FUN. A set containing all the commands added by all the FUs within a FUN is called *command pool*, or in other words, the command pool is the union of all commands. A detailed description on command and command pool is given in [47, 92]. Figure B.1 shows the concepts of PDU and compound in openWNS.

B.2.2 Functional Unit

In openWNS, the protocol layers correspond to OSI/ISO layers and these protocol layers are assembled from reusable protocol basic building blocks, mentioned as FUs. The granularity and interfaces of these FUs are very carefully defined, so that on the one hand, they are sufficient enough to handle each protocol functions, and on the other hand they can be connected to build a larger systems based on these interfaces. Note that protocol layers are generally handling different kind of functionalities which are very different from each other like flow control, error handling, segmentation and reassembly and so on. To model these different functions, a set of Functional units is required to be developed from the base FU architecture. Figure B.2(a) shows the FU with its interfaces. The interfaces that are used by the functional unit are: Data handling, Flow control, Management, and Custom.

Data Handling Interface: Every FU is able to handle data. As already discussed, in openWNS the basic data unit that is transmitted among the

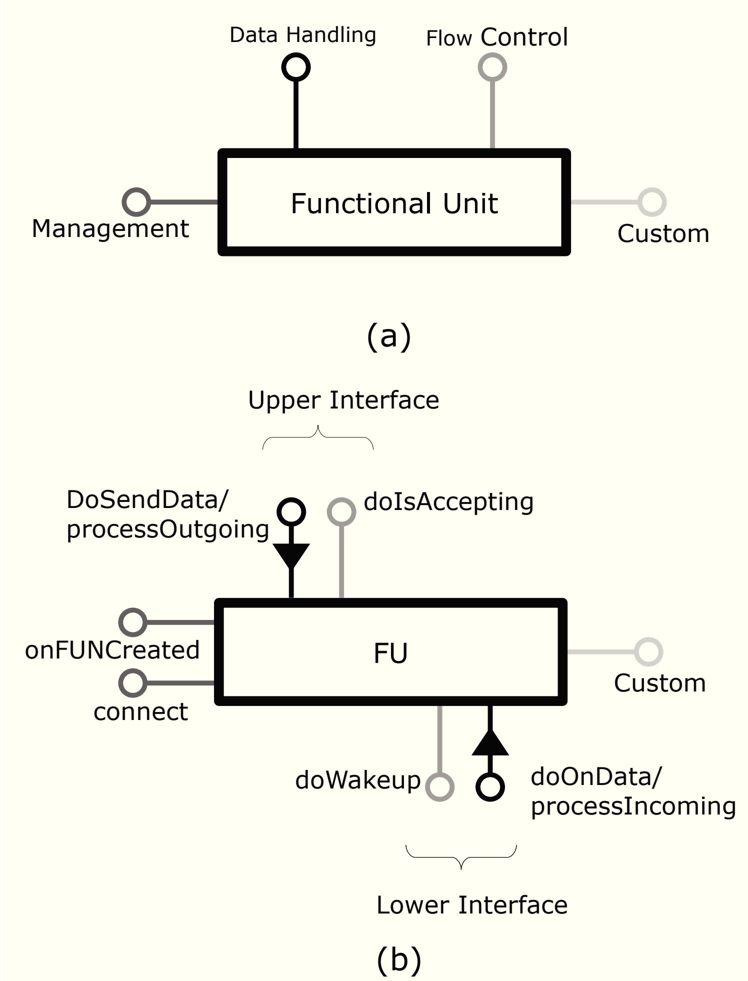


Figure B.2: Functional Unit and its Interfaces

FUs is called a compound. As a part of a protocol layer, a FU can receive compounds for processing in two cases: before and after such a compound has been transmitted over a channel (wired or wireless). The cases are referred as outgoing and incoming data flow respectively. The interface provides services for accepting data in both directions by means of two different methods which also helps the FU to separate compounds coming from different flows: `doSendData(Compound)` for compounds in the outgoing flow and `doOnData(Compound)` for compounds in the incoming flow as depicted in Figure B.2(b).

Flow Control: There are several reasons for a FU not to accept compounds, as described in [47, 92], however, limited resources of the physical layer are directly correlated to all the reasons. That is why an intra layer flow control method is modeled in FUs for outgoing flows. The implementation of this flow control mechanism is realized with two methods `doIsAccepting(Compound)` and `doWakeup()` as shown in Figure B.2(b). Upper FUs ask lower FUs before they send outgoing compounds by extending the first method. Flow control for incoming flows is not necessary.

Management: The management interface provides the support to manage the composition of a functional unit network (FUN). The FUN is the framework which holds a number of interconnected FUs, realized as forming a protocol stack in the node-component model. Generally the management interface has two methods: `connect(FunctionalUnit)` and `onFUNCreated()`.

Custom Interface: OpenWNS provides an optional interface named custom interface, under which additional interfaces can be defined to provide better system performance in the context of optimization. An example of a custom interface in the buffer functional unit can be `getLength`, which provides the length of the buffer. This can be used by the other FU to select a particular buffer depending on its length, for example during scheduling.

B.2.3 Layer Development Kit

The Layer Development Kit (LDK) is a set of tools for building protocol layers out of functional units (FUs). It provides several ready-to-use FUs realizing different protocol functions, like ARQ, buffer, scheduler, multiplexer, de-multiplexer, etc. New protocols can be easily built by selecting appropriate FUs from the LDK. It is also promoted to contribute to the LDK by extracting the generic parts of the protocol functions when possible. It will increase the number of reusable components within the LDK.

B.3 Simulation Modules

Some simulation modules are described briefly in the following which are regarded in this thesis.

B.3.1 Traffic Model

There are two points to be mentioned about the traffic generator module of openWNS: one is the traffic generator itself which generates packets, and another is the binding which adapts the traffic generator to the desired lower layer. Binding binds the traffic generator in the source side and a corresponding *Listener* binding collects the packet statistics in the sink side of that particular layer. In openWNS, binding can be possible in three layers.

- Data Link Layer (DLL)

- Network Layer (IP)
- Transport Layer (TCP, UDP)

In this thesis work, the IP binding is used in a way that the binding is aware of the IP addresses of the source and sink node. It is worth mentioning that an IP overhead of zero is considered in this thesis, unless stated otherwise, as the impact of the routing protocol is not taken into consideration.

Three different traffic models are available as following:

- Simplistic Point Process (PP) models
- Markov-Modulated Poisson Process (MMPP) models
- Autoregressive Moving Average (ARMA) models.

In this thesis, simplistic point process is used to model Constant Bitrate and Poisson distributed traffic. A fixed interarrival time and a fixed packet size is used in the PP model to realize the G.711 [43] VoIP traffic and a negative exponentially distributed interarrival time and a fixed packet size is used to realize the best effort data traffic.

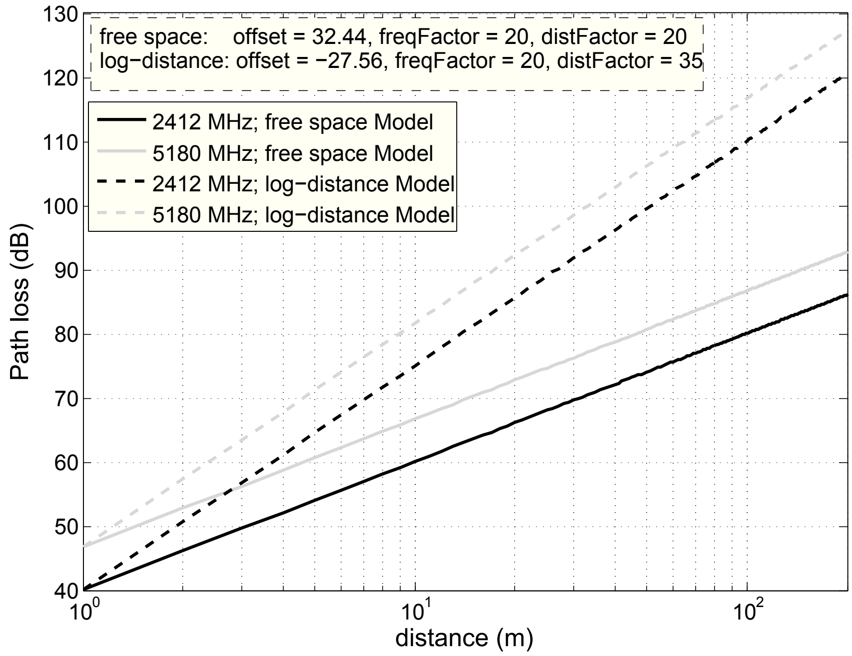


Figure B.3: Path loss model

B.3.2 Channel Model

The overall channel model supported by openWNS to calculate the received signal power for every transmission is defined by the following equation

$$P_R = P_T - L_{PL} - L_{Sh} - L_{FF} + G_T + G_R \tag{B.1}$$

where, P_R is the received power, P_T is the transmitted signal power, L_{PL}, L_{Sh} and L_{FF} are the losses due to path-loss, shadowing and fast fading respectively, and G_T and G_R are the antenna gains at the transmitter and the receiver. Note that the equation is provided in dB.

However, the radio channel propagation model can be independently chosen for each transceiver type pair. This can be used, for example, to have different models for different moving speeds or to define line-of-sight (LOS) and non-line-of-sight (NLOS) connections [42].

Path-loss is considered in this thesis. Several models to calculate the path loss between transmitter and receiver are available. Those are:

- Constant (distance independent)
- Free space
- Single slope
- Multi slope

The free space and the log-distance single-slope path loss model are discussed in Section 2.3.1. In this thesis, the log-distance single-slope path loss model, as shown in Equation 2.14, is considered with γ equal to 3.5, representing the residential/indoor scenario. Figure B.3 shows the pathloss against distance for the log-distance single-slope path loss model and free space path loss model for two different frequency channels located in the 2.4 GHz and the 5 GHz ISM bands. Equation 2.10 gives the free space model.

B.3.3 Interference Calculation Model

The interference calculation engine is using the received power level to calculate the Signal to Noise plus Interference Ratio (SINR). The basic calculation principle of SINR is given in the following. An example scenario shown in Figure B.4.(a) is considered in this case, where RX is receiving the intended signal from the TX_1 and the transmissions of TX_2 and TX_3 are interfering the intended signal. Received power levels are denoted as P_1, P_2 and P_3 respectively. The timing diagram of the intended signal and interfering signals are shown in Figure B.4.(b). In the model, the SINRs for

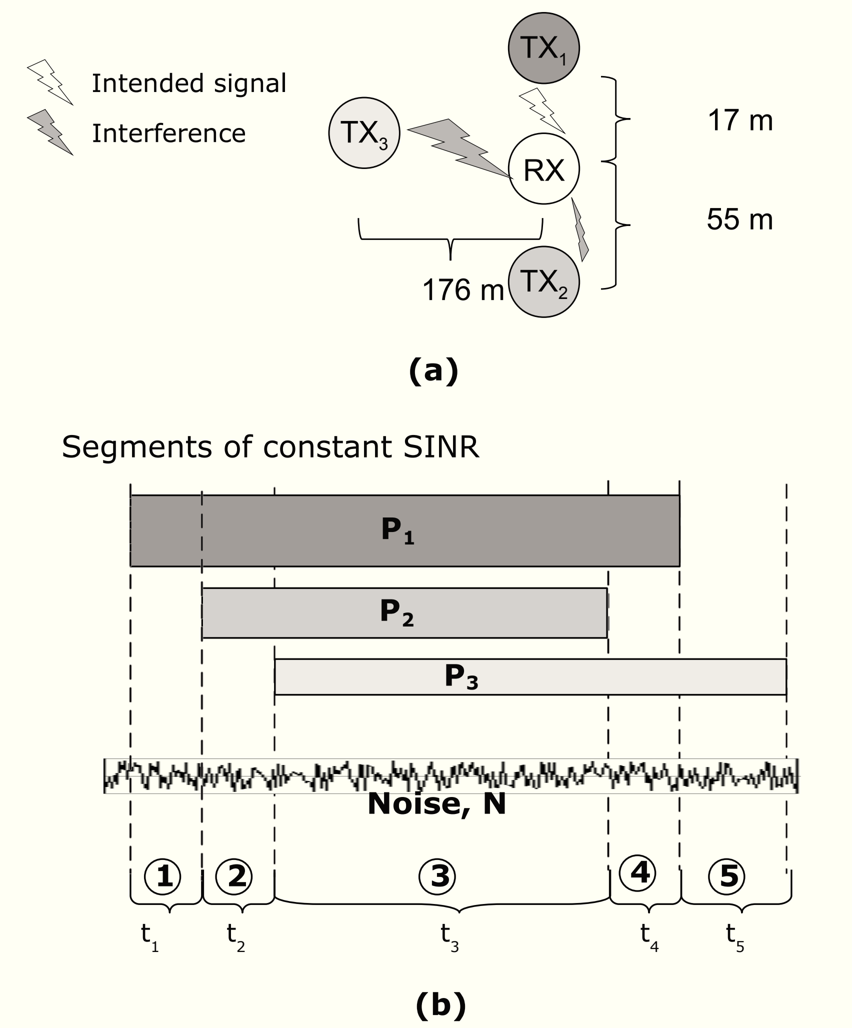


Figure B.4: Interference Calculation Model

each segment are calculated according to Equation 2.15 and those are as follows:

$$\begin{array}{cc} SINR_1 = \frac{P_1}{N}, & SINR_2 = \frac{P_1}{P_2+N} \\ SINR_3 = \frac{P_1}{P_2+P_3+N}, & SINR_4 = \frac{P_1}{P_3+N}. \end{array} \tag{B.2}$$

Then the time-weighted average (TWA) SINR is estimated by averaging SINRs for all segments over the total time duration as given in the following

$$SINR = \frac{SINR_1 * t_1 + SINR_2 * t_2 + SINR_3 * t_3 + SINR_4 * t_4}{t_1+t_2+t_3+t_4}. \tag{B.3}$$

B.3.4 IEEE 802.11 Model

The simulation model of IEEE 802.11 is the model of medium access control and physical layer according to the IEEE 802.11 standard. The model is partitioned in three parts:

- **Higher MAC**: this part mainly contains the features of multi-hop 802.11 networks like path selection and is also responsible for coordinating one or more lower MACs. This is not in the focus of this work as static paths are assumed here.
- **Lower MAC**: Most of the 802.11 functionalities are implemented in this part. Details of the lower MAC are given in the following.
- **Convergence**: 802.11 OFDM Physical layer functionalities are provided in this part by means of several Functional Units (FUs). It also provides the FUs for error modelling, frame synchronization and current channel state (has the interface to signal the channel condition to the MAC layer).

There is a management block which has the functionalities for the management plane. It has the FUs for management information bases, e.g., for measuring the Signal to Noise plus Interference Ratio (SINR) and Packet Error Rate (PER). It also has the FUs for Beacon frame transmission, reception and association.

Some additional helping functions like filtering the frames based on type, size, etc. and sorting probe output according to the context are available under the helper FUs.

In the framework of this thesis, the modification and enhancement is done in the lower MAC. Therefore a detailed description on the lower MAC is given as follows.

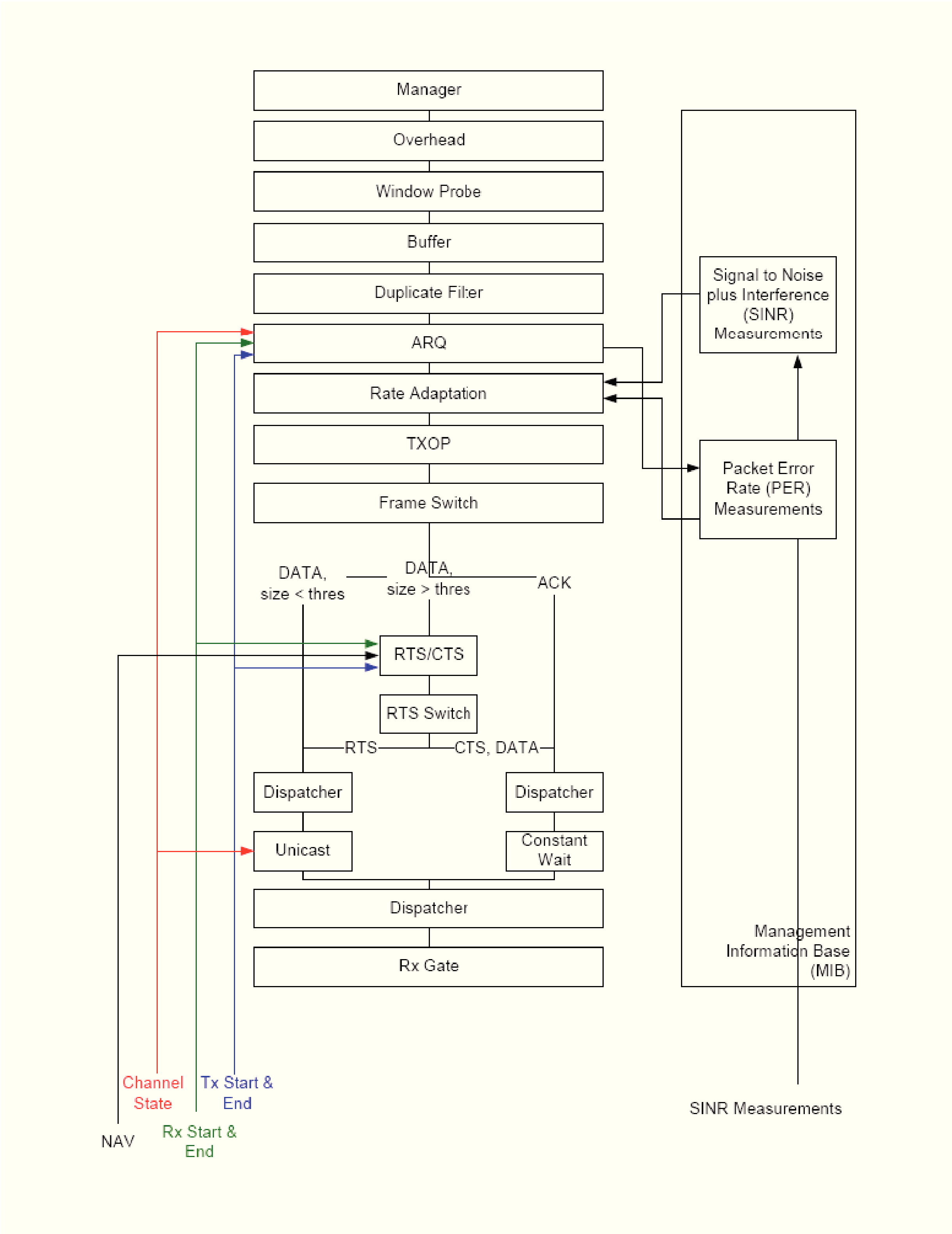


Figure B.5: Lower MAC Functional Unit Networks: 802.11 simulation model (as provided in the simulation package)

B.3.5 Lower MAC: 802.11 DCF Simulation Model

The implementation of the 802.11 MAC using a set of functional units in openWNS is shown in Figure B.5. The brief description of all the functional units from top to bottom are as follows based on [89].

- **Management FU**: This is the management entity for a single IEEE 802.11 transceiver, i.e., the MAC sublayer.
- **Overhead FU**: models a fixed overhead if required during the configuration process.
- **Window Probe**: records measurements for a given time window, which is a configurable parameter called `windowSize`. Window probe measures the throughput in a windowed fashion. Six different values are measured by this probing: incoming, outgoing and aggregated throughput in compounds per second and bits per second. In openWNS, compound is analogous to packet. The values are averaged over `windowSize`.
- **Buffer FU**: as the name indicates, Buffer FU stores data for a certain amount of time, modeling the queue in the MAC layer. The buffer size can be configured as the number of compounds or bits. First In, First Out (FIFO) queue processing strategy is implemented in this functional unit. Special kinds of buffers are also modeled for having special functionality. For example, a dropping buffer drops the compound based on its dropping strategies when the buffer is full. The dropping strategies tell the buffer from where it will drop the compound. So, dropping buffer can drop the compound either from the tail or from the front of the queue. The buffer can be either fixed size or variable size. A fixed size buffer is called bounded buffer. A buffer can contain a single queue or a set of queues. When a set of queues is used for buffering, then this type of buffer is called multi-buffer or multi-queued buffer. By default, a fixed and dropping buffer is modeled in the Buffer FU of Figure B.5. This is inherited from the Buffer super FU from the Layer Development Kit (LDK).
- **Duplicate Filter FU**: The functionality of this FU is used to retransmit the compound in case of compound loss, for example, due to collision during the transmission from the sender to the receiver. It keeps the last compound until receiving the positive signal from the ARQ.
- **ARQ FU**: models the error control method, Automatic Repeat reQuest (ARQ). ARQ generally uses positive acknowledgments, negative acknowledgements and timeouts to control errors. When the receiver

receives an error-free compound, then it sends a positive acknowledgment to the sender. In case of getting an erroneous frame, the receiver sends a negative acknowledgement to the sender or sends nothing. The sender retransmits the compound after getting either a negative acknowledgement from the receiver or after the expiration of its timeout. Different standardized ARQ methods are: Stop-and-wait, go-back-N and selective repeat ARQ. The ARQ FU in Figure B.5 models the stop-and-wait ARQ method and is used by all nodes' transceivers (transmitter and receiver). Stop-and-wait ARQ is the simplest and widely used error control mechanism. In this case, the source transmits a compound and waits until it receives an acknowledgement from the receiver. The source does not send any further compound until it receives an acknowledgement. That is why this is called Stop-and-wait ARQ. If the source does not get any acknowledgement from the receiver within certain time, due to the loss of the compound on the channel or the discartion of received erroneous frames by the receiver, then it retransmits the same frame again. This is inherited from the ARQ super FU from the LDK.

- **Rate Adaptation (RA) FU**: is used to adjust the current data transmission rate based on the observed Signal to Noise plus Interference Ratio (SINR) and Packet Error Rate (PER) as shown in Figure B.5. It has the option to be configured to switch on and off.
- **TXOP FU**: this is used to provide the transmission opportunity (TXOP) duration, which is according to the IEEE 802.11e enhanced DCF (EDCF). It is important to note that the existing MAC DCF model is not pure DCF. During a contention period, the stations can also get a TXOP by contention, which is referred to as contention-based TXOP, described in Section 2.1.4.5. However, the functionality of TXOP can be switched off by means of configuring the TXOP duration to zero.
- **Frame Switch FU**: this is used to deliver the compound to the appropriate FU based on the type and size of the compound. If the size of the DATA compound is greater than a threshold, then it forwards to the RTS/CTS FU, otherwise it is delivered to the Dispatcher FU.
- **RTS/CTS FU**: models the RTS/CTS mechanism to solve the hidden node problem. The principle of the RTS/CTS mechanism is discussed in 2.1.4.
- **Dispatcher FU**: is used for multiplexing and de-multiplexing of compound between FUs. The frame switch forwards the acknowledgement

to the constant wait dispatcher. Next to the RTS/CTS FU, there is another FU named RTS Switch.

- **RTS Switch FU**: models the functionality similar to the Frame Switch. It delivers RTS frames to the unicast dispatcher and CTS/DATA frames to the constant wait dispatcher.
- **Rx Gate FU**: is used to receive the compound.
- **Unicast FU**: models backoff functionality, which is discussed in Section 2.1.4.3.
- **Constant wait FU**: models the constant waiting time, for example, different Interframe Spaces (IFSs) before delivering the compound to the Rx gate.

B.3.6 IEEE 802.11e Model

The implementation details of each FU are given below. Each FU implements several interfaces. The description and functionality of each of the interfaces has been given in Section B.2.

The interfaces of the **QoS CF-Poll Functional Unit** are:

- `onFUNCreated`: This interface initialized friend FUs of the QoS CF-Poll FU, which are Manager and TXOP11e FUs. This FU provides certain parameters based on the type of station. For the HC, it provides the value of the start delay for sending the QoS CF-Poll frame and periodic service interval, which in the case of the RCA algorithm is RCA_Interval.
- `processIncoming`: This interface assures whether the receiving frame is the QoS CF-Poll frame. If the frame is the QoS CF-Poll frame, then the station receives the frame. After that, it calls the method named `onCFPollReceived` of the TXOP11e FU providing TXOP limit so that the TXOP11e FU starts using the TXOP limit.
- `periodically`: This interface gets the number of associated stations from the Association FU. If the number of associated stations is more than 0, then it calculates the transmission opportunity using the formula specified in 2.1.4.7 on HCF Controlled Channel Access.

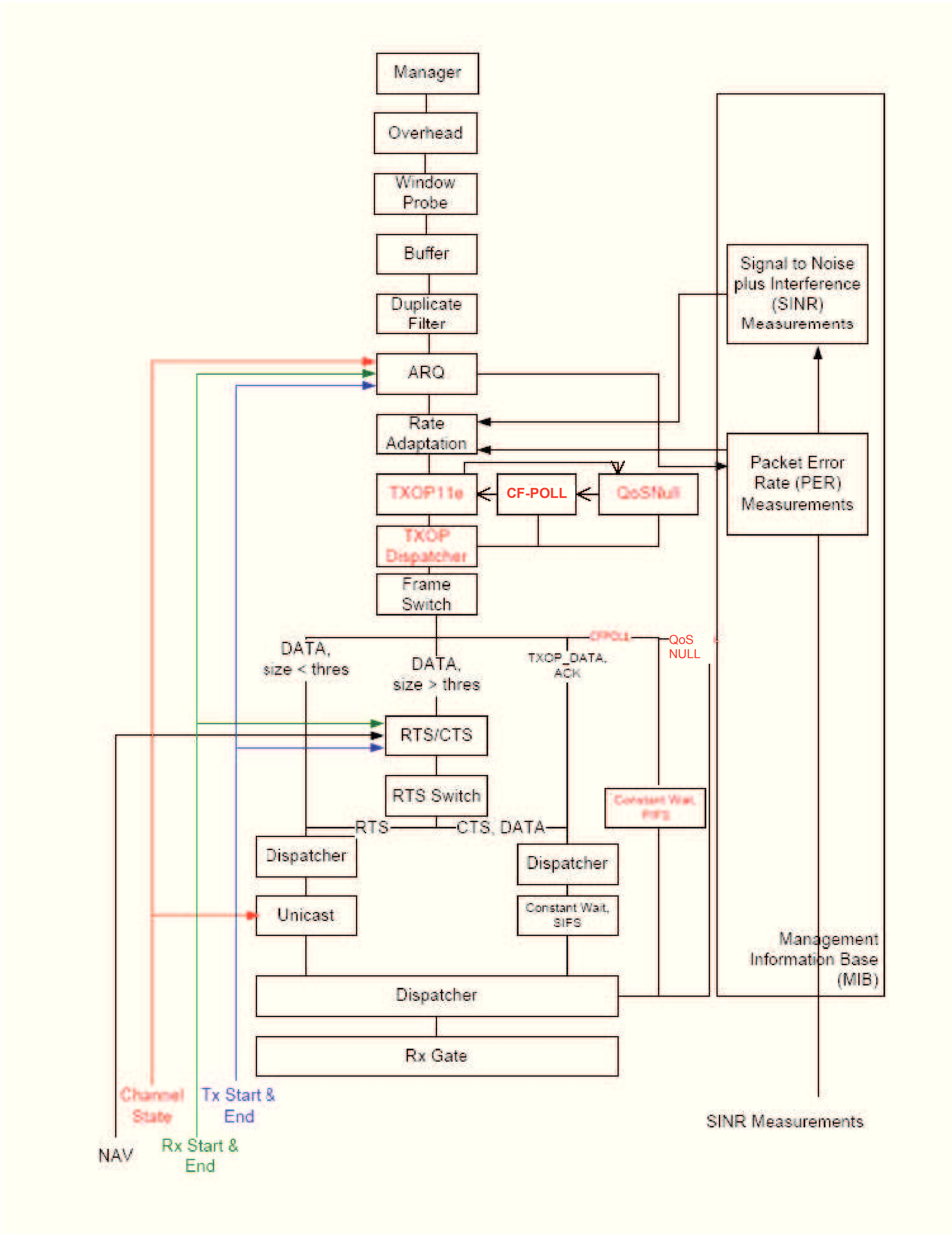


Figure B.6: Functional Unit Network of 802.11e based Access Points and Stations [89]

- `onTimeout`: It calculates the actual transmission opportunity (TXOP) by deducting the duration of the QoS CF-Poll frame, PIFS and the QoS Null frame and sends to each associated station one after another.
- `onQosNullReceived`: This method starts after receiving the QoS Null frame. This method checks whether this is the last station in the cycle or any other station. In the case of the last station, the timeout is not reset but for any other station, the timeout is reset so that the next station can start immediately.
- `calculateSizes`: This method calculates the size of the QoS CF-Poll frame.

The interfaces of the **TXOP11e Functional Unit** are:

- `onFUNCreated`: As like in the QoS CF-Poll FU, this interface assigns the name of the friend FUs. `Manager`, `PhyUser`, `nextFrameHolder`, `RateAdaptation`, and `QoSNull` are the friends of this FU.
- `getSomethingToSend`: This method receives different types of frames. Based on frame types, then it takes certain actions.
- `onTimeout`: This method is called when the timer expires. It is also called when the size of the data is more than TXOP or the current TXOP has ended. At that time, the method named `noNextCompound` of the QoS Null FU is called for sending the QoS Null frame.
- `onCFPollReceived`: This method is called from the QoS CF-Poll FU when the station of that FU receives the QoS CF-Poll frame. The remaining TXOP is calculated by deducting PIFS duration, QoS CF-Poll duration and QoS Null frames duration.

The interfaces of the **QoS Null Functional Unit** are:

- `onFUNCreated`: As with other FUs, this interface assigns the name of the friend FUs. Manager and QoS CF-Poll are the friends of this FU.
- `processIncoming`: Before receiving, it assures that the received frame is the QoS Null frame. Moreover, only the HC can receive this frame. It also keeps track of the source address of the frame. After receiving the frame, it calls the method named onQosNullReceived of the QoS CF-Poll FU so that the called FU can send the QoS CF-Poll frame immediately.
- `noNextCompound`: This method is called from the TXOP11e FU as soon as there is no frame in the buffer or the size of the data is more

than TXOP. The station constitutes the QoS Null frame and sends the frame to the HC after getting called from the TXOP11e FU.

- `calculateSizes`: This method calculates the size of the QoS Null frame.

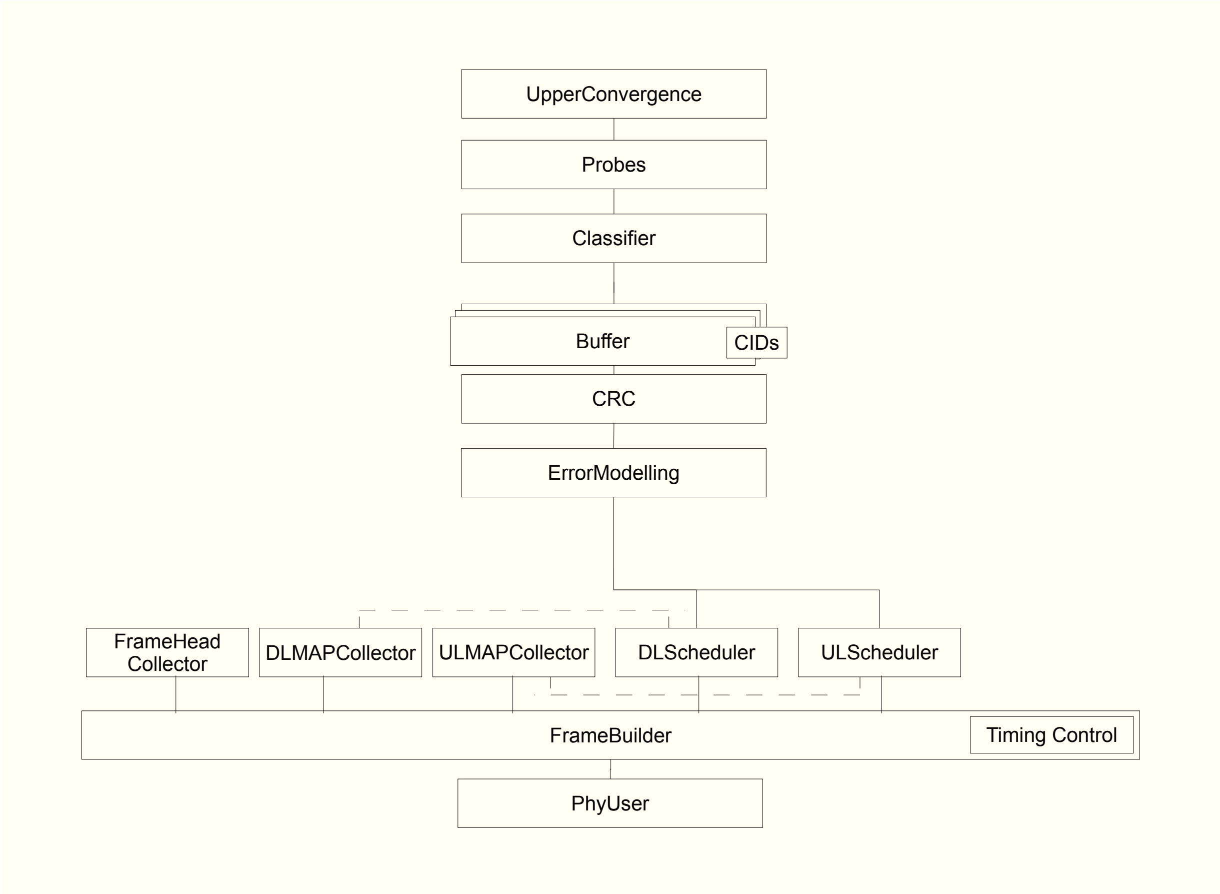


Figure B.7: Functional Unit Networks: IEEE 802.16 BS and SS

B.3.7 IEEE 802.16 Model

Figure B.7 shows the functional unit network of an 802.16 protocol stack which realizes the Base Station (BS) and the Subscriber Station (SS) data plane and the OFDM PHY layer.

The brief description of all the functional units from top to bottom are as follows.

- **Upper Convergence**: is used to write the source and destination MAC address. The Upper Convergence Functional Unit in Layer 2 generally accepts compounds from below and PDUs from above respectively and then forwards them to the corresponding TCP/IP instance and the lower Functional Unit respectively.

- **Probes**: are implemented to measure different performance parameters, like throughput, delay, buffer size, buffer loss ratio, CRC loss ratio, and carrier to interference ratio. There are options to include and implement different new probes in detailed level.
- **Classifier**: creates the connection IDs for new addresses. The connection classifier classifies compounds by using the **Connection Manager**. The connection manager holds a database for registered connections. There are two different classification methods for incoming and outgoing compounds.
- **Buffer**: Queue data that cannot be sent on current frame. A dropping Buffer is used.
- **CRC**: As the name suggests, this FU models the cyclic redundancy check (CRC), meaning that it is used to decide whether the transmission of the compound was successful or failed. In this case, a random test is applied on the Packet Error Rate (PER) of the Packet it is currently inspecting. The PER is provided by the **Error Model FU**. A dropping characteristic of the CRC is used by default, i.e, the CRC does not provide the compound to the next FUs in the 'incoming' chain if its transmission is detected as failed.
- **Error Model**: The Error model functional unit performs the error modeling where the Carrier to Interference Ratio (CIR) for a particular physical modulation and coding scheme (MCS) maps to the Symbol Error Rate (SER). Then, the Packet Error Rate (PER) is calculated from the SER.
- **Frame Builder**: This FU is responsible for building the frame. It is a generic FU in openWNS, which is used to build the IEEE 802.16 frame. The Frame is created with the help of FUs, like Frame head collector, Downlink MAP Collector, Uplink MAP Collector, and Downlink and Uplink Scheduler. **Timing Control**, which is part of the Frame Builder, is responsible for 'activation' of the specified FUs, e.g, Frame head collector, Downlink MAP Collector, etc. and synchronization of time. The Timing Control is a system specific component, i.e., the chronological ordered list of activations is configurable (created from / defined in the configuration) from the point of each system. For example, Figure 2.16 shows two options of frame building, where the random access phase is positioned differently in the frame.

- **Phy User**: It is the interface to the OFDM(A) Phy layer. The Phy User receives all incoming compounds.

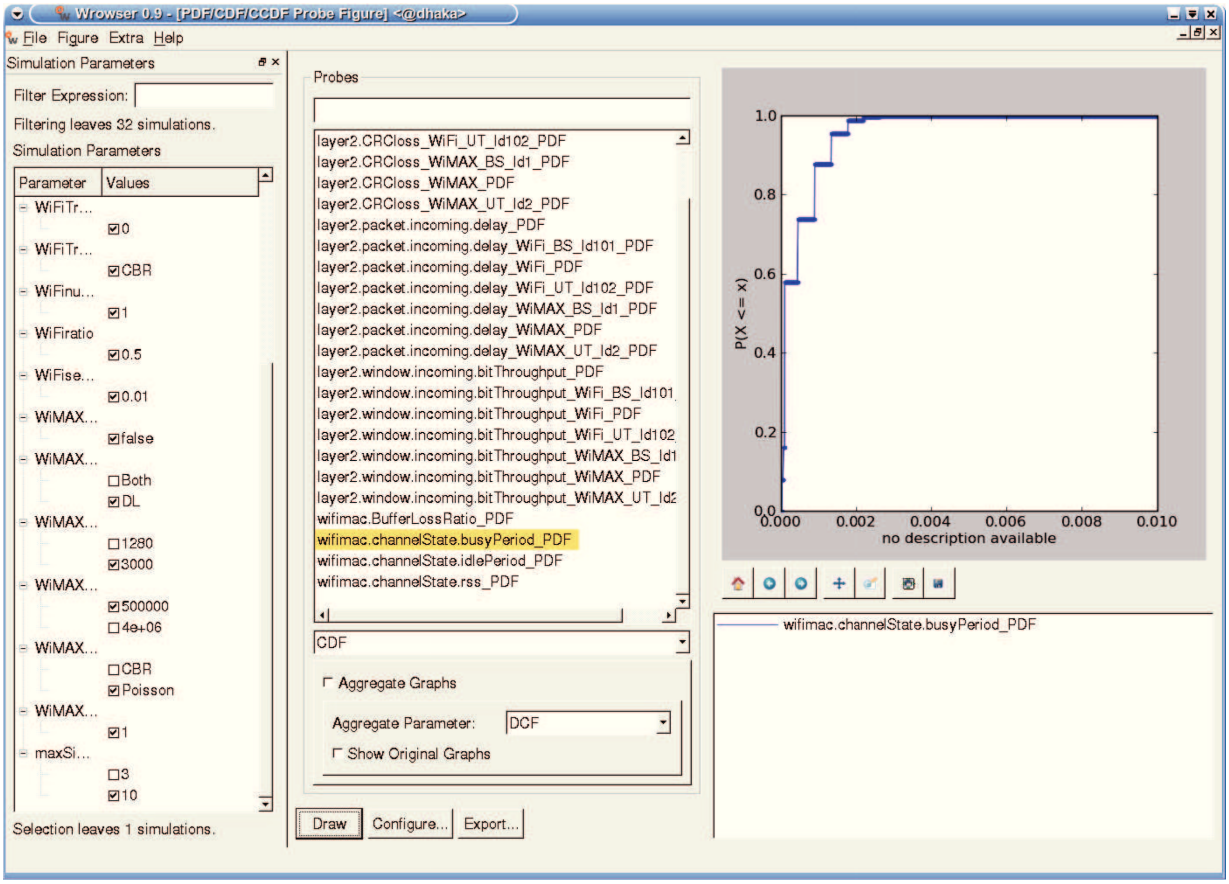


Figure B.8: A snapshot of the Wrowser

B.4 Wrowser

The openWNS simulator has a GUI (Graphical User Interface) tool to plot the graphs generated from the openWNS simulation results. It is called Wrowser (Wireless network simulator Result brOWSER). It makes the process of browsing the results fast and easy. There is a backend tool for wrowser, called probeselector, which is doing the main tasks, like access campaign data from different data sources, represent the fetched campaign data, and generate the graphs. The wrowser generally displays the graphs.

Figure B.8 is an example snapshot of the wrowser tool showing the parameter selection window in the left side, different probes in the middle and an example graph in the right side.

In the framework of this thesis, the data is fetched from probe files in a directory tree (no campaign) and from a Postgres database containing simulation campaigns. There are two different ways how the graphs are constructed: one way is to get a complete graph from each scenario. This is the method used for the histogram-/time-log-graphs from LogEval, PDF, (D)LRE and BatchMeans-probes. Figure B.8 shows the PDF of a busy duration. Another way is to get one graph point from each scenario. This is used for parameter graphs.

APPENDIX C

The Busy and Idle Period Duration Probabilities

C.1 Derivation of the Probabilities of the Busy and Idle Period Durations that are Equal to DATA and ACK Transmission Durations under Collision Case

Let consider a case where a number of frames is collided during the transmissions. In such case, let P_S is the probability that a transmission occurring on the channel is successful. So, (1-P_S) is the probability of collisions.

If a data frame collides and assumed to succeed always in the first retransmission, then the number of busy duration equal to the DATA transmission duration would be,

$$N_D^* = N_D + P_D.(1 - P_S) \tag{C.1}$$

where, N_D is the number of busy duration equal to the DATA transmission duration in 'ideal' case, i.e a data frame is assumed to succeed always in the first transmission, so there is no collisions in the scenario.

In Equation C.1, two terms in the right side are mutually independent.

In case of i number of retransmissions, N_D^* would be

$$\begin{aligned} N_D^* &= N_D + N_D.(1 - P_S) + N_D.(1 - P_S)^2 + N_D.(1 - P_S)^3 + ... \\ &= N_D.\textstyle\sum_{i=0}^{\infty}(1 - P_S)^i \end{aligned} \tag{C.2}$$

As the right part of Equation C.2 is a geometric series, so

$$\begin{aligned} N_D^* &= N_D.\tfrac{1}{1-(1-P_S)} \\ &= \tfrac{N_D}{P_S} \end{aligned} \tag{C.3}$$

Assume that the number of received ACK frames is constant, i.e. $N_A^* = N_A$.

The probability that the busy period duration equal to the DATA transmission duration is as follows.

$$
\begin{aligned}
P_D^* &= \tfrac{N_D^*}{N_D^*+N_A^*+N_{Be}^*} \\
&= \tfrac{\frac{N_D}{P_S}}{\frac{N_D}{P_S}+N_A+N_{Be}^*} \\
&= \tfrac{N_D}{N_D+P_S(N_D+N_{Be}^*)}, \qquad \text{as } N_A = N_D \\
&= \tfrac{N_D}{N_D(1+P_S)+P_S N_{Be}^*} \\
&= \tfrac{N_D}{N_D(1+P_S)}, \qquad \text{taking into account that } N_{Be}^* \ll N_D \\
&= \tfrac{1}{1+P_S}
\end{aligned}
\tag{C.4}
$$

And the probability that the idle period duration equal to the DATA transmission duration is as follows.

$$
\begin{aligned}
P_A^* &= \tfrac{N_A^*}{N_D^*+N_A^*+N_{Be}^*} \\
&= \tfrac{\frac{N_D}{P_S}}{\frac{N_D}{P_S}+N_A+N_{Be}^*} \\
&= \tfrac{\frac{N_D}{P_S}}{\frac{N_D}{P_S}+N_D+N_{Be}^*} \\
&= \tfrac{N_D P_S}{N_D(1+P_S)+P_S N_{Be}^*} \\
&= \tfrac{N_D P_S}{N_D(1+P_S)}, \qquad \text{taking into account that } N_{Be}^* \ll N_D \\
&= \tfrac{P_S}{1+P_S}
\end{aligned}
\tag{C.5}
$$

C.2 Results Evaluation of the Coexistence Scenarios: DCF-DCF, RCA-RCA, and RCA-DCF with Data Traffic

In this section, three different combinations of coexistence scenarios are evaluated. For this evaluation, the existing DCF model and newly implemented RCA model in a stochastic discrete event simulator called Wireless Access Radio Protocol 2 (WARP2) are considered.

Simulation setup: Two systems, each consisting of 5 STAs, are considered for evaluation. Each STA has one data traffic stream which is configured as Poisson distribution. The mean offered traffic in each traffic stream is set up as 0.4 Mbit/s, resulting in an overall offered load of 4 Mbit/s (i.e. 66 % of available bandwidth). The offered load of 4 Mbit/s is considered as a high load condition. Uniform packet length distribution with Min: 250 bytes and Max: 750 bytes is considered. Different simulation runs are conducted with RCA Intervals of 20 ms and 100 ms. The starting point (SP) offset of System 2 is configured as 50 % of the RCA_Interval.

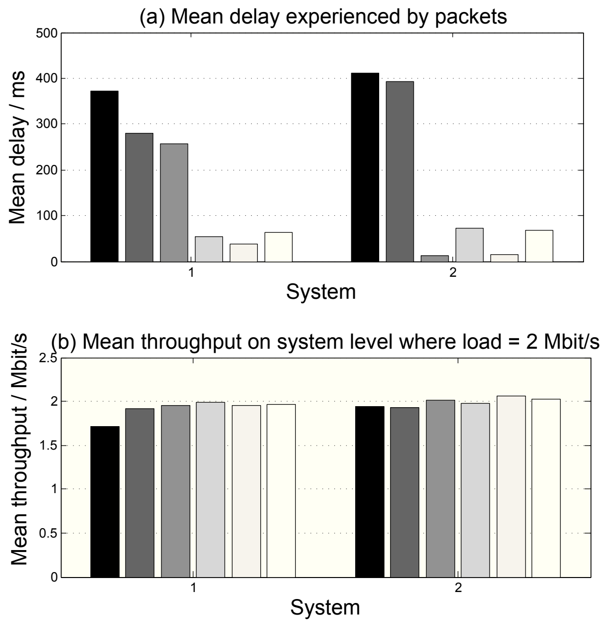


Figure C.1: Simulation results: (a) Mean delay, (b) throughput and (b) packet loss ratio in two coexisting networks following RCA and DCF channel access methods and transmitting data traffic

Results evaluation: Three different combinations of systems based on their channel access techniques are considered in the coexistence scenario: 1. DCF-DCF, 2. RCA-RCA, and 3. RCA-DCF. For example, in case RCA-DCF, the first system follows the RCA method, and the second system follows the DCF. In case of RCA based systems, RCA_Interval is varied for comparison. Figure C.1 shows the mean delay and throughput of the two systems for different cases. The x-axis represents the system number.

Considering the performance metrics, the DCF-DCF case provides the worst performance in this case of high load. It is shown in literature, that the transmission probability in any time slot depends inversely on the offered traffic load even for a stand-alone DCF based system. For a system with less than 50 stations, after the overall traffic load exceeds 65 %, the mean access delay increases sharply and the throughput becomes saturated. After the overall traffic load exceeds 80 %, the mean access delay does not change much.The similar phenomena are also seen in the coexistence scenario of DCF-DCF, which is basically equivalent to a DCF system of 10 stations from the perspective of channel access method.

Applying the RCA method reduces the delays in the systems. However, what is important to see is as following. The lower RCA_Interval of 20 ms results in a high delay compared to the other RCA_Interval cases, basically due to queue buildup in each station. The higher RCA_Interval of 100 ms results in delay around 75 ms due to an average waiting time of packets in each RCA_Interval. The key finding of this test is as following. In the coexistence scenario of RCA-DCF, both systems benefit, however the DCF system benefits more from the traffic diversity of the RCA system. For example, when the RCA system requires only 20 % air-time of the RCA_Interval, the rest 30 % air-time is used by the DCF system opportunistically.

A better performance is achieved by applying the RCA method in the coexistence case compared to the legacy DCF method.

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LIST OF ABBREVIATIONS

AC	Access Category
ACC	Autocorrelation Coefficients
ACF	Autocorrelation Function
ACK	Acknowledgement
AIFS	Arbitration IFS
AP	Access Point
aRCA	Adaptive RCA
ARQ	Automatic Repeat reQuest
ASN	Access service network
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BRH	Bandwidth Request Header
BS	Base Station (IEEE 802.16)
BSA	Basic Service Area
BSS	Basic Service Set
BSSID	Basic service set identification
BWA	Broadband Wireless Access
CBR	Constant Bit Rate
CCA	Clear Channel Assessment
CCDF	Complementary Cumulative Distribution Function
CFP	Contention Free Period
CID	Connection ID
CP	Contention Period
CAP	Controlled Access Phase
CR	Cognitive Radio
CRC	Cyclic Redundancy Check
CS	Carrier Sense (IEEE 802.11)
CS	Convergence Sublayer (IEEE 802.16)
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance

CPS	Common Part Sublayer
CSN	Connectivity Service Network
CTS	Clear To Send
DA	Destination Address
DARPA	Defense Advance Research Project Agency
dB	Decibels
dBm	Decibels related to 1 mW
DCF	Distributed Coordination Function
DFS	Dynamic Frequency Selection
DIEngine	Detection, Identification and Estimation Engine
DIFS	Distributed Coordination Function Interframe Space
DL	Downlink
DLC	Data Link Control
DS	Distribution System
DSL	Digital Subscriber Line
DSSS	Direct Sequence Spread Spectrum
EDCA	Enhanced Distributed Channel Access
EIFS	Extended IFS
EMA	Exponential Moving Average
EP	End point
ESS	Extended Service Set
FCC	Federal Communications Commission
FCS	Frame Check Sequence
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplex
FHSS	Frequency Hopping Spread Spectrum
FSH	Frame Subheader
FU	Functional Unit
FUN	Functional Unit Network
GHz	Gigahertz
GSM	Global System for Mobile Communication
GMH	Generic MAC Header
GW	Gateway

HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
IBSS	Independent Basic Service Set
ID	Identification
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
ETSI	European Telecommunications Standards Institute
IFS	Interframe Space
IP	Internet Protocol
ISI	Inter-symbol Interference
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
kHz	Kilohertz
KPI	Key Performance Indicator
ITU	International Telecommunication Union
LBT	Listen-Before-Talk
LAN	Local Area Network
LDK	Layer Development Kit
LLC	Logical Link Control
LOS	line-of-sight
ms	Milliseconds
μs	Microseconds
Mbit/s	Megabit per Second
Mbps	Megabit per Second
MAC	Media Access Control
MAP	Medium Access Pointer
MCS	Modulation and Coding Scheme
MHz	Megahertz
MIMO	Multiple Input Multiple Output
MLME	MAC Layer Management
MSDU	MAC Service Data Units
NAV	Network Allocation Vector
NLOS	Non-line-of-sight

OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
openWNS	open Wireless Network Simulator
OSI	Open Systems Interconnection
PCF	Point Coordination Function
PCS	Physical Carrier Sense
PDF	Probability Distribution Function
PDU	Protocol Data Unit
PHY	Physical
PIFS	Point Coordination Function Interframe Spacing
PLCP	Physical Layer Convergence Protocol
PLME	Physical Layer Management Entity
PMD	Physical Media Dependent
PPDU	Physical layer Protocol Data Unit
PS	Physical Slot
PSH	Packing Subheader
QAM	Quadrature Amplitude Modulation
QBM	QoS-aware Buffer Management
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RA	Receiving Address (IEEE 802.11)
RA	Random Access (IEEE 802.16)
RA	Resource Allocation (RCA)
RCA	Regular Channel Access
RF	Radio Frequency
RSS	Received Signal Strength
RTG	Receive Transition Gap
RTS	Request To Send
Rx	Receiver
SA	Source Address
SAP	Service Access Point
SCC	Standards Coordinating Committee
SDU	Service Data Unit

SDR	Software Defined Radio
SFID	Service Flow ID
SIFS	Short Interframe Spacing
SINR	Signal to Interference plus Noise Ratio
SME	Station Management Entity
SP	Starting point
SS	Subscriber Station
STA	Station
STI	System Type Identification
TA	Transmitting STA Address
TBTT	Target Beacon Transmission Time
TDD	Time Division Duplexing
TD	Traffic Demand
TDE	Traffic Demand Estimation
TDMA	Time Division Multiple Access
TTG	Transmit Transition Gap
Tx	Transmitter
TXOP	Transmission Opportunity
UMTS	Universal Mobile Telecommunications System
U-NII	Unlicensed National Information Infrastructure
UL	Uplink
VBR	Variable Bit Rate
VCS	Virtual Carrier Sense
VoIP	Voice over IP
WG	Working Group
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WME	Wireless Multimedia Extension
XG	neXt Generation

Table D.1: List of used mathematical symbols

Symbol	Area	See Page	Meaning
P_R	ChannelModel	39	received power
P_T	ChannelModel	39	transmitted power
G_T / G_R	ChannelModel	39	antenna gain at the transmitter / the receiver
L_{path}	ChannelModel	39	overall propagation loss factor
L_{PL}	ChannelModel	39	loss factor due to large scale pathloss
L_{Sh}	ChannelModel	39	loss factor due to shadowing
L_{FF}	ChannelModel	39	loss factor due to multipath fast fading
λ	ChannelModel	40	wavelength in meters
f	ChannelModel	40	frequency
c	ChannelModel	40	light speed in meters/s
d	ChannelModel	40	distance
d_0	ChannelModel	40	close-in reference distance
d_f	ChannelModel	40	far-field distance
γ	ChannelModel	40	path loss exponent
α	TrafficDemand	103	smoothing factor in Exponential Moving Average algorithm
$R(t_j)$	Sensing	77	RSS measurement sample at time instance t_j
N	Sensing	77	The number of time instances inside the measurement period
γ_{th}	Sensing	79	decision threshold (energy level)
R_c	Sensing	79	classified measurements
t	Sensing	77	time
IP	Sensing	81	idle period duration
BP	Sensing	81	busy period duration
T	Sensing	81	time
r	Autocorr.	83	autocorrelation coefficient
q	Autocorr.	81	lag
BI	Beacon	88	beacon interval
P_B	Sensing	88	probability of busy period durations equal to beacon transmission duration

Table D.1: List of used mathematical symbols (continued)

Symbol	Area	See Page	Meaning
P_D / P_D^*	Sensing	88	probability of busy period durations equal to DATA transmission duration in collision free / collision condition
P_A / P_A^*	Sensing	88	the probability of busy period durations equal to ACK transmission duration in collision free / collision condition
P_S / P_S^*	Sensing	88	the probability of idle period durations equal to SIFS duration in collision free / collision condition
P_s	Sensing	88	the probability that a transmission occurring on the channel is successful
$P_{S->A}$	Sensing	88	transition probability from SIFS to ACK
RA_{own}	SpecSharing	123	resource allocation for one's own system
RA_{others}	SpecSharing	123	resource allocation for the other systems
TD_{own}	SpecSharing	123	estimated traffic demand of one's own system
RA_{others}	SpecSharing	123	estimated traffic demand of the other systems
RI	SpecSharing	123	RCA_Interval
PL_{max}	SpecSharing	127	the maximum packet length
T_{frame}	AirtimeModel	134	frame transmission time
$T_{\text{PLCP-PRE}}$	AirtimeModel	134	PLCP preamble transmission time
$T_{\text{PLCP-SIGNAL}}$	AirtimeModel	134	SIGNAL transmission time
$T_{\text{OFDM-SYM}}$	AirtimeModel	134	one OFDM symbol transmission time
N_{DBPS}	AirtimeModel	134	number of data bits per symbol
L_{MPDU}	AirtimeModel	134	the length of MAC PDU, or MAC frame
L_{Pad}	AirtimeModel	134	number of padding bits
L_{MAC}	AirtimeModel	135	the length of MAC header
L_{Upper}	AirtimeModel	135	the length of Upper layer header
L_{P}	AirtimeModel	135	the length of packet in application layer
L_{PHY}	AirtimeModel	135	the length of PHY header

Table D.1: List of used mathematical symbols (continued)

Symbol	Area	See Page	Meaning
T_{dl}	AirtimeModel	137	transmission time of a downlink frame
T_{PIFS}	AirtimeModel	137	PIFS period
T_{SIFS}	AirtimeModel	137	SIFS period
T_{SIFS}	AirtimeModel	137	DATA frame transmission time
T_{ACK}	AirtimeModel	137	ACK frame transmission time
$T_{\mathrm{CF\text{-}POLL}}$	AirtimeModel	137	QoS CF-Poll frame transmission time
T_{ul}	AirtimeModel	137	transmission time of a uplink frame
T_{NULL}	AirtimeModel	137	QoS Null frame transmission time
n_{DATA}	AirtimeModel	140	number of data frames that fits into the TXOP
n_{DATA}	AirtimeModel	140	number of data frames that fits into the TXOP
$TXOP$	AirtimeModel	143	Transmission Opportunity
SI	AirtimeModel	143	service interval
N_{STA}	ThrpModel	143	number of stations
N_{System}	ThrpModel	143	number of system
S_{max}	ThrpModel	142	maximum throughput
S_{max}^{n}	ThrpModel	142	normalized maximum throughput
SP	SpecSharing	147	starting point of transmission
D_{Q}	SpecSharing	151	queuing delay
D_{Ch}	SpecSharing	151	channel access delay
D_{Tx}	SpecSharing	151	transmission delay
D_{Prop}	SpecSharing	151	propagation delay
D_{Proc}	SpecSharing	151	processing delay
plr	SpecSharing	171	packet loss ratio
N_d	SpecSharing	171	measured number of packet dropped
N_t	SpecSharing	171	measured total number of packet input during the measurement window
μ	StatEval	219	confidence limit for population mean
$\overline{x}$	StatEval	219	sample mean
σ^2	StatEval	219	population variance
S^2	StatEval	219	sample variance
n	StatEval	219	sample size

[1] About the Forum - Wireless World Research Forum. [Online]. Available: http://www.wireless-world-research.org [Last visited: 28/09/2010].

[2] Boost C++ Libraries. [Online]. Available: http://www.boost.org [Last visited: 16/02/2010].

[3] Cisco Aironet Antenna Reference Guide. [Online]. Available: http://www.univers-spb.ru/products/cisco/wireless/cisco_aironet_antennas.php [Last visited: 28/09/2010].

[4] Definition of ISM band in the Free Online Encyclopedia. [Online]. Available: http://encyclopedia2.thefreedictionary.com/ISM+band [Last visited: 28/09/2010].

[5] Electricity network uses wimax to monitor smart-meters in homes). [Online]. Available: http://www.cellular-news.com/story/36993.php [Last visited: 28/09/2010].

[6] ETSI Reconfigurable Radio Systems. [Online]. Available: http://www.etsi.org/WebSite/technologies/RRS.aspx [Last visited: 28/09/2010].

[7] IEEE 802.11 Official Timelines. [Online]. Available: http://www.ieee802.org/11/Reports/802.11_Timelines.htm [Last visited: 03/10/2010].

[8] IEEE 802.16 Published Standards and Drafts. [Online]. Available: http://www.ieee802.org/16/published.html [Last visited: 27/05/2011].

[9] IEEE Standards Coordinating Committee 41 (Dynamic Spectrum Access Network). [Online]. Available: http://www.scc41.org [Last visited: 28/09/2010].

[10] Motorola eZine for Service Provider: Bringing New Energy to Smart Metering. [Online]. Available: http://ezine.motorola.com/serviceprovider?a=458 [Last visited: : 28/09/2010].

[11] Personal Email Feedback from Hiroshi Harada, Chair, IEEE SCC41 on 10.11.2010.

[12] Python Programming Language - Official Website. [Online]. Available: http://www.python.org [Last visited: 10/01/2011].

[13] Radiocommunication Sector (ITU-R) - Working Party 1B (WP 1B) - Spectrum management methodologies and economic strategies).

[14] Random Number Library Generators. [Online]. Available: http://www.boost.org/doc/libs/1_33_1/libs/random/random-generators.html [Last visited: 16/02/2010].

[15] The IEEE 802.16 Working Group on Broadband Wireless Access Standards. [Online]. Available: http://www.ieee802.org/16/ [Last visited: 27/05/2011].

[16] What is Unlicensed Spectrum? What Frequencies are They in? [Online]. Available: http://www.wimax.com/wimax-regulatory/what-is-unlicensed-spectrum-what-frequencies-are-they-in [Last visited: : 16/09/2010].

[17] Wi-Fi Multimedia (WMM). [Online]. Available: http://www.wi-fi.org/knowledge_center/wmm [Last visited: 16/02/2010].

[18] WiMAX Application in Education. [Online]. Available: http://www.wimax.com/commentary/spotlight/wimax-in-education-the-obvious-application [Last visited: 26/05/2010].

[19] WiMAX Forum - Mobile WiMAX Plugfest, Technical white paper, September 24-30, 2006 Frederick, MD, USA.

[20] Wimax forum network architecture: Architecture tenets, reference model and reference points base specification. WMF-T32-001-R016v01, WiMAX Forum Proprietary, 2010.

[21] WiMAX Maps: WiMAX Forum - WiMAX Deployment. [Online]. Available: http://www.wimaxmaps.org [Last visited: 15/06/2011].

[22] xG Technology Mobile VoIP Unlicensed Spectrum. [Online]. Available: http://www.xgtechnology.com [Last visited: 28/09/2010].

[23] The E-model, a Computational Model for Use in Transmission Planning, May 2000. [Online]. Available: http://eu.sabotage.org/www/ITU/G/G107.doc [Last visited: 16/02/2010].

[24] Open Spectrum: A Path to Ubiquitous Connectivity. *Queue*, 1(3):60–68, 2003.

[25] The XG Architectural Framework, Request for Comments, Version 1.0, July 2003.

[26] ITU-R Radio Regulations, 2004 edition, Appendix 5, 2004.

[27] The XG Vision, Request for Comments, Version 2.0, January 2004.

[28] XG Policy Language Framework, Request for Comments, April 2004.

[29] openWNS - Open Wireless Network Simulator, 2009. [Online]. Available: http://www.openwns.org [Last visited: 26/02/2010].

[30] openWNS - RWTH Aachen University Open Source Wireless Network Simulator in Launchpad, 2009. [Online]. Available: http://launchpad.net/openwns [Last visited: 26/02/2010].

[31] K. Adere and G. R. Murthy. Solving the Hidden and Exposed Terminal Problems using Directional-antenna based MAC Protocol for Wireless Sensor Networks. In *WOCN*, pages 1–5. IEEE, 2010.

[32] G. Aggelou. *Wireless Mesh Networking.* McGraw-Hill Professional, 1st edition, 2008.

[33] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan. Cooperative spectrum sensing in cognitive radio networks: A survey. *Physical Communication*, 4(1):40–62, 2011.

[34] J. G. Andrews, A. Ghosh, and R. Muhamed. *Fundamentals of WiMAX: Understanding Broadband Wireless Networking (Prentice Hall Communications Engineering and Emerging Technologies Series).* Prentice Hall PTR, Upper Saddle River, NJ, USA, 2007.

[35] L Bao, S Liao, and E Bozorgzadeh. Spectrum Access Scheduling among Heterogeneous Wireless Systems.

[36] L. Berlemann, C. Hoymann, G. Hiertz, and B. Walke. Unlicensed Operation of IEEE 802.16: Coexistence with 802.11(a) in Shared Frequency Bands. In *Proceedings of the 17th Annual IEEE International Symposium onPersonal, Indoor and Mobile Radio Communications*, page 5, Helsinki, Finland, 2006.

[37] L. Berlemann and B. Walke. Spectrum Load Smoothing for Optimized Spectrum Utilization - Rationale and Algorithm. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC) 2005*, page 6, New Orleans LA, USA, 2005.

[38] G. Bianchi. Performance Analysis of the IEEE 802. 11 Distributed Coordination Function. *IEEE Journal on selected areas in communications*, 18(3):535–547, 2000.

[39] G. Bianchi and I. Tinnirello. Remarks on IEEE 802.11 DCF Performance Analysis. *IEEE Communications Letters*, 2005.

[40] P. Bjorklund, P. Varbrand, and Di Yuan. Resource Optimization of Spatial TDMA in Ad Hoc Radio Networks: A Column Generation Approach. 2:818–824 vol.2, March 2003.

[41] I. N. Bronshtein, K. A. Semendyayev, Gerhard Musiol, and Heiner Mühlig. *Handbook of Mathematics.* Springer, 5th edition, October 2007.

[42] D. Bültmann, M. Mühleisen, K. Klagges, and M. Schinnenburg. openWNS - open Wireless Network Simulator. In *15th European Wireless Conference 2009 Electronic Proceedings*, pages 205–210, Aalborg, Denmark, May 2009.

[43] G. Cecchetti and A. L. Ruscelli. Performance Evaluation of Real-time Schedulers for HCCA Function in IEEE 802.11e Wireless Networks. In *Proceedings of the 4th ACM symposium on QoS and security for wireless and mobile networks*, pages 1–8. ACM New York, NY, USA, 2008.

[44] J. Chen, C. Wang, F. Tsai, C. Chang, S. Liu, J. Guo, W. Lien, J. Sum, and C. Hung. The design and implementation of wimax module for ns-2 simulator. In *Proceeding from the 2006 workshop on NS-2: the IP network simulator*, WNS2 '06, New York, NY, USA, 2006. ACM.

[45] Cisco Systems, Inc. *Voice over Wireless LAN 4.1 Design Guide, Cisco Validated Design I*, January 2010.

[46] D. Datla, R. Rajbanshi, A. M. Wyglinski, and G. J. Minden. An Adaptive Spectrum Sensing Architecture for Dynamic Spectrum Access Networks. *Trans. Wireless. Comm.*, 8(8):4211–4219, 2009.

[47] F. Debus. Performance Evaluation of a Multi-Mode Capable Layer 2 for Relay Enhanced Cells in 4th Generation Mobile Radio Networks. Master's thesis, Chair of Communication Networks, Aachen University of Technology, Aachen, Germany, 2005.

[48] E. Erkip, A. Sendonaris, A. Stefanov, and B. Aazhang. Cooperative Communication in Wireless Systems. In *Advances in Network Information Theory*, pages 303–320. AMS DIMACS Series, 2004. edited by Gupta, P., Kramber, G., and Adriaan J. van Winjgaarden.

[49] Y. Fang, D. Gu, A. B. McDonald, and J. Zhang. A Two-level Carrier Sensing Mechanism for overlapping BSS Problem in WLAN. In *Proceedings of LANMAN 2005*, pages 1–6, September 2005.

[50] E. Gamma, R. Helm, R. Johnson, and J. M. Vlissides. *Design Patterns: Elements of Reusable Object-Oriented Software.* Addison-Wesley Professional, 1 edition, November 1994.

[51] M. Gast. *802.11 Wireless Networks: The Definitive Guide, Second Edition (Definitive Guide).* O'Reilly Media, Inc., April 2005.

[52] S. Geirhofer, L. Tong, and B Sadler. A Measurement-Based Model for Dynamic Spectrum Access in WLAN Channels. *MILCOM*, 0:1–7, 2006.

[53] S. Geirhofer, L. Tong, and B. M. Sadler. Dynamic Spectrum Access in WLAN Channels: Empirical Model and Its Stochastic Analysis. In *TAPAS '06: Proceedings of the first international workshop on Technology and policy for accessing spectrum*, page 14, New York, NY, USA, 2006. ACM.

[54] E. Guainella, E. Borcoci, M. Katz, P. Neves, M. Curado, F. Andreotti, and E. Angori. WiMAX Technology Support for Applications in Environmental Monitoring, Fire Prevention and Telemedicine. In *Proc. IEEE Mobile WiMAX Symposium*, pages 125–131, March 2007.

[55] B. Han, L. Ji, S. Lee, R. R. Miller, and B. Bhattacharjee. Channel Access Throttling for Overlapping BSS Management. 2009.

[56] S. Haykin. Cognitive Radio: Brain-empowered Wireless Communications. *Selected Areas in Communications, IEEE Journal on*, 23(2):201–220, February 2005.

[57] O. Holland, A. Attar, M. Sooriyabandara, T. Farnham, H. Aghvami, M. Muck, V. Ivanov, and K. Nolte. Architectures and Protocols for Dynamic Spectrum Sharing in Heterogeneous Wireless Access Networks. In Ekram Hossain, editor, *Heterogeneous Wireless Access Networks Architectures and Protocols*, pages 55–90. Springer Science+Business Media, LLC, 2008.

[58] IEEE Std. *Information Technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 1999.

[59] IEEE Std. *Supplement to IEEE Standard for Information Technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 5: Spectrum and Transmit Power Management Extensions in the 5 GHz band in Europe*, 1999.

[60] IEEE Std. *IEEE Standard for Local and metropolitan area networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems, IEEE Std. 802.16-2004*, October 2004.

[61] IEEE Std. *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements*, November 2005.

[62] IEEE Std. *IEEE Standard for Local and metropolitan area networks, Part 16: Air Interface for Fixed Broadband Wireless Access Systems, Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, IEEE Std. 802.16e-2005*, February 2005.

[63] IEEE Std. *IEEE standard for Information Technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 2007.

[64] IEEE Std. *IEEE Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence Between Radio Systems* , July 2008.

[65] IEEE Std. *IEEE Standard Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management*, September 2008.

[66] IEEE Std. *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 1: Radio Resource Measurement of Wireless LANs*, June 2008.

[67] IEEE Std. *IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks*, February 2009.

[68] IEEE Std. *IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed Broadband Wireless Access Systems. Amendment 2: Improved Coexistence Mechanisms for License-Exempt Operation*, July 2010.

[69] IEEE Std. *IEEE Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence Between Radio Systems*, 29 July 2008.

[70] M. Ihmig and P. Steenikiste. Distributed Dynamic Channel Selection in Chaotic Wireless Networks. In *Proceedings of the 13th European Wireless Conference*, Paris, France, April 2007.

[71] T. Irnich. *A New Methodology for Radio Spectrum Requirement Estimation of Wireless Communication Systems.* PhD thesis, RWTH Aachen University, Lehrstuhl für Kommunikationsnetze, Aachen, Germany, Jan 2009.

[72] R. Janka and V. Dorfman. System Considerations for Autonomous Dynamic Spectrum Utilization. In *Software Defined Radio Technical Conference and Product Exposition*, California, USA, November 14-18 2005.

[73] X Jing, S Mau, D Raychaudhuri, and R Matyas. Reactive Cognitive Radio Algorithms for Co-Existence between IEEE 802.11b and 802.16a Networks. 2005.

[74] M. Johnsson. HiperLAN/2: The Broadband Radio Transmission Technologyoperating in the 5 GHz Frequency Band, 1999.

[75] A. Könsgen. *Design and Simulation of Spectrum Management Methods for Wireless Local Area Networks*. PhD thesis, University of Bremen, Bremen, Germany, 2009.

[76] A. Könsgen and C. Görg. Performance Evaluation of Dynamic Frequency Selection Strategies in IEEE 802.11h based Networks. In *Proc. 1st Regional Conference on ICT and E-Paradigms*, 2004.

[77] A. Könsgen, A. S. M. Hossain, and C. Görg. Transmit Power Control Algorithms in IEEE 802.11h based Networks. In *Proc. 16th Annual IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, 2005.

[78] A. Könsgen, M. M. Siddique, C. Görg, L. Berlemann, G. Hiertz, S. Mangold, S. Max, and M. Mühleisen. *Coexistence and Radio Resource Optimization of Wireless Networking Technologies*, pages 43–55. Number 1000. Aachen, 2008.

[79] A. Kumar, E. Altman, D. Miorandi, and M. Goyal. New Insights from a Fixed Point Analysis of Single Cell IEEE 802.11 WLANs. In *In Proc. of IEEE INFOCOM*, 2004.

[80] Ajay R. Mishra. *Fundamentals of Cellular Network Planning and Optimisation: 2G/2.5G/3G... Evolution to 4G.* John Wiley & Sons, 2004.

[81] S. M. Mishra, A. Sahai, and R. W. Brodersen. Cooperative Sensing among Cognitive Radios. In *Proc. of the IEEE International Conference on Communications (ICC)*, pages 1658–1663, 2006.

[82] M. Mühleisen, D. Bültmann, R. Jennen, S. Max, J. Mirkovic, R. Pabst, and M. Schinnenburg. *openWNS: Open Source Wireless Network Simulator*, pages 121–140. Number 1000. Aachen, 2008.

[83] M. Mühleisen, R. Jennen, M. M. Siddique, and C. Görg. Analysis of a TDMA Coexistence Approach for IEEE 802.16 Systems. In *Leistungs-, Zuverlässigkeits- und Verlässlichkeitsbewertung von Kommunikationsnetzen*

und verteilten Systemen, MMBnet 2009, pages 65–69, Hamburg, Germany, 2009.

[84] M. Mühleisen, R. Jennen, M. M. Siddique, and C. Görg. IEEE 802.16 Coexistence through Regular Channel Occupation. In *Proceedings of the European Wireless*, pages 211–215, European Wireless, 2009.

[85] Q. Ni. Performance Analysis and Enhancements for IEEE 802.11e Wireless Networks. *IEEE Network*, 19(4):21–27, 2005.

[86] N. Nikopoulos. WiMAX MAC Scheduler Design and Extensible Simulation Framework for Network Simulator (NS-2). Master's thesis, Athens Information Technology, Athens, Greece, 2008.

[87] N. Prasad and A. Prasad. *WLAN Systems and Wireless IP for Next Generation Communication.* Boston, Mass. [u.a.] : Artech House, 2002.

[88] R. Pries, D. Staehle, and D. Marsico. IEEE 802.16 Capacity Enhancement Using an Adaptive TDD Split. In *VTC Spring*, pages 1539–1543, 2008.

[89] K. Rahamatullah. Implementation and Evaluation of Regular Channel Access for Cooperative Spectrum Sharing between Coexisting WLAN Systems. Master's thesis, University of Bremen, Bremen, Germany, 2009.

[90] J. Rapp. Hiperlan/2 System Throughput and QoS with Interference Improving Strategies. In *IEEE VTS 53rd Vehicular Technology Conference*, volume 4, 2001.

[91] T. Rappaport. *Wireless Communications: Principles and Practice.* Prentice Hall PTR, Upper Saddle River, NJ, USA, 2nd edition, 2001.

[92] M. Schinnenburg, R. Pabst, K. Klagges, and B. Walke. A Software Architecture for Modular Implementation of Adaptive Protocol Stacks. In *MMBnet Workshop, Hamburg, Germany, Sep 2007*, page 94, 2007.

[93] J. She, F. Hou, P. Ho, and L. Xie. IPTV over WiMAX: Key Success Factors, Challenges, and Solutions [Advances in Mobile Multimedia. *Communications Magazine, IEEE*, 45:87–93, August 2007.

[94] M. M. Siddique. Design and Performance Evaluation of the Parallelisation of Discrete Event Simulators using High Level Architecture. Master's thesis, University of Bremen, Bremen, Germany, 2004.

[95] M. M. Siddique, A. Könsgen, C. Görg, G. Hiertz, and S. Max. Extending IEEE 802.11 by DARPA XG Spectrum Management: A Feasibility Study. In *12th European Wireless Conference 2006 - Enabling Technologies for Wireless Multimedia Communications (European Wireless)*, pages 1 –7, Athens, Greece, april 2006.

[96] M. M. Siddique, M. Mühleisen, B.-L. Wenning, and C. Görg. Generic Coexistence Method between IEEE 802.16 and IEEE 802.11 based Wireless Networks. In *6th Karlsruhe Workshop on Software Radios (WSR10)*, pages 193–202, Karlsruhe, Germany, March 2010.

[97] M. M. Siddique, M. Mühleisen, B.-L. Wenning, and C. Görg. Spectrum sharing between IEEE 802.16 and IEEE 802.11 based wireless networks. In *Proceedings of the 2010 IEEE International Symposium on A World of Wireless Mobile and Multimedia Networks (WoWMoM)*, pages 1–6, Montreal, Canada, June 2010.

[98] M. M. Siddique, B.-L. Wenning, and M. Görg, C. Mühleisen. An Adaptive Resource Sharing Method for IEEE 802.16 and IEEE 802.11 based Wireless Networks. In *Proceeding of the 15. ITG Fachtagung Mobilkommunikation*, pages 33–38, Osnabrück, Germany, May 2010.

[99] M. M. Siddique, B.-L. Wenning, M. Mühleisen, A. Timm-Giel, and C. Görg. Generic Spectrum Sharing Method Applied to IEEE 802.11e WLANs. In *The Sixth Advanced International Conference on Telecommunications (AICT 2010)*, pages 57–63, Barcelona, Spain, May 2010.

[100] S. Simoens, P. Pellati, J. Gosteau, C. Ware, and K. Gosse. The Evolution of 5 GHz WLAN toward Higher Throughputs. *IEEE Wireless Commun. Mag*, 10:6–13, 2003.

[101] W. Stallings. *Wireless Communications & Networks.* Prentice Hall, 2004.

[102] A. S. Tanenbaum. *Computer Networks.* Fourth Edition, Person Education International, 2003.

[103] M. A. Uusitalo. Global Visions for the Future Wireless World from the WWRF. In *In IEEE Vehicular Technology Magazine*, pages 4–8, June 2006.

[104] B. Walke, S. Mangold, and L. Berlemann. *IEEE 802 Wireless Systems: Protocols, Multi-Hop Mesh/Relaying, Performance and Spectrum Coexistence.* John Wiley & Sons, 2006.

[105] J. Yang, Y. Chen, and W. Trappe. Detecting Spoofing Attacks in Mobile Wireless Environments. In *SECON'09: Proceedings of the 6th Annual IEEE communications society conference on Sensor, Mesh and Ad Hoc Communications and Networks*, pages 189–197, Piscataway, NJ, USA, 2009. IEEE Press.

[106] Q. Zhao. Low-Complexity Approaches to Spectrum Opportunity Tracking. In *in Proc. of CrownCom*, 2007.

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CURRICULUM VITAE

Name:	Mohammad Muttakin Siddique
Date of Birth:	10.12.1976
Place of Birth:	Dhaka, Bangladesh
Nationality:	Bangladeshi

01/1995 - 06/2000:	BSc in Electrical and Electronic Engineering at Bangladesh University of Engineering & Technology, Dhaka
04/2002 - 11/2004:	MSc in Communication and Information Technology at the University of Bremen
01/2001 - 03/2002:	Enterprise Engineer I and II at BASE Ltd, Dhaka, Bangladesh
06/2002 - 10/2004:	Student Research Assistant at the Department of Communication Networks, University of Bremen
02/2005 - 06/2011:	Research Scientist, Doctoral Candidate at the Department of Communication Networks, University of Bremen