Universität Bremen

Wireless Mesh Network
A rural community case

by

M.Sc. Jean Louis Fendji Kedieng Ebongué

Thesis

Submitted in partial Fulfillment of the

Requirements for the Degree of Dr.-Ing.

Fachbereich Mathematik / Informatik

Universität Bremen

July 2015

Supervisors:
Prof. Dr. Karl-Heinz Rödiger, University of Bremen
Prof. Dr. David Békollé, University of Ngaoundéré

Acknowledgements

First and foremost I thank my advisor Prof. Karl-Heinz Rödiger for accepting the supervision of this work. I have been fortunate to work with him. He watched over my thesis schedule more than me. I thank him for all the fruitful discussions we had in Bremen, Berlin, and in Ngaoundéré.

A special thank goes to Prof. David Békollé for acting as an expert and writing a report about my thesis. This is really a great honour for me.

Further on I thank Prof. Hans-Jörg Kreowski for the fruitful discussions and recommendations. I am also grateful to Prof. Carsten Bormann for the discussions.

I would also like to acknowledge Dr. Jean Michel Nlong and Dr. Chris Thron for different discussions and suggestions as well as Dr. Berthold Hoffmann for his support during my stay in Bremen.

I thank the former master students, who assisted me during the survey in Mbé and Garoua-Boulaï; especially Mafai Nelson who also worked with me on the path loss model.

Last not least I thank my family, especially my father Fendji Benjamin and my wife Cecile Fabiola, who sacrificed a lot for me, just to see me achieving my aim.

The research work and the time to write this thesis would never have been possible without a grant: Many thanks to Deutscher Akademischer Austauschdienst (DAAD).

Abstract

We observe an emphasis on deploying wireless networks in a mesh topology, which is a cost-effective approach to extend their coverage, since a decade. But this approach of planning a network is lowly adopted in Africa, especially in rural regions, despite the suitability of this type of network for bridging the digital divide.
In this thesis, we tackle the planning problem of wireless mesh networks in rural regions: How they can be deployed in rural communities using a landline node such as a telecentre at low cost. Since this problem is not only a technical one, it is important to study the feasibility of such a planning process. We consider two rural communities in Cameroon that are hosting a telecentre as a case study for this purpose.
Then we investigate, which wireless technology could be appropriate, and discuss the propagation of the signal in rural regions. After justifying the choice of the 802.11n wireless network, empirical studies are conducted in different scenarios: free space, built-up areas, and wooded areas. Different path loss models are compared and the best one is improved.
The main part of this work deals with the placement problem of mesh routers in a given rural region hosting a predefined Internet gateway. This issue is a critical one, especially in rural regions where we usually observe low density and sparse population. We suppose the planning of wireless mesh networks to be coverage-driven, meaning that we are more concerned about the space to cover than about the capacity to provide. We provide a network model tied to rural regions by considering the area to cover as decomposed into a set of elementary areas. Each elementary area may be of different types: an area of interest in terms of coverage, an area representing an obstacle, an area where a node can be placed or an area requiring a lower settlement cost. The placement problem is therefore considered as a multi-objective optimisation problem with conflicted objectives such as maximising the coverage while minimising the cost.
To solve this problem, we consider at first the case where the area to cover is continuous. We propose different algorithms based on simulated annealing. The first one maximises the coverage while reducing the number of routers; the second one improves the cost by relocating nodes into cost-effective locations. A set of trade-offs resulting from a Pareto optimisation is produced. The case where areas of interest are disjoint is considered later. The approach proposed to solve this new model reuses the previous optimisation algorithms and adapts some algorithms used in graph theory, such as Depth First Search, Breath First

Search, closest pair, and Graham Scan for Convex Hull. They are used in order to detect sub-networks and to link them efficiently. Finally, the problem of channel assignment is addressed. After assimilating this problem to the one of list edge colouring, a strategy aiming to assign channels by creating a spanning tree from the sole Internet gateway is proposed. All proposed algorithms are evaluated on different regions. The results show a certain convergence and an efficiency of the approach despite the probabilistic nature of underlying algorithms.

Zusammenfassung

Seit etwa einem Jahrzehnt ist zu beobachten, dass kabellose Netzwerke in einer Netz-Topologie verbreitet werden; sie sind ein kostengünstiger Ansatz, ihre Abdeckung zu vergrößern. Dieser Ansatz ist jedoch bislang in Afrika besonders in den ländlichen Regionen wenig verbreitet, obwohl er geeignet ist, die digitalen Kluft zu überbrücken.
In dieser Arbeit nehmen wir uns des Problems an, kabellose Netzwerke für den ländlichen Raum zu planen: Wie können sie zu niedrigen Kosten in dörflichen Gemeinschaften mit einem Festnetz-Knoten beispielsweise bei einem Telezentrum eingesetzt werden. Da dieses Problem nicht nur ein technisches ist, ist es wichtig, die Machbarkeit eines solchen Planungsprozesses zu untersuchen. Hierzu betrachten wir zwei Landgemeinden in Kamerun mit je einem Telezentrum als Fallstudie.
Wir untersuchen weiterhin, welche Funktechnologie geeignet sein könnte und diskutieren die Signal-Ausbreitung in ländlichen Regionen. Nach der Begründung der Wahl des 802.11n kabellosen Netzwerks, werden empirische Studien mit verschiedenen Szenarien durchgeführt: freien Raum, bebaute und bewaldete Gebiete. Verschiedene Funkfelddämpfungen werden verglichen und die beste wird verbessert.
Der Hauptteil dieser Arbeit befasst sich mit dem Platzierungs-Problem der Netz-Router in einer bestimmten ländlichen Region, die schon ein vordefiniertes Internet-Gateway besitzt. Dies ist besonders in ländlichen Regionen, in denen wir normalerweise eine geringe Bebauung und eine dünne Besiedlung beobachten, ein kritischer Punkt. Wir gehen davon aus, dass die Planung von kabellosen Netzwerken durch den Grad der Abdeckung gesteuert wird. Das bedeutet, dass die Abdeckung des Raums wichtiger als die zur Verfügung gestellte Kapazität ist. Wir stellen ein Netzwerk-Modell für den ländlichen Raum vor, von dem wir annehmen, dass er sich in eine Menge elementarer Areale unterteilen lässt. Die Elementarbereiche können von verschiedenem Typ sein: Interessant im Sinne der Abdeckung; oder er kann ein Hindernis enthalten; oder ein Bereich, an dem ein Knoten platziert werden kann; oder ein Bereich, der geringere Abwicklungskosten benötigt. Das Platzierungs-Problem wird daher als ein Mehrzieloptimierungs-Problem mit konfligierenden Zielen, wie der Maximierung der Abdeckung bei gleichzeitiger Minimierung der Kosten, betrachtet.
Um dieses Problem zu lösen, betrachten wir zuerst den Fall, dass der abzudeckende Bereich ein Kontinuum darstellt. Wir schlagen verschiedene Algorithmen basierend auf Simulated

Annealing vor. Der erste maximiert die Abdeckung während die Anzahl der Router verringert wird; der zweite minimiert die Kosten durch Verlagerung von Knoten in kostengünstige Standorte. Ein Mende von Kompromissen, die aus einer Pareto-Optimierung resultieren. werden erzeugt. Der Fall, dass Bereiche von Interesse disjunkt sind, wird später betrachtet. Der zur Lösung des neuen Modells vorgeschlagene Ansatz benutzt die vorhergehenden Optimierungsalgorithmen und adaptiert einige Algorithmen aus der Graphentheorie, wie Depth First Search, Breath First Search, dichtestes Punktpaar und Graham Scan für konvexe Hüllen. Sie werden benutzt, um Teilnetze zu identifizieren und um sie effizient zu verknüpfen. Schließlich wird das Problem der Kanalzuweisung behandelt. Nach dessen Umwandlung zu einem Kantenfärbungsproblem wird eine Strategie mit dem Ziel vorgeschlagen, Kanäle mittels eines Spannbaums, ausgehend vom einzigen Internet-Gateway, zuzuweisen. Alle vorgeschlagenen Algorithmen werden in unterschiedlichen Regionen evaluiert. Die Ergebnisse weisen trotz der probabilistischen Natur der zugrundeliegenden Algorithmen Konvergenz und Effizienz auf.

Contents

Acknowledgements i

Abstract (English/Deutsch) ii

List of figures x

List of tables xiii

List of Algorithms xiv

1 Introduction 1
- 1.1 Problem statement . . . 3
- 1.2 Aim of this thesis . . . 4
- 1.3 Motivation . . . 4
- 1.4 Structure of the thesis . . . 5

2 Cameroon telecommunications and rural communities 7
- 2.1 Telecommunication system in Cameroon . . . 7
  - 2.1.1 Network and Internet service providers . . . 8
  - 2.1.2 Major projects from MINPOSTEL . . . 9
  - 2.1.3 Figures of the Cameroonian telecommunication sector . . . 11
- 2.2 Multipurpose community telecentres and rural areas . . . 12
  - 2.2.1 Project presentation . . . 12
  - 2.2.2 Actual state . . . 12
- 2.3 Selected rural communities in Cameroon . . . 14
  - 2.3.1 Rural community of Mbé . . . 14
  - 2.3.2 Rural community of Garoua-Boulai . . . 15
- 2.4 Requirement analysis . . . 16
  - 2.4.1 Methodology . . . 16
- 2.5 Results and interpretation . . . 16
  - 2.5.1 Socio-economical aspect . . . 17
  - 2.5.2 Telecommunication device availability . . . 17

2.5.3 Internet adoption . . . 18
2.5.4 Telecentre assessment . . . 19
2.5.5 Web and social networks . . . 20
2.5.6 Affordability . . . 21
2.5.7 Desired services and applications . . . 22
2.6 Local challenges and needs . . . 22
2.6.1 Local challenges . . . 22
2.6.2 Local needs . . . 23
2.7 Discussion and recommendations . . . 25
2.7.1 Network design . . . 25
2.7.2 Software utilisation . . . 26
2.7.3 Business Strategy . . . 27

3 Wireless technologies in rural areas 29
3.1 Wireless communication systems . . . 29
3.1.1 Orbital wireless communication . . . 30
3.1.2 Terrestrial wireless communication . . . 33
3.2 Rural constraints to wireless network technology selection . . . 34
3.2.1 Cost of the overall system . . . 35
3.2.2 Energy consumption . . . 35
3.2.3 Application requirements . . . 35
3.2.4 Coverage constraints . . . 37
3.2.5 Legal framework . . . 37
3.3 Wireless network technology . . . 40
3.3.1 Wireless Personal Area Network (WPAN) . . . 40
3.3.2 Wireless Local Area Network (WLAN) . . . 41
3.3.3 Broadband Wireless MAN (WMAN) . . . 43
3.3.4 Wireless Regional Area Network (WRAN) . . . 44
3.3.5 Selecting a suitable technology . . . 45
3.3.6 Wi-Fi mesh or WiMAX? . . . 46
3.3.7 Why 802.11n? . . . 47

4 Path loss models 48
4.1 Prediction models for wireless networks . . . 48
4.1.1 Characteristics of path loss models . . . 49
4.1.2 Propagation environment . . . 51
4.1.3 Selected models . . . 53
4.2 Environment and measurement methodology . . . 55
4.2.1 Environment of the study . . . 56
4.2.2 Description of the hardware and software tools . . . 56

4.2.3 Data collection . . . 59
4.3 Data analysis and interpretation . . . 59
4.3.1 Determination of parameters . . . 59
4.3.2 Result analysis in free space . . . 60
4.3.3 Result analysis in a wooded area . . . 63
4.3.4 Result analysis in a built-up area . . . 65
4.3.5 Summary of results . . . 67
4.4 Proposal for a new empirical model . . . 67
4.4.1 Path loss expression . . . 68
4.4.2 Analysis of the accuracy of the new model . . . 69

5 Wireless mesh networks: The planning problem 72
5.1 Wireless mesh networks . . . 72
5.1.1 Network architecture . . . 73
5.1.2 Characteristics of WMNs . . . 74
5.1.3 WMN applications . . . 75
5.2 Optimisation techniques . . . 75
5.2.1 Method of operation . . . 76
5.2.2 Properties . . . 77
5.2.3 Single-objective optimisation . . . 78
5.2.4 Multi-objective optimisation . . . 79
5.3 WMN planning . . . 80
5.3.1 Predefined topology . . . 81
5.3.2 Planning constraints . . . 82
5.3.3 Objectiveness in planning . . . 84
5.3.4 Partial planning . . . 84
5.3.5 Planning from scratch . . . 86
5.4 WMN planning in rural regions . . . 88

6 Mesh router nodes placement in rural areas 90
6.1 Placement problem formulation . . . 90
6.1.1 Region description . . . 90
6.1.2 Network model . . . 91
6.1.3 Problem statement . . . 93
6.2 Simulated annealing . . . 94
6.2.1 Basic SA algorithm . . . 94
6.2.2 Parameter setting . . . 95
6.3 Mesh router placement approach using the SA algorithm . . . 96
6.3.1 Algorithm particularisation . . . 96
6.3.2 Experimentation . . . 103

6.4 Cost consideration . . . 109
6.4.1 Algorithm (PARSA) . . . 111
6.4.2 Experimentation . . . 113

7 Case of disjoint areas of interest and channel assignment 116
7.1 Network model and placement approach . . . 116
7.1.1 Network model . . . 117
7.1.2 Placement approach . . . 117
7.2 Initial placement . . . 119
7.2.1 Experimentation . . . 119
7.2.2 Results and discussion . . . 120
7.3 Recalls in graph theory . . . 122
7.4 Detecting sub-networks . . . 123
7.5 Joining sub-networks . . . 125
7.5.1 Convex hull . . . 125
7.5.2 Joining strategy . . . 127
7.6 Channel assignment . . . 129
7.6.1 Bridge problem . . . 131
7.6.2 Approach for channel assignment . . . 133

8 Conclusion and Future work 140
8.1 Summary of results . . . 140
8.2 Future work . . . 142

Terms and acronyms 144

Literature 146

Appendix 162

List of Figures

2.1 Overview of services offered by MCT 13
2.2 Number of MCTs per region in Cameroon in December 2014 14
2.3 Location of the selected rural communities 15
2.4 Availability of computing devices in selected areas 18
2.5 Computer usage in selected areas 18
2.6 Means of connections to the Internet in selected area 19
2.7 Distance to telecentres in selected areas 19
2.8 Time spent in telecentres in selected areas 20
2.9 Goal of using telecentres in selected areas 20
2.10 Usage of websites and social networks in selected areas 21
2.11 Affordability in selected areas 21
2.12 Desired e-services in selected areas 22

3.1 Wireless communication based on satellites 31
3.2 Wireless communication based on balloons 32
3.3 Areas of interest in Garoua-Boulaï 38
3.4 Map of licensing regimes for the 2.4GHz and 5GHz band 39
3.5 Characteristics of wireless networks 45

4.1 Relation between most of the common path loss models 53
4.2 Environment of the study for empirical path loss models 56
4.3 Free space scenario 57
4.4 Wooded area scenario 57
4.5 Built-up area scenario 58
4.6 Mean losses in free space 61
4.7 Fitting curves in free space: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver 61
4.8 Comparison of the predicted values in free space: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver 62
4.9 Mean losses in wooded area 63

4.10 Fitting curves in the wooded area: (a) 300Mbps wireless receiver; (b) 150Mbps wireless receiver . . . 64
4.11 Comparison of the predicted values in the wooded area: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver . . . 65
4.12 Mean losses in a built-up area . . . 66
4.13 Fitting curves in a built-up area: (a) 300Mbps wireless receiver; (b) 150Mbps wireless receiver . . . 66
4.14 Comparison of predicted values in wooded area: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver . . . 67
4.15 Mean losses in the wooded area for accuracy analysis . . . 69
4.16 Accuracy of models in the wooded area: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver . . . 70
4.17 Mean losses in the built-up area for accuracy analysis . . . 70
4.18 Accuracy of models in the built-up area: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver . . . 71

5.1 Infrastructure/backbone WMN . . . 74
5.2 Global optimisation techniques . . . 76
5.3 onte Carlo-based optimisation algorithms . . . 77
5.4 Optima of a two-dimensional function . . . 79
5.5 Example of Pareto optimisation . . . 80
5.6 Planning problem in wireless mesh networks . . . 81
5.7 Rural application of a wireless mesh networks . . . 88

6.1 An example of a region decomposed in EA . . . 92
6.2 Flowchart of the modified SA algorithm for solving the mesh router placement 98
6.3 Cooling process:(a) Variation of the temperature; (b) Corresponding router coverage . . . 99
6.4 Considering only EAs affected by a movement of a router . . . 100
6.5 Influence of obstacles in the connectivity of routers . . . 101
6.6 Strategies for removing routers . . . 102
6.7 Areas to cover with random obstacles . . . 105
6.8 Coverage percentage of the area of interest . . . 109
6.9 SA results on instance 1 . . . 110
6.10 SA results on instance 2 . . . 110
6.11 SA results on instance 3 . . . 110
6.12 Connected configuration with dead spots in instance 2 . . . 111
6.13 Pareto front between the percentage of routers in CEAs and the coverage percentage of the area of interest in instance 3 . . . 115
6.14 Result after cost improvement . . . 115

7.1 An example of a region decomposed in EA with disjoint areas of interest . . 117
7.2 Flowchart of the complete placement approach of mesh routers 118
7.3 Region instances with disjoint areas of interest 119
7.4 Percentage coverage of the areas of interest from instances 1 and 2 120
7.5 Router locations in disjoint areas of interest 121
7.6 Pareto front between the coverage percentage of the areas of interest and the percentage of routers in CEAs 121
7.7 Router locations after optimising the cost of the architecture 122
7.8 Detected sub-networks 125
7.9 Example of convex hull 126
7.10 Convex hulls of sub-networks 128
7.11 Connected network after joining strategy 129
7.12 Network topology and channel assignment 130
7.13 Bridge determination 132
7.14 Channel assignment approach 134
7.15 Step by step application of the channel assignment approach 135
7.16 Result of channel assignment for instance 1 138
7.17 Result of channel assignment for instance 2 139

Diagrams are partly created with MS Excel.

List of Tables

2.1 Some socio-economic and demographic factors of Cameroon 7
2.2 Telecommunication indicators in Cameroon, Africa, and World 11

3.1 Application requirements in terms of throughput 36
3.2 Characteristics of areas of interest in Garoua-Boulaï 37
3.3 Characteristics of common wireless standards 45

4.1 List of the most common macro-cellular path loss models 52
4.2 Description of the hardware used for measurements 58
4.3 Experimental results in free space 62
4.4 Experimental results in the wooded area 64
4.5 Experimental results in a built-up area 67
4.6 Empirical values of the model parameters 68
4.7 Best prediction in different scenarios 68
4.8 Results of the accuracy analysis in the wooded area 69
4.9 Results of the accuracy analysis in the built-up area 71

6.1 Parameter values for experimentation (adapted SA algorithm) 104
6.2 Partial results of the router placement in instance 1 106
6.3 Partial results of the router placement in instance 2 107
6.4 Partial results of the router placement in instance 3 108
6.5 Parameter values for experimentation (PARSA algorithm) 113
6.6 Pareto front in instance 3 with 50 CEAs 114
6.7 Pareto front in instance 3 with 100 CEAs 114

7.1 Parameter values for experimentation (SA and PARSA) 120

List of Algorithms

6.1 Simulated annealing 95
6.2 Checking the connectivity of the network 102
6.3 Local compensation 103
6.4 Pareto Archived Reverse SA (PARSA) 112
7.1 Breadth-first search 124
7.2 Sub-networks Detection 124
7.3 Graham scan (Convex hull) 127
7.4 Merging sub-networks 128
7.5 DFSE-BD (DFS Extended-Bridge Determination) 131
7.6 BFSE-STCA (BFS Extended-Spanning Tree Channel Assignment) 137

These algorithms have been implemented in Scilab, which is an open-source software for numerical computation [Ramchandran/Nair 2011].

1 Introduction

The development of a region depends not only on the circulation of persons but also on the circulation of information. In a world that claims to be a global one, good information traffic is one of the most important concerns. Because it enables the development of business models, the prevention of disasters or diseases, the implementation of new learning processes etc... But many rural regions, sometimes also semi-urban and even urban regions in developing countries are still suffering from the lack of connectivity. That hinders the development, resulting in degradation of both social communication and business advances in these regions; subsequently the "digital divide" becomes more and more apparent. As the map of the Internet World Stats can show, African Internet users represent only 7% of the world Internet users in 2012 and 9.8% in 2014[1]. "The Internet is becoming the town square for the global village of tomorrow"[2], but Africa is still neglecting. This statement is reinforced by the figures revealed by the International Telecommunication Union (ITU) in its annual report, ICT facts and figures 2015 [ITU 2015]. According to this report, only 10.7% of the households in Africa will have Internet access by end of 2015 compared to 34% of households in developing countries in the world.

The contribution of the Internet to the development of Africa is nevertheless noticeable. The Minister of Communications Technology of Nigeria stated that the Internet can contribute up to 300 billion USD to Africa's Gross Domestic Product (GDP) by 2025 against an estimated 18 billion in 2013 [3]. This declaration was based on a 2013 report from McKinsey Global Institute [McKinsey 2013]. The same report reveals that the contribution of the Internet to GDP could match those of leading economies such as Sweden, Taiwan, and the

[1] The percentage of African Internet users in 2012 was retrieved from the web site: http://www.internetworldstats.com/stats.htm in 2013. Today (June 2015), only figures of 2014 are available.

[2] This is a well-known statement from Bill Gates.

[3] It was stated at the 3rd African Internet Governance Forum that held in Abuja from 10 to 12 July 2014. http://allafrica.com/stories/201407161115.html

United Kingdom by the same due date.

The actual low percentage of Internet users in Africa, particularly in its developing countries, is primarily distributed among urban areas; showing a digital divide between urban and rural areas. Usually the national strategies to reduce the digital divide do not consider rural regions. Consequently the intra digital divide is more and more apparent. The disregard of rural regions is due to many reasons. The first one is their location with sometimes a lack of proper roads and a hostile environment that makes it difficult to reach them. Another reason is the lack, the deficiency or the instability of the power infrastructure that seriously hinders the deployment of technology since an autonomous way of powering the devices and the network equipment could be required. The lack of local capacity in network administration and maintenance in these regions is another important inhibiting factor. Besides these constraints ([Johnson 2013], p. 10) other ones like language and cultural barriers, transportation issues, tampering and theft (in some regions) decelerate the development. As telecommunication operators are driven by profit, the low-density population with low-income in rural regions cannot insure a return of investment. Moreover, in some countries, the lack of awareness about the potential of wireless networks to support the development of rural regions, leads the government not to define a clear policy to solve this problem. In contrary, law and regulations constitute a real barrier for providing some solutions like licensing spectrum policies.

Nevertheless, outstanding research efforts have been particularly carried out in the development of wireless networks for rural regions since a decade. Most of the prior work was carried out in some parts of Asia, particularly in India. It tried to overcome the long distances between rural population and towns; distances that prevent them from accessing educational, medical, governmental or other services. The focus was directed to the careful design of long link wireless networks, usually called WiLD standing for Wifi Long Distance [Sen 2007]. A typical deployment consists of linking a nearby city to a so-called kiosk located in a remote village. Usually, these kiosks or points of interest host some basic services like Internet access, health, call services or others. Although the results of this prior kiosk model have been acceptable, the increase of user connectivity demand and the opportunity to develop new business models in order to bridge the digital divide requires more than just a kiosk model. The aim is therefore to spread this signal in a rural region rather than just providing connectivity to a point of interest in a locality. According to this, some rural networks based on wireless mesh network (WMN) have been already set-up. We can list the Peeples network in South Africa and the Macha network in Zambia.

Wireless mesh networks have presently been shown as an appealing solution to connect rural regions. To foster the deployment of this type of network in difficult to wire areas, there has been an emphasis on developing cost-effective and energy-efficient wireless

technologies recently. Among the noticeable projects we can list the Wireless Backhaul Technology (WiBACK[4]) project from Fraunhofer-Institut für Offene Kommunikationssysteme (FOKUS) and Mesh potato[5] from Village Telco. The first project aims to provide backhaul connectivity for fast deployment at very low cost. The WiBACK products are essentially wireless repeaters or mesh routers. The second project is a combination of a low-cost wireless access point (running a mesh networking protocol) and an analogue telephony adapter (ATA). This project aims to provide low-cost telephony and Internet in areas neglected by telecommunication operators.

1.1 Problem statement

Despite the efforts focusing on the development of suitable technologies for difficult to wire areas such as rural ones, and the success of already launched wireless mesh networks, the number of network deployments in rural areas is still insignificant. In Cameroon some efforts have been made to reduce the urban-rural digital divide by the launch of the multipurpose community telecentres (MCT) project for rural communities since 2003. These MCTs are connected via satellite; one perspective is to spread the signal around each telecentre. But this perspective has been realised in none of the 170 deployed MCTs up to now, despite all opportunities such a deployment could provide for the local community. How can this signal be spread at very low cost in a rural community? How can this network be useful and sustainable for the local community?

The planning of networks is typically rather coverage- than capacity-driven in rural regions ([Bernardi et al. 2011], p. 1 f.). This means, we are more concerned with the area to cover than the capacity to provide. In other terms: In case of wireless mesh network planning the number of mesh routers is rather determined by the area to cover than the throughput required by a defined set of clients. The suitability of the coverage-driven planning in rural regions is truer when most applications accessible by the network are more text- than audio- or video-based. Consequently, the efficiency of a network planning approach in rural areas is not mainly measured by the quality of service (QoS) of the solution, but by the cost of the solution. The main research problem in the framework of this thesis is the following:

Given a region to be provided with wireless network connectivity from a landline node (such as a telecentre), determine a cost-effective network architecture.

[4] http://net4dc.fokus.fraunhofer.de/en/projects/wiback.html
[5] http://villagetelco.org/mesh-potato/

1.2 Aim of this thesis

The present work aims to contribute to the planning of wireless networks in rural regions, especially wireless mesh networks. The specific objectives are:

1. To assess the ICT penetration in some rural communities and their readiness to welcome and sustain a rural wireless network deployment;
2. To propose an accurate model to evaluate the signal attenuation in these regions;
3. To provide an efficient approach for the placement of wireless mesh networks that optimise the coverage and the cost of the architecture;
4. To define a minimal interfering channel assignment strategy for wireless mesh networks.

1.3 Motivation

The prevision by McKinsey Global Institute about the contribution of the Internet in the development of Africa by 2025 is a strong motivation, but not the only one.

Potential markets and great workforces

Rural regions host the majority of the population in Africa. According to UN DESA [2012], the percentage of the African population living in these regions is estimated to 60.1 per cent in the second semester of 2012. This represents a great market; and to take advantage, new suitable and affordable services should be developed.

Moreover, the emerging policy of some African developing countries essentially relies on agriculture that is mostly done in rural regions. Therefore, a greater percentage of the rural population constitutes also an important workforce for reaching the emerging goals of reducing poverty to socially acceptable levels and of becoming a middle-income[6] country. The rural exodus however could seriously hinder such a program. A report from UN-Habitat [Davies 2010] states that 14 million people in Sub-Saharan Africa migrate from rural to urban regions every year. Considering this migration, the report predicts that more Africans will live in urban than in rural regions by 2030. This constitutes a real danger for the economy of these countries.

[6]According to the World Bank a middle-income country is defined as having a per capita gross national income between US$1,026 and $12,475.

Impact of actual rural networks

The success of rural networks, such as in Zambia (Macha), South-Africa (Dwesa) or India (Airjaldi), shows the role this type of network can play in the development of rural communities. Although basic human needs are not completely satisfied in these regions, access to information enables education, medicare, participation in social and political processes, and so on. Some examples show how simple the access to information transforms impoverished regions: Fishing industry in India, sunflower farming in Zambia. Even some social problems such as gender inequality can be overcome ([Pejovic 2012], p. 3).

Personal challenge

The last and probably the most important motivation is my personal burden for the development of these regions. Coming from an underprivileged family in Cameroon, I saw a lot of people struggling for life in order to survive. I realised later that the living conditions could be improved just by access to the right information. For instance, the Cameroonian government is running a lot of programs to sustain the agricultural sector. But the potential beneficiaries of such programs for people living in rural regions are not known, because they have no possibilities to access the (right) information.

1.4 Structure of the thesis

The thesis is organised as follows:

The second chapter figures out the Cameroonian telecommunication sector with an insight on ICT penetration in rural regions. The telecommunication system in Cameroon is portrayed, and the major projects of the Ministry of Posts and Telecommunication are presented with a focus on the Multipurpose Community Telecentres (MCT) project designed for rural regions. This chapter also shows the results of the survey about ICT penetration and the impact of MCTs in two selected rural regions, namely Garoua-Boulaï and Mbé. After outlining the local challenges and needs, this chapter ends with providing some recommendations about the network design, software utilisation and business strategy.

The third chapter discusses wireless technologies in rural areas. Orbital wireless communication systems, mainly satellite and balloons, are firstly presented with their limitation in solving the present problem. Terrestrial wireless communication systems are then introduced. Afterwards, constraints to wireless network technology selection are presented, among which cost of the overall system, energy consumption, application requirements, coverage, and the legal framework are important constraints. After presenting the most common wireless network technologies, this chapter discusses the suitability of wire-

less mesh networks over WiMAX in our scenario and justifies the choice of the 802.11n standard.

The fourth chapter focuses on path loss models. It starts with presenting prediction models for wireless networks, their characteristics and a classification according to their propagation environment. Five path loss models are therefore selected for an empirical study. Three scenarios are defined: free space, wooded area, and built-up area. The measurement methodology and the description of hardware and software used during the study are then presented. The data, which were gathered during the measurement campaigns, are afterwards analysed and the results are interpreted. Finally, a new path loss model is proposed and its accuracy is analysed.

The fifth chapter presents the planning problem of wireless mesh networks. It begins by defining what a wireless mesh network is, its architecture and characteristics. To understand the planning phase of such a network, recalls in optimisation techniques are provided. Then the planning problem is tackled by presenting the constraints, the objectiveness, and the type of planning. At the end of this chapter, the planning problem of wireless mesh networks in rural regions is introduced.

The sixth chapter deals with the mesh router nodes placement in rural scenarios. The first section of this chapter provides a formulation of this problem and justifies the need of a meta-heuristic. The selected meta-heuristic algorithm is therefore presented: Simulated annealing. The tailoring of this algorithm to solve the present placement problem is detailed afterwards. The adapted algorithm tries to maximise the coverage while minimising the number of router nodes. The last section tries to optimise the cost by relocating router nodes. A multi-objective algorithm is therefore proposed: Pareto-Archived Reverse Simulated Annealing (PARSA).

The seventh chapter considers the situation in which areas to be covered with mesh router nodes are disjointed. It starts by defining a new placement approach comprising four steps: initial placement based on the prior approach; detection of sub-networks; connection of sub-networks; channel assignment. Since some algorithms used in graph theory are adapted later, some recalls are provided. An algorithm based on Breadth-First Search (BFS) is provided for the detection of sub-networks. To join the detected sub-networks, an algorithm based on the determination of the closest-pair and the convex hull is therefore proposed. The end of this chapter focuses on the channel assignment. The bridge problem is outlined with an algorithm to determine bridges based on Depth-First Search: DFS Extended-Bridge Determination (DFSE-BD). Channels are assigned using an algorithm based on BFS: BFS Extended-Spanning Tree Channel Assignment (BFSE-STCA).

2 Cameroon telecommunications and rural communities

Cameroon is a country in central Africa that covers an area of 475 442 km² with a population estimated at 23 130 708 of inhabitants in 2014 [World Statistics 2014]. Six countries border it: Nigeria, Chad, Central African Republic, Equatorial Guinea, Gabon, and Republic of the Congo. Because of its geological and cultural diversity it is called "Africa in miniature". It comprises natural features like deserts, rainforests, savannahs, beaches, and mountains. Cameroon hosts more than 250 different ethnic and linguistic groups. Official languages are French and English. Table 2.1 provides some socio-economic and demographic key factors of Cameroon [World Statistics 2014], [World Bank 2014], [CIA 2014].

2.1 Telecommunication system in Cameroon

As it was the case in most African countries, a national institution managed exclusively the telecommunication services in Cameroon before the 90s. But in 1995 the process of restructuring the telecommunication sector really started with the privatisation of public and semi-public enterprises [ITU 2001]. The first law governing telecommunications in Cameroon was promulgated in 1998. Two public enterprises were set up in the same year

Population (2014)	23.130.708
Density of the population (2013)	43.2 inh. / Km²
GDP in millions of dollars (2013)	25.800
Contribution of agricultural sector in GDP (2013)	20.6%
Agricultural Population (2004)	47.91%
Percentage of undernourished population (2011)	16%
Poverty headcount ratio at national poverty line (% of population 2007)	39.90%

Table 2.1 – Some socio-economic and demographic factors of Cameroon.

in September: CAMTEL (Cameroon Telecommunication) for fixed telephony service and CAMTEL Mobile for mobile telephony service. Almost two decades later, the telecommunication sector in Cameroon has undergone an in-depth transformation both on side of regulatory and institutional framework.

2.1.1 Network and Internet service providers

There are four accredited network operators in Cameroon presently: CAMTEL, Orange Cameroon, MTN Cameroon and recently Viettel rebranded Nexttel Cameroon. There is also one virtual network operator: SET'Mobile operating like Orange Cameroon support.

Cameroon Telecommunication (CAMTEL)

The fixed telephony is exclusively operated by CAMTEL, which is established by the Decree No. 98/198 of September 8, 1998 following the reform of the telecommunication sector. Initially, CAMTEL also had a 2G license, but it sold this license two years later to the South African MTN and satisfied itself with the operation of the fixed network. The fixed-telephone subscription represents only 3.59% of the market share today. To increase its market share, CAMTEL provided wings to fixed telephones by introducing in 2005 the CTPhone (city phone) project, which is the mobile version of CAMTEL's fixed telephone. But its total penetration (fixed and mobile) is still very low with 5.7% of market share representing not more than one million subscribers.

However, on September 26, 2014, CAMTEL marked its strong return on the market of mobile telephony with a 3G license with duration of 15 years, starting in January 2015 [Africatopsuccess.com 2014].

Orange Cameroon

The second operator after CAMTEL Mobile to enter the Cameroon's mobile telephony market is "Société Mobile du Cameroon" SCM, founded in 1999. Since 2003 it changes its name and operates as Orange Cameroon. Orange ranks second in the mobile market behind MTN today, with around six millions of active subscribers at the end of 2013; that means a market share of 41%. With an increase of 12% in coverage in 2013, Orange covers around 72% of the population [Orange.com 2014].

At the launch of the 9-digit dialling system on September 24, 2014, the Minister of Posts and Telecommunications called network operators to be more transparent and reiterated that consumers have the right to know the terms of the services they accept, including charges and other fees. Orange applied this recommendation just a few weeks later by sending automatically an alert after each call, telling to the customer the duration and the

charge of the call [Businessincameroon.com 2014]. MTN and Nexttel customers are still waiting such a service.

MTN Cameroon

Mobile Telephone Network (MTN) Cameroon bought back the CAMTEL Mobile 2G license for a duration of 15 years and started to operate in February 2000. It is the subsidiary of MTN International, whose head-quarter is in South Africa. It represents the largest mobile network in terms of coverage and users with around 10 million active subscribers that means 54.5% of the market share today.

After many complaints from MTN and Orange, the exclusivity of Nexttel on offering 3G services has finally turned down.

Nexttel Cameroon

After postponing many times the launch of its services since December 2012 when the concession agreement was approved, Vietnamese-owned Nexttel Cameroon finally launched its activities in September 2014. Nexttel services are present in all ten regions today. The 3G services are effective, particularly video calls using Tango application. However, the promise of dropping the price at15% to 20% was not met [Ecofin 2014].

Internet service providers

All network operators are also Internet service providers: CAMTEL, Nexttel, MTN Cameroon with MTN Network Solutions and Orange Cameroon with Orange Multimedia. In sum, more than 50 Internet Service Providers operate in Cameroon among these are Ringo, YooMee, Creolink, Matrix, Saconets. However, the percentage of individuals using the Internet in Cameroon is 6.40% [World Bank 2014].

2.1.2 Major projects from MINPOSTEL

Several projects in the field of posts, telecommunication and information and communication technologies are led by the Ministry of Posts and Telecommunications; some of them are undersea cables, Central African backbone, urban optical loops, National Broadband Network (NBN) project, e-post project, Pan-African network of online services and multipurpose community telecentres ([MINPOSTEL 2012], pp. 10-15).

Urban optical loops

MINPOSTEL has launched a vast construction of urban optical loops within some regional capitals in order to improve Internet accessibility and to reduce telecommunication costs.

The optical loop in Douala measuring 50 km, has already been received and the construction of the one in Yaoundé, measuring 67.681Km has already started. The towns of Buea, Limbe and Maroua measuring respectively 29.186km, 35.20km, and 49,423km will benefit from these investments in the coming months [Cameroon-tribune 2014]. In medium-term, the objective of the government is to take this infrastructure to all ten regional capitals. The Chinese company Huawei Technologies carries this work into execution.

National Broadband Network Project (NBN):

In contrary to the urban optical loops project, the NBN project aims to link the ten regions of Cameroon by optical fibre with the ultimate goal to cover the territory in broadband infrastructure and to provide people with home connections of 2 Mb/s. NBN in fact includes several components, among which the diversification of optical fibre networks, the development of mobile broadband Internet and the introduction of new generation of mobile networks. At the end of the project, NBN will be available to companies and several Cameroonian public administrations, providing services such as Triple Play (TV, telephone, Internet), high-definition TV, online video, online gaming, video conferencing, and so on.

E-Post

The postal sector plays an important role in the national economy. But this sector always faces real problems in Cameroon, particularly with the entry of the Internet. In its strategic plan to develop this sector, the government has begun improving the sector offerings and to boost existing services by upgrading the infrastructure of Cameroon Postal Services (CAMPOST), the public postal operator together with the People's Republic of China. The e-post project was created in this context. This project aims to construct a computer and telecommunication network for connecting post offices with optical fibre or wireless links; to build a data centre; to provide equipment and material and to train the staff.

Pan-African network of online services

Initiated on September 16, 2004 by the President of India, the Pan-African network of online services has the overall objective to interconnect the 53 countries members of the African Union by a telecommunications network via satellite and optical fibre, to provide communication for tele-education, telemedicine, Internet, video conferencing, and also support e-governance, e-commerce and meteorological services. Later, this network should allow the delivery of training contents and health care programs from regional universities towards other African countries.

2.1.3 Figures of the Cameroonian telecommunication sector

When looking at all these projects, the number of network operators and Internet service providers and the established legal and institutional framework, we may conclude that things are moving forward. Indeed things are moving forward but a lot of efforts still remain especially when comparing some telecommunication sector figures between Cameroon and Africa. The comparison of main telecommunication indicators between Cameroon, Africa and the World is given in Table 2.2 [World Bank 2014], [McKinsey 2014].

	Cameroon	Africa	World
Fixed-telephone subscriptions	3.59%	1.30%	16.20%
Mobile telephone subscriptions	70.39%	65.90%	93.10%
Fixed (wired)-broadband subscriptions	0.08%	0.30%	9.40%
Percentage of individuals using the Internet	6.40%	16.80%	37.9%
Internet contribution to GDP (2012)	1.20%	1,10%	3,7%

Table 2.2 – Telecommunication indicators in Cameroon, Africa, and World.

Despite the fact that the percentage of fixed-telephone subscriptions in Cameroon is three times greater than the one in Africa, it is still very low. But surprisingly the low percentage of fixed (wired)-broadband subscriptions in Africa is nearly four times higher than the one of Cameroon. Moreover, with percentages of mobile and fixed-telephone subscriptions greater than the ones in Africa, the percentage of individuals using the Internet in Cameroon is barely greater than a third of the percentage in Africa. Despite this low percentage of users accessing the Internet, the contribution of the Internet to the Gross Domestic Product (GDP) in Cameroon is higher than the one of Africa.

Why is the Internet penetration in Cameroon still very slow? A recent study from the Alliance for Affordable Internet (A4AI) pointed out the high prices for accessing the Internet and CAMTEL's monopoly on the management of the optical fibre in Cameroon [A4AI 2014].In their study on an affordability index, Cameroon is ranked 40th out of 46 countries surveyed. In the same direction, the report of ITU on *Measuring the Information Society* ranks Cameroon 152nd out of 169 countries concerning costs of fixed broadband [ITU 2012].

According to A4AI, Cameroon has also not yet developed an Internet Exchange Point (IXP); high costs are the consequence of the heavy taxation charged to network and Internet service providers in order to access the international gateway. Lowering the telecommunication taxes may lead to an extension of telecommunication services to underserved areas (last mile solution) and to improvements in quality of service ([GSMA 2014], p. 29).

The report of the McKinsey Global Institute [McKinsey 2013] presents the agricultural

sector as one of the six key sectors, in which the greatest impact of the Internet in Africa is likely to be concentrated; its contribution of 20.6% to the GDP in 2013 (not too far from industry with 27.3%) [CIA 2014] indicates not to wait for the last mile solutions from network and Internet service providers but to think about deploying first mile solutions from localities where agricultural activities are developing. These localities are indeed rural areas.

Presently, there is an on-going project from MINPOSTEL aiming to provide some ICT services to rural Cameroon: Multipurpose Community Telecentre.

2.2 Multipurpose community telecentres and rural areas

2.2.1 Project presentation

Rural areas are generally characterised in Cameroon as well as in many African countries by scattered settlements, low-income population, agriculture as predominant activity, low penetration of telecommunication infrastructure, difficult access to information, as well as to educational resources and to healthcare.

In 1998, competition in mobile telephony was introduced with the aim of providing a network coverage throughout the country. But mobile operators, which are profit-driven, are looking for more attractive regions, where the return on investment can be guaranteed. Doing so, they left the coverage of these rural regions to the responsibility of the government. In this situation, the government has designed Multipurpose Community Telecentres (MCTs) to be deployed in rural and sub-urban areas in order to reduce the digital divide between these neglected areas and urban ones.

A MCT is a public infrastructure for telecommunication services, computers and the Internet to enable access to telecommunication services and the Internet at a low cost to the whole local community. It should also be a support to all activities and projects of the area. Other services like postal services, money transfer, telemedicine and distance learning may also be part of the services offered by MCT [MINPOSTEL 2014]. The set of services a MCT can offer is presented in Figure 2.1.

2.2.2 Actual state

The initial goal when launching this project in 2003 was to create 2000 MCTs by 2015 but only 170 MCTs are deployed throughout the country in December 2014. Most of them are connected through VSAT technology, offering limited capacity with reduced service quality

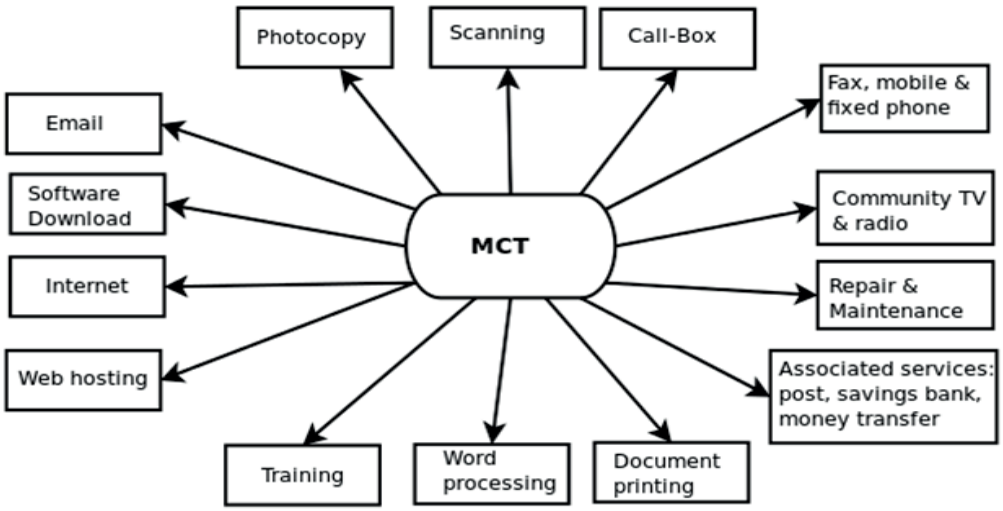


Figure 2.1 – Overview of services offered by MCT (Adapted from [MINPOSTEL 2014].

and extremely high costs. There are presently four operational community radio stations and ten being installed.

To strengthen the connectivity of MCT, the Ministry of Posts and Telecommunications has set up a program to switch over to optical fibre MCTs located in areas, where the optical fibre is going through. Indeed some MCTs are already connected to the optical fibre. Released VSAT will be redeployed in areas not yet served by optical fibre or difficult to reach. Figure 2.2 gives the distribution of MCTs throughout the country in December 2014.

Since a few months, a web portal has been developed to allow people living around telecentres to post some information. It is a kind of forum trying to group discussions by theme: agriculture, farming, tourism, health, trading, education, fishing, craft, and culture.

This project is really important since we count 330 townships with 305 rural ones (more than 92%) but the rural population represents only 41.60% in 2010, compared to 47.46% in 2002 in Cameroon [Trading Economics 2012]. This diminution of the rural population is mainly caused by exodus, as it is the case in Africa in general. This situation is a real hindrance to Cameroon, which intends to become an emerging country at the horizon of 2035, because its policy relies largely on agriculture that is mainly done in these rural regions. With its high contribution to GDP, the agricultural sector is a real pillar of the national development. Improving access to information and providing relevant information to rural areas can seriously help to improve local activities and to foster national development.

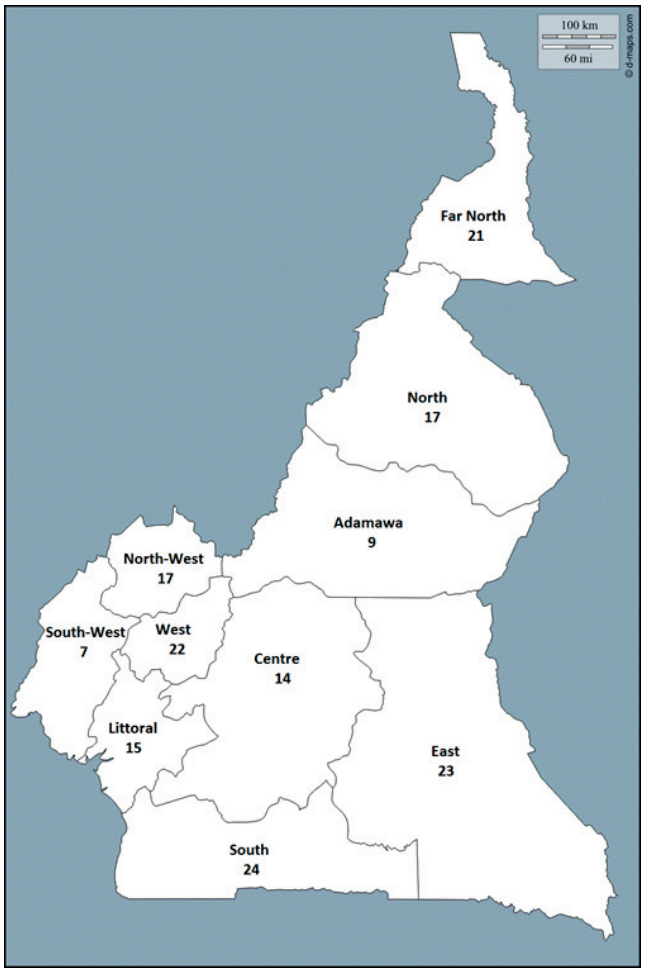


Figure 2.2 – Number of MCTs per region in Cameroon in December 2014 (Adapted from d-maps.com).

2.3 Selected rural communities in Cameroon

In order to design a network in rural regions we have analysed the situation in two rural areas in Cameroon: Mbé located in the Adamawa region not too far from Ngaoundéré and Garoua-Boulai located in the east region at the border with the Central African Republic. Figure 2.3 shows the locations of the selected communities.

2.3.1 Rural community of Mbé

The rural community of Mbé has been created in 1982 by the Decree N°082/455 of September 20, 1982 with an area of 3000 km². This community is composed of 43 villages. The population is estimated at 42,763 inhabitants with around 80% involved in agricultural activities. It has a flat terrain with slopes between 0 and 10% [CDP Mbé 2014].

Figure 2.3 – Location of the selected rural communities (Google Maps 2014).

2.3.2 Rural community of Garoua-Boulai

The rural community of Garoua-Boulaï covers an area of 2125 Km² with an estimated population of about 55,000 inhabitants in 2010. This community is composed of 51 villages. Agriculture is its main economic activity involving more than 80% of the population [CDP GB 2014].

Both communities own a MCT. The aim of the study of these regions is threefold:

1. To provide a real insight of ICT penetration and the local impact of MCT;
2. To find out concrete problems and challenges and to identify useful applications and services;
3. To propose some recommendations on network (re) organization and service design for local impact and sustainability of the project.

2.4 Requirement analysis

2.4.1 Methodology

A questionnaire and two structured interviews have been designed to carry out our research. Because of the lack of infrastructure, mainly Internet connexion, and the lack of skills for using online survey tools, the more appropriate methods are using a questionnaire and personal face-to-face interviews. The interviewer can affect the sample member's response. To reduce this effect, the sample member shall itself fill the questionnaire. A team member assists only if the sample member cannot read or write.

Questionnaire

Questions are grouped into four parts: questions 1 to 6 intend to describe the socio-economic situation; questions 7 to 10 aim to depict the ICT utilisation; questions 11 to 15 intend to portray the telecentre impact, and questions 16 to 18 aim to identify important e-services and the affordability of the local population. The questionnaire is translated into two languages (English and French); it is given in Appendix A.

Structured interviews

Structured interview are business people and telecentre managers. The aim of these interviews is to retrieve relevant information to help people doing business, to improve their activities, and also to learn from the experience of telecentre managers what can be done and what can be avoided. The structured interviews for telecentre manager and business people are provided in Appendix B and C.

We discussed also with directors of local schools, persons responsible for public services and healthcare centres, and we retrieved important information from the Communal Development Plan. These documents are elaborated by the National Participatory Development Program (PNDP). The 2004 implemented program aims to improve the living conditions of the population in rural areas, particularly the most disadvantaged.

2.5 Results and interpretation

202 persons responded to the questionnaire: 90 in the community of Mbé and 112 in the community of Garoua-Boulai, 151 men and only 51 women.

2.5.1 Socio-economical aspect

According to the Community Development Plan of Mbé [CD PMbé 2014] and that one of Garoua-Boulaï [CDP GB 2014], 80% of the local population is involved in the agricultural sector.

Regarding the educational level, almost half of the sample declared to have a secondary level. Less than 10% did not go to school and around 13% have a primary level of education. Around 30% have at least the certificate for university entrance. This last category mainly consists of civil servants and lecturers.

French is the most dominant language spoken by nearly 92% per cent of the sample, before FoFoulbé (60%), which is one of the local languages. English is not so common (35%) and is essentially spoken by those, who are also used to French. These figures may also reflect the fact that local languages tend to be not practiced. However, to be understandable, services and applications should use French as language for the human machine interface.

Concerning the incomes, 20% do not mention their incomes. However, a third of the sample has no more than 25000 XAF (38 EUR) per month. That means less than 1.25 EUR per day. So the purchasing power is very low as it is the case in many other rural regions.

2.5.2 Telecommunication device availability

Half of the sample indicates to have access to a computer at home, at school, in the office, or somewhere else. Figure 2.4 shows that more than 92% have a telephone or a smartphone and around 8% own a tablet. Only less than 5% do not possess a telecommunication device. These figures indicate the fact that ICT is gradually penetrating the rural and suburban region. This shows also that developing applications and services targeting telephones may be the best option.

Almost all computers run with Windows as operating system. The main reason is that these computers have been bought with a pre-installed Windows. The results also show that around 70% of telephones have a browser. However, numerous browsers offer just basic features using the Wireless Application Protocol (WAP) instead of real HTTP.

Regarding the computer usage, Figure 2.5 shows that a third of the sample has never used a computer while approximately the same percentage is using a computer on a daily base, and half at least once per week.

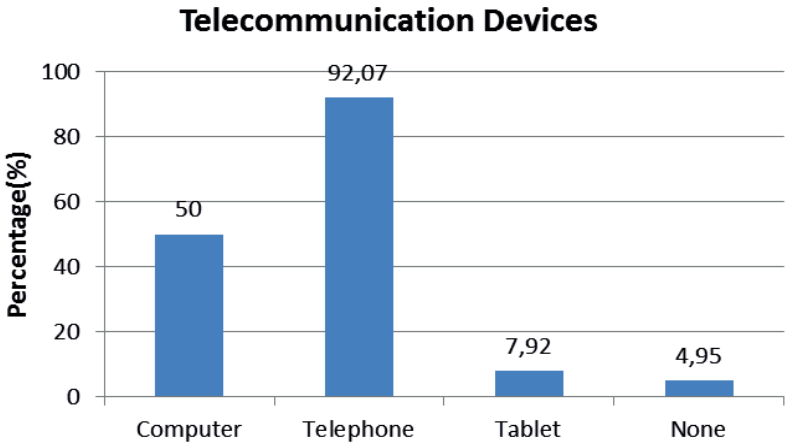


Figure 2.4 – Availability of computing devices in selected areas.

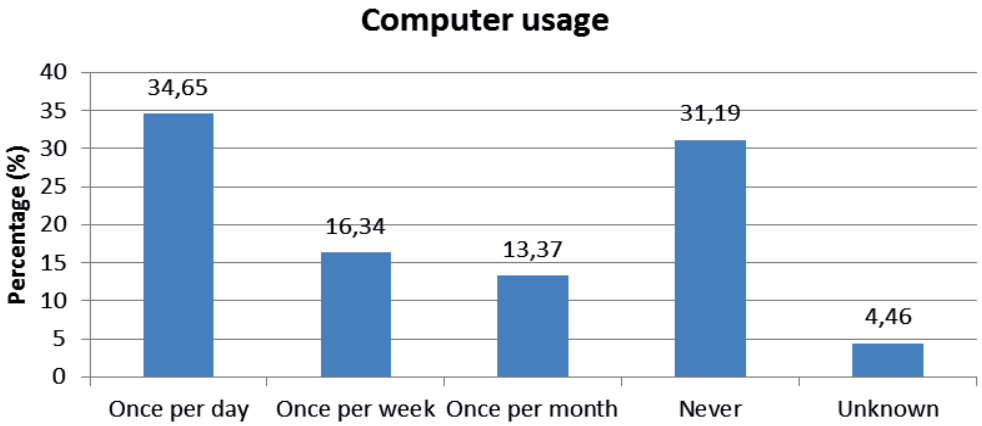


Figure 2.5 – Computer usage in selected areas.

2.5.3 Internet adoption

As it is shown in Figure 2.6, around half of the respondents indicated not having a personal opportunity to access the Internet. The majority of those who have access to Internet use only their telephones or smartphones. One of the most important reasons is the cost of the equipment (USB dongle or router); the connexion fees are also very expensive for this social category. For example, offers from MTN are 350 XAF (0,53 EUR) per day with a limit of 150MB of data; 8000XAF (12,19 EUR) per month with a limit of 1GB. These offers slightly differ from those of Orange.

The Internet has been never used by around 40% of the sample because of the still very expensive costs. Nevertheless, just less than a quarter recognises using the Internet on a daily or weekly base.

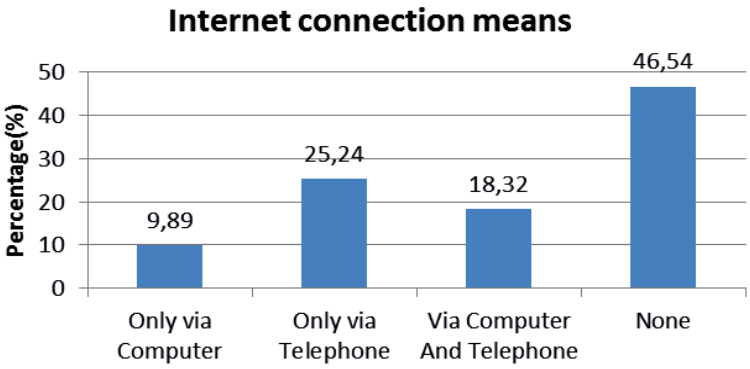


Figure 2.6 – Means of connections to the Internet in selected area.

2.5.4 Telecentre assessment

Figure 2.7 shows that telecentres are located in the centre of the community close to the population. 40% mentioned that they are living in a radius of less than one kilometre around the telecentre and a total percentage of 77% live not more than three kilometres away from it.

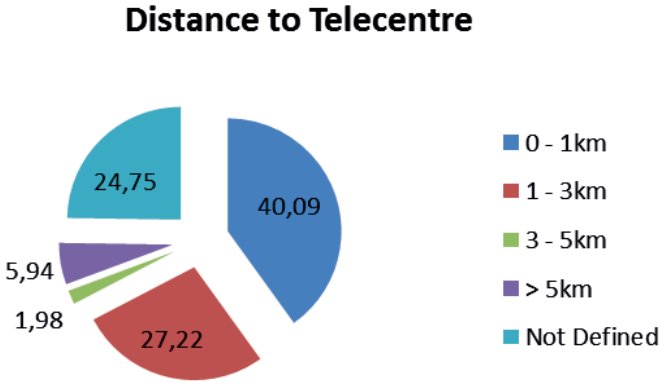


Figure 2.7 – Distance to telecentres in selected areas.

Despite the fact that more than two third of the sample are located at not more than three km from a telecentre, 70% of the sample are never gone to it, as shown in Figure 2.8. A great number of clients spends just one hour in the telecentres. They could spend more time but the cost of a working session is very expensive for them, around 300XAF (0,46 EUR).

Figure 2.9 shows that the few number of telecentre clients principally use it for education by performing some research in Google or accessing some online encyclopaedias like Wikipedia. Beside education, some people are using the telecentre for working purposes.

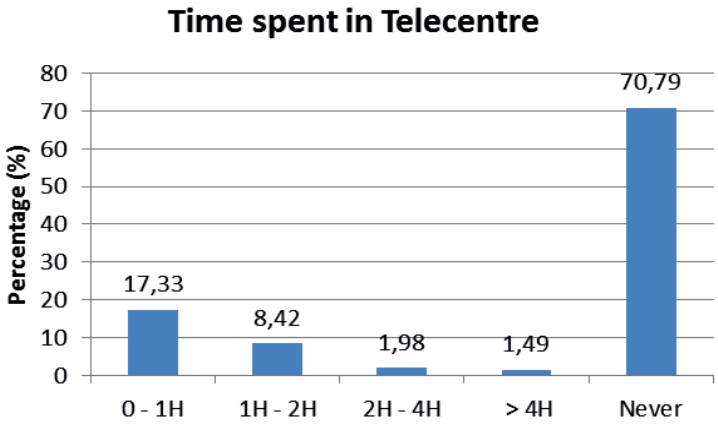


Figure 2.8 – Time spent in telecentres in selected areas.

Keeping in touch with relatives is the concern of less than a quarter of the telecentre clients.

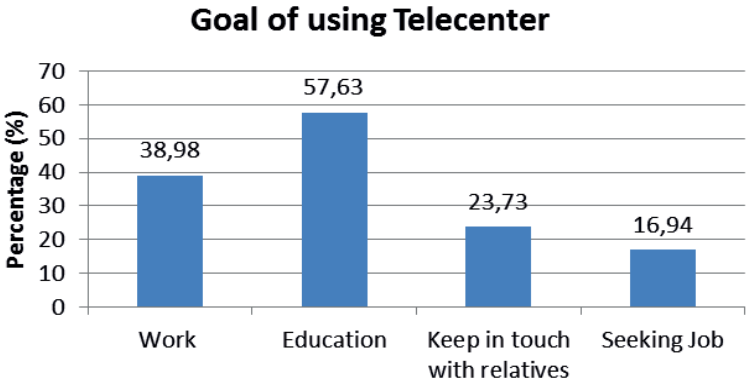


Figure 2.9 – Goal of using telecentres in selected areas.

2.5.5 Web and social networks

As presented in Figure 2.10, the most used website is Google with 44% of the sample. Since it is a search engine, it is known by almost all of those who access the Internet. Yahoo is also known but usually as no more than a messaging service. With around 40%, Facebook is the most famous social network. With these figures and adding the fact that more than two third of the sample have telephones with a browser, developing web-based solutions for these regions may be more efficient.

Services providing voice over IP like Skype are not really known. Youtube is known by less than 10% of those accessing the Internet.

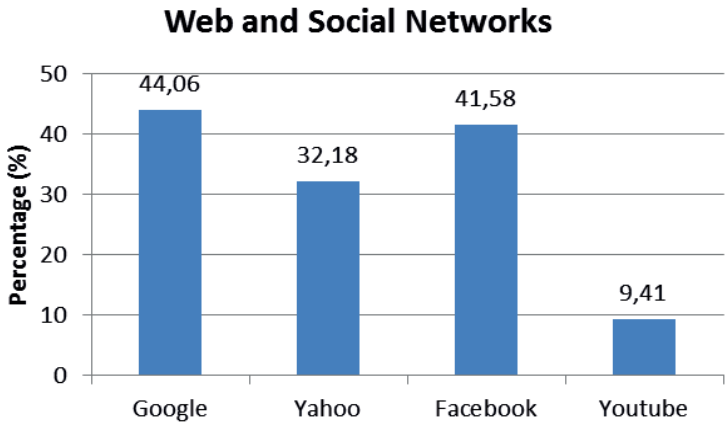


Figure 2.10 – Usage of websites and social networks in selected areas.

2.5.6 Affordability

With very low incomes, around 40% of the sample are ready to pay no more than 1000XAF (1,52 EUR) per month. Only 26% declare to be able to pay at least 5000XAF (7,62 EUR) per month. This result shows also that only around 10% are able to afford the monthly offer of mobile operators (12,19 EUR). A monthly fee should be set to not more than 2500 XAF (3,80EUR) in order to allow the majority to afford the service. The affordability of the sample is presented in Figure 2.11.

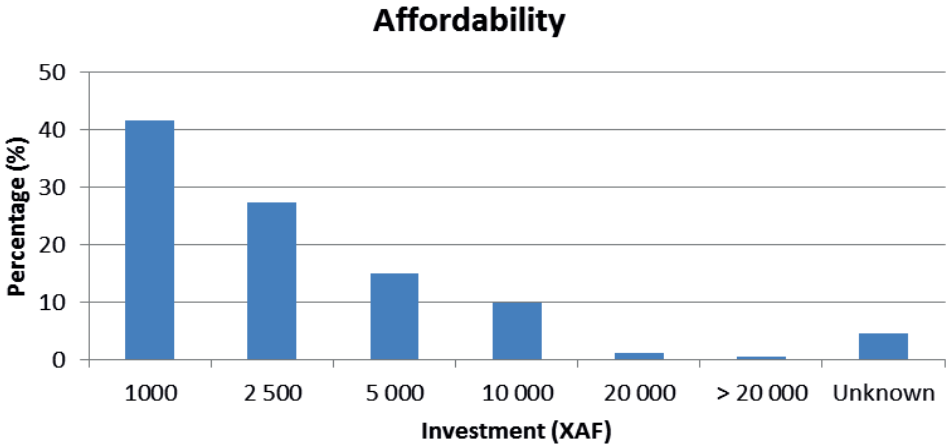


Figure 2.11 – Affordability in selected areas.

2.5.7 Desired services and applications

As shown in Figure 2.12, e-education appears to be the most desired service. This is confirmed by the fact that education is the most important reason of using telecentres. Moreover, the result is closed to the result from the ITU analysis on global survey on rural communication [Kawasumi 2004]. E-health is the second most important and e-administration the third one.

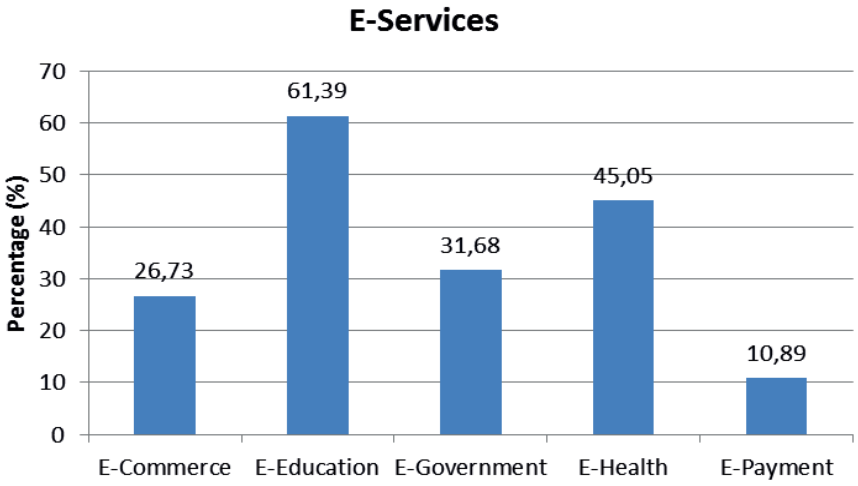


Figure 2.12 – Desired e-services in selected areas.

In the light of these results the impact of MCTs on the local population is very low since only few people know about it. Despite this fact, the ICT penetration shows the readiness of the local population to welcome ICT projects and the potential of these projects to sustain the local development. However, to achieve this last goal, ICT projects should overcome local challenges and meet local needs.

2.6 Local challenges and needs

Besides the results coming from the questionnaires, some challenges and needs were found via observations, interviews, and the Communal Development Plans.

2.6.1 Local challenges

Power problem

Only 53.7% of the population in Cameroon has access to electricity in 2011 [World Bank 2011]. Even urban regions suffer from frequent blackouts. Most of rural regions have either

no electricity or a very bad quality.

The community of Mbé does not have an electricity network from the national company (AES-Sonel rebrands ENEO); people are instead using the communal generator, which is functioning only between 6pm to 6am. During our study in April 2014, the communal generator was broken down.

On the contrary, Garoua-Boulaï has access to the national electricity network. However, the multiple outages and the instability of voltage make the equipment very vulnerable.

Communication limitations

In Mbé and Garoua-Boulaï, as in most parts of rural Cameroon, there exists no newspaper; a national TV signal is also not available and the local radio is not functioning. Network operators are almost missing. Even when a signal from a network operator can be reached, this signal is very poor resulting in bad communication.

Technical skills limitation

Normally, network maintenance of the MCTs is ensured by some network engineers from MINPOSTEL. But their number is very low for the whole country. Therefore faulty equipment is sometimes out of service for a long time. Most MCT managers are not network technicians. They have just learnt by doing how to deal with some problems in order to allow the MCT running. Those who have some skills in computers and networks prefer to leave when they get a better position elsewhere. To deal with this problem of lack of technical skills, MINPOSTEL is opening a maintenance centre in collaboration with the National School of Posts and Telecommunications.

Local mentality and culture

A very big problem is corruption; the whole country is affected. A lot of projects are failing because some people are waiting for a bribe before signing a document. In addition many thefts and assaults are reported especially in Garoua-Boulaï with the flight of refugees coming from the Central African Republic. However, with increasing literacy of the population, culture is no longer a problem. MCT managers and some local authorities share this view.

2.6.2 Local needs

Among the locally identified needs, three sectors are more glaring than others since they are affecting directly the local development.

Need to support the educational sector

Results in the educational sector are very bad. Local schools are experiencing very high failure rates in official exams. For example the pass rate to the Primary School Leaving Certificate was 11% in Mbé in 2012 [CDP Mbé 2014]. A solution for the following problems is needed:

- Lack of qualified teachers especially in mathematics, French language and English;
- Lack of infrastructure (classrooms, laboratories) and teaching material especially books;
- Poor monitoring of pupils by parents.

There is presently a project on the improvement of the quality of primary education in rural areas called *Project d'Amélioration de la Qualité de l'Education de Base* (PAQUEB). This project aims to deploy schools in rural regions with the necessary infrastructure to improve the quality of education. In Mbé is a pilot school of this project provided with computers and solar panels to overcome electricity problems. But even this school is suffering from the lack of teachers and teaching materials.

Need to support the agricultural sector

The main local activity is agriculture. Almost all interviewed business people are involved in this activity. This sector is facing a lot of problems among them:

- Looking for funding: people would like to improve their productivity but they are financially limited. Presently, the government is running a lot of projects aiming to finance the agricultural sector in rural areas. But these projects are unknown to a great part of potential recipients. In Mbé for example, the lack of information (no newspaper, radio out of service, no TV) is worsening the situation.
- Looking for seed and fertiliser: besides looking for funding, people are also looking for seed and fertiliser at very low cost.
- Looking for information about market prices: because of the lack of information about market prices, farmers are sometimes selling off their products.

To sustain this sector, there is a need for providing farmers with relevant information before starting their activities (funding, seed, fertiliser, materials), during their activities (organisation, technics) and after their activities (storage, selling).

Need to improve healthcare

The health sector needs to be supported. As everywhere else in rural regions, this sector is facing the absence of doctors, shortage of skilled staff and infrastructure and difficulties in drugs supply.

Up to now hospitals are suffering from missing sensibility about critical diseases as well as from deficient information about screening and vaccination campaigns. The most widespread tool for such a task is the radio. But in Mbé the local radio is out of service, and in Garoua-Boulaï the functional capacity of the community radio is limited. Other means should be found for sensitizing them. A potentially fruitful idea is to take advantage of the great penetration of mobile telephones.

2.7 Discussion and recommendations

The analysis of the questionnaires and the results from interviews lead to some recommendations in order to overcome identified challenges and to meet local needs. These recommendations can be classified into three main categories: network design, software utilisation, and Business strategy.

While some works are focusing on network design [Nungu/Bjorn/Nsubis 2008] and others are paying attention to the development of services [Noutat/Ndie/Tangha 2013], [Louenkam/Gaspard/Ndie 2013], we argue that these tasks are linked and that they influence each other; they should therefore be considered as a whole. The design of the network should keep in mind not only infrastructural, environmental and cultural challenges but also the ICT profile of the local population, the legal framework and the requirements of the services that shall run on it. The design of services should meet local needs and make use of the ICT availability.

2.7.1 Network design

The design of the network should consider the following recommendations:

Covering areas of interest

Since rural areas in Cameroon as in many other African countries are generally characterised by scattered settlements, there is no need to cover a whole region. Only areas of interest should be covered to minimise deployment cost. Therefore, wireless mesh networks are more cost-efficient than the infrastructure of common national network operators.

An area of interest should satisfy some criteria:

- There is a need to be met or a problem to be solved by the network;
- Recipients should be able to access the network. That means they have the required compatible equipment;
- Recipients should be able to contribute to the sustainability of the network.

Lowering CAPEX: using off-the-shelf materials

To lowering capital expenditures, low cost materials should be used. For example routers and servers can be based on standard PC hardware using free and open source software [Nungu/Bjorn/Nsubis 2008].

Catching and caching

Despite the fact that some MCTs are switched onto the optical fibre, the majority of MCTs will stay connected by VSAT technology, which provides a very small and costly bandwidth. There is therefore a crucial need to reduce external traffic, since the bandwidth is very small (256 or 512Kbps in downlink and half in up). Thus, the first attempt to optimise the bandwidth is to use a caching proxy. It reduces the bandwidth and improves response times of frequently requested web pages by caching and reusing them.

Distance monitoring

Due to the lack of local capacity in network administration, it is important to allow distance monitoring [Nungu/Bjorn/Nsubis 2008]. This can be done by providing remote login to all network components by configuring free monitoring tools such as *Icinga* (backward compatible to Nagios), *nmap*, *ntop*.

Independent powering

To overcome the challenge of powering devices, an independent source of powering should be used. Solar panels are very good candidates since the climate in many regions in Cameroon is most of the time sunny.

2.7.2 Software utilisation

The way software is sending and receiving data could affect the network performance especially when the traffic is external. To optimise the network performance, the following recommendations should be applied:

Using free software

With 98% of computers using Windows as operating system, system update and updates of antivirus programs and other Windows applications could require huge amount of outgoing traffic as reported in [Nungu 2011].

Therefore, to save bandwidth and also to avoid illegal use of licensed applications, it is important to switch on free software. Free operating systems like Linux allow the creation of local repositories containing most of the packages we could need. By creating a local repository, programs are downloaded from the Internet to local repository once and from this they can be installed on any computer connected to the local network.

Making contents locally available

Using local repositories and caching proxies is a good attempt to make a better use of bandwidth. Nevertheless, this can still be optimised by hosting useful online materials locally. So, the external traffic will be limited, contributing in saving bandwidth.

Coupling Web and SMS

Web content can be accessible via Wifi and readable by a browser using smartphones or computers. Despite the fact that around 70% of telephones have a browser, these browsers offer just basic features by using WAP instead of real HTTP. Moreover almost all these telephones do not have a wireless interface such as Wifi to directly communicate with the network. Therefore we are obliged to consider SMS.

2.7.3 Business Strategy

Creation of local market

The first reason why people do not access the Internet is not the costs but rather the lack of knowledge about the benefits of using the Internet ([GSMA 2014], p. 38). Thus, the creation of a local market goes via information and sensitising of the population about the benefits of ICT and the Internet in their daily live. Presenting some success stories might help to stimulate some sceptics. However, having the will is not enough. People should also have the capacity in using electronic services. Therefore, building capacity is of great importance.

Public Private Partnership

The great beneficiary of building first mile solutions in rural areas is the government. In fact, most of the services and infrastructure deployed in rural areas are public because

enterprises, which are looking for profit, are not interested in these regions. But the government alone cannot provide a sustainable first mile solution. The analysis of MCTs showed their limitation and the poor impact on the local population. The government should be accompanied in this task by the private sector and the local population. For synergy effects it is important to point out the role, which each stakeholder might play.

Different access: local and Internet

The costs of accessing the Internet are still very high even for those living in urban and suburban Cameroon. With the low capacity and the high costs of the Internet in rural regions, it is important to provide different access possibilities:

1. Bronze Package -Local access: the user can access local services and local content at very low costs;
2. Silver Package - Local access + specific online services: the user can access local services and local content + some specific online applications, for example to retrieve market prices of product;
3. Gold Package - Local access + Internet: the user has access to local services and local content + Internet.

In this chapter we depicted the telecommunication system in Cameroon by giving an insight into the legal and institutional framework; we also gave an overview over operators and actual large projects. After presenting the MCT project designed by the government to reduce the digital gap between rural and urban Cameroon, we portrayed the ICT penetration in two rural communities. The results showed that the impact of MCTs on the local population is very poor despite the readiness of the local population to adopt ICT in their daily life, and the potential of ICT to boost the local development. Although some challenges are identified, switching from MCT to a rural wireless community could support the local development. To achieve this with a particular consideration of sustainability, we provided some recommendations in three plans: network design, software utilisation and services development, and business model.

As we said, the network specifications depend on the requirements of those applications that shall run on it. But this factor is not the only one. To operate a judicious choice, it is crucial to provide a framework for network technology selection. Moreover, we recommended covering only areas of interest. To achieve this, it is also important to predict the behaviour of the signal in these regions.

3 Wireless technologies in rural areas

The first recommendation in the previous chapter about the network design is to cover only areas of interest around a telecentre. To achieve this goal, we should select a suitable technology satisfying the identified constraints. Although wireless options are appropriate for difficult-to-wire areas, the selection of a suitable technology among these wireless options is not trivial.

This chapter presents the most common wireless communication systems with emphasis on wireless network technologies. It also points out the different constraints associated with the selection of a specific technology for rural areas, in particular the areas we are studying. Finally the choice of a Wi-Fi mesh network over WiMAX is discussed as well as the selection of 802.11n among the Wi-Fi standards.

3.1 Wireless communication systems

The inconvenience and the expensiveness of extending wires into rural regions require wireless communication systems. These systems are based on radio transmission in which a transmitter sends information to a receiver using a radio frequency (RF) signal. In such a configuration, the characteristics of the radio channel depend particularly on the operating frequency and the transmission mode ([Stüber 2002], p. 39). However, a Line of Sight (LOS) is necessary to achieve a good communication quality. According to their position relative to earth, we distinguish two groups of wireless communications systems: Orbital and terrestrial.

3.1.1 Orbital wireless communication

It is not always possible to ensure a LOS between transmitter and receiver, especially in long distances or when we want to reach remote or isolated areas (Islands, sea station ...). In these scenarios, orbital communication appears as an appealing solution.

Orbital communication involves two types of equipment: ground-based equipment (the transmitter and the receiver) and orbital equipment (a satellite or a balloon).

Satellite communication

A satellite for this purpose is normally called artificial in order to differentiate it from a celestial body that orbits another body. A satellite is an artificial object intentionally placed into the orbit in order to serve different purposes. Several application requirements and restrictions result in three classes of satellites: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) ([Schiller 2003], p. 165).

In the early 1990's, communication satellites designed for telecommunication purposes have been used to provide the Internet into remote areas. This technological breakthrough brought Internet access to areas, which seemed impossible to be reached. GEO satellites are used in telecommunication; they are located at 35790 Km above earth ([Zhao et al. 2012], p. 615).

A typical configuration of a satellite communication is the one presented in Figure 3.1[1]. The process works as following [vsat-systems.com 2015]:

1. A request for data transfer is sent from end a user PC to the indoor satellite modem, which modulates the signal and transmits it to the VSAT (Very Small Aperture Terminal) dish. The VSAT dish converts this signal to a RF signal and sends it to a satellite located in the orbit at the speed of light (3.10^8metres per second).
2. The satellite in the orbit receives this signal and sends it to one of the VSAT teleport systems, which is a ground station of the satellite communication.
3. The request then goes to the VSAT Hub NOC, which retrieves the requested data from the Internet backbone.
4. Finally, the requested data are sent in reverse direction to the end user. This journey of around 145 000 Km across millions of dollars of infrastructure lasts approximately 560 milliseconds ([Nirmala/Pujeri 2012], p. 40).

[1] Figures 3.1 and 3.2 are created with Creately.
https://creately.com

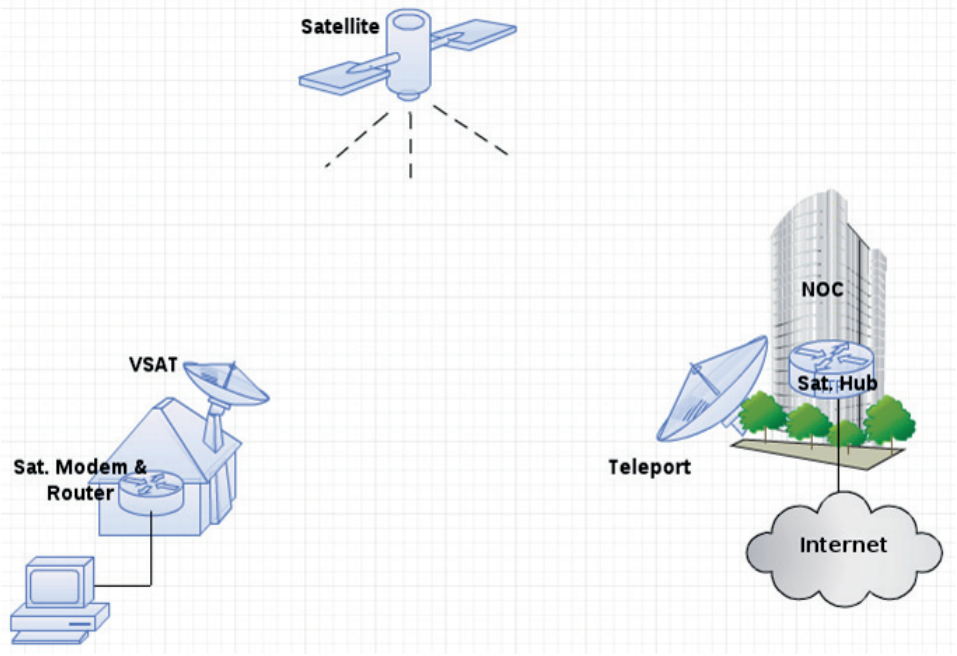


Figure 3.1 – Wireless communication based on satellites.

Due to the lack of infrastructure, satellite communication is one of the simplest ways to connect rural and suburban regions. In fact, a single GEO satellite could cover 40% of earth ([Manohar 2001], p. 8). But this advantage goes along with some limitations. First there is a need of LOS between the end user VSAT and the satellite. Also satellite communication experiences a bandwidth limitation due to a shared download carrier with a bit rate ranging from 1 to 40 Mbit/s and shared between at most 4.000 users [Technology inventory 2012]. Finally, the cost of data traffic is still very expensive for rural regions. That is why it is used as a last mile solution to provide connectivity to a particular point such as a telecentre or an E-Kiosk.

We have two VSAT Hubs in Cameroon: “C” band and “Ku” band, both operating at 18 MHz ([NAICT 2007], p. 22). Most MCT deployed in rural and suburban Cameroon are using VSAT with a downlink of 256 KB/s.

Balloons

A more recent system similar to satellite communication is the one of balloons lifted above the earth. Because of their high altitude between 18 and 37 Km above earth they are normally called high-altitude balloons considerably used to gather information about the weather.

The idea of using balloons in telecommunication was put forward by Jerry Knoblach,

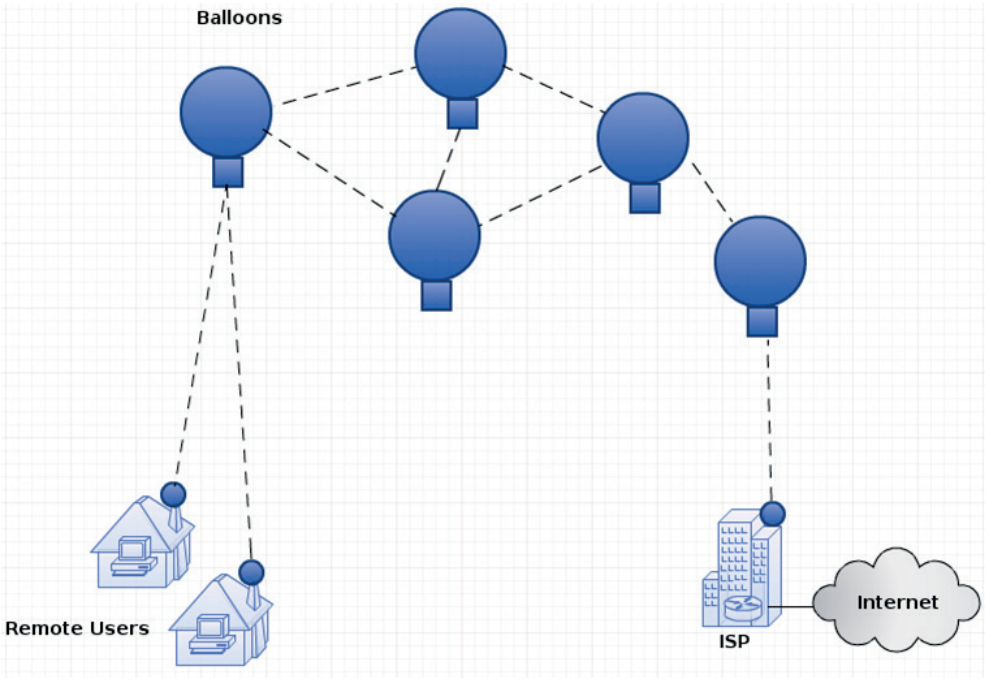


Figure 3.2 – Wireless communication based on balloons.

founder and chairman of Space Data Inc. the first time in 2001. The aim was to provide specialised telecom services to truckers and oil companies [Sharma 2008]. But this idea has been widespread with the launch of the Google project called “Loon” in rural New Zealand only since June 2013. In this project, balloons float in the stratosphere twice as high as airplanes, and go where they are needed. Google established partnerships with telecommunication companies in order to share the cellular spectrum and thus enable people to connect to the balloon network directly from their phones and other LTE-enabled devices [Loon 2015]. In contrary to satellite communication where only one satellite is involved in a communication, the signal is passing across a network of balloons and back down to the Internet on earth as depicted in Figure 3.2.

By covering a large area, around 40 times the area covered by a base station of a cellular network, balloons are an interesting alternative to get rural and remote areas connected. Moreover, they do not require as carefully calculated or technical launches as satellites [Codr 2008].

However, balloons share some disadvantages with satellites such as the need of LOS and the possible interference in communication caused by weather. In addition, the lifetime of balloons in space is very short and requires balloons to be re-released once they drop down. It is also not easy to track down balloons despite the fact that they are equipped with a GPS [Sharma 2008]. Balloons are not easily used in long term connectivity, because of their

limited lifetime in space. However, an interesting application is to help people to regain communication quickly after a natural disaster [Shibata et al. 2009], [Itnewsafrica.com 2013].

Although this kind of project may be successful in rural regions of developed countries, its adoption in rural Africa is still very difficult since users should have smartphones or LTE-enabled devices, which are not yet common here. Nevertheless, Google pumped a lot of work into its project Loon to make it a viable solution to connect remote areas. Google is in talks with the Indian government at this time„ in order to launch project Loon in India by 2016 [Bhatnagar 2015].

Orbital solutions are usually used as last mile solution to connect rural or remote areas, especially a point of interest within the community. Connecting the rest of the community usually requires terrestrial wireless communication systems.

3.1.2 Terrestrial wireless communication

Terrestrial wireless communication implies a direct communication between transmitter and receiver without a third orbital system. All components involved in the signal transmission are ground-based in this type of communication. Terrestrial wireless communication encompasses cellular and wireless networks.

Cellular networks

Cellular networks have experienced an explosive growth since their first generation in the 1980s. This type of networks operating with a base station model is the heart of every mobile telephone system. Initially designed to establish and to maintain phone conversation, cellular networks have known great improvements and can presently support high-speed data transfer.

The basic architecture of a cellular network from a telecom service provider comprises:

1. The base station subsystem containing base transceiver stations (BTS) with an antenna and base station controllers (BSC);
2. A mobile switching centre (MSC) which contains the home location registers (home and the visitor location register for handling voice calls and text;
3. A packet switched network for handling mobile data;
4. The link to the public switched telephone network (PSTN).

With the ever increasing market share of smartphones in the mobile market and the huge number of mobile applications accessing the Internet, offers from telecom service providers presently include different packages for Internet access in order to fit customers' desires.

Although the GSM network is available in all African countries, there is a great disparity in the coverage. While Egypt and South-Africa had 100 % GSM coverage other countries like Mali or Ethiopia had less than 20% [GSMA 2009] in 2009. The main reason is that cellular networks are only cost effective for areas with high population densities and an acceptable affordability. The cost of the base station subsystem is too expensive to make the cellular approach economically viable in rural areas, especially in sparsely populated regions where the low number of inhabitants are not potential users because of their low affordability.

Since the cellular approach is not economically viable, most of the rural networks are based on wireless ones, which provide more economical solutions.

Wireless networks

Initially designed for short or home coverage, wireless networks have been progressively improved for covering outdoor environments. These types of networks are particularly suitable since we are considering in this work that the telecentre has already an Internet connection. Then we are not planning a last mile solution to bring the Internet to a rural community; we are rather thinking about how to deploy a first mile solution within a local community starting at the telecentre.

This type of networks is the most used today; it proposes different technologies with different characteristics. Before discussing the fittingness of each technology to a rural area, it is necessary to present the constraints guiding their selection in such areas.

3.2 Rural constraints to wireless network technology selection

Although there are a quite good number of wireless alternatives to connect rural areas, the selection of a particular technology depends on some constraints tied to these areas. Among the constraints pointed out we have: cost, energy consumption, application requirements, coverage constraints, and legal framework.

3.2.1 Cost of the overall system

One of the biggest concerns is indeed the cost of the overall system. Among the recommendations provided in chapter 3, we talked about lowering the CAPEX by using off-the-shelf material. CAPEX does not depend only on the cost of the network technology, but it also encompasses all costs related to the system setup. The first mistake that must be avoided is considering only the cost of the network technology while omitting the accompanying infrastructure. The second mistake to be avoided is not to consider the operational expenditures (OPEX) of the system, mainly maintenance cost and possibly the license cost for using a licensed band. A suitable wireless network technology should minimise both CAPEX and OPEX.

3.2.2 Energy consumption

The power problem is not only a matter of rural regions in developing countries; suburban and even urban areas are suffering from its instability or scarcity. The way of powering equipment has a direct impact on the cost and the performance of the network. Using national electricity usually results in frequent shortages and the damage of equipment because of the bad quality of power. To overcome this problem, another recommendation in chapter 3 was to use independent powering sources, particularly solar panels, due to the sunny climate in sub-Saharan regions. This option may increase CAPEX due to the independent powering system, but the OPEX could be significantly reduced. The power limitation of solar panels implies that a suitable technology should require as less power as possible to allow a long-lasting life of the powering source. But the transmission range is proportional to the consumed power. Thus, low power wireless technologies usually offer limited range transmission. Therefore, a suitable technology should offer a good compromise between the energy consumed and the transmission with respect to the coverage constraint.

3.2.3 Application requirements

The quality of service (QoS) required by some applications imposes strong constraints on the network technology selection. The QoS depends not only on the type of application, which enforces the acceptable latency, but also on the number of simultaneous users in the network, which influences the required throughput.

Latency

Video and voice applications have been pointed out as the more useful type of service in

Type of application	Requirements	Information
Text Messaging	< 1 Kbits/s	Non-connected and tolerates high latency
E-mail	1 to 100 Kbits/s	Non-connected and tolerates latency
Web browsing	50 to 100 Kbits/s	Not connected and tolerates latency
Audio streaming	96 to 160 Kbits/s	Connected with constant amount of a relatively large bandwidth
Voice over IP	24 to 100 Kbits/s	Connected with constant amount of bandwidth
Video streaming	64 to 200 Kbits/s	Connected high throughput and low latency
Peer to peer	0 to max throughput	Tolerate any amount of latency, but tend to use up all available throughput

Table 3.1 – Application requirements in terms of throughput.

rural regions during a long time; this because of the low literacy level observed in these regions or the need of distant interaction especially for medical intervention. But text-based services like mobile payment, market price services, online platforms for agriculture, weather services and so on are knowing a rapid growth and a real success presently. This is justified by the fact that these services are more useful for rural communities since they sustain local activities.

Latency could be tolerated if the network provides text-based or non-connected services like e-mail and web browsing. But if connected services such as voice over IP are expected to be supported by the network, then the latency should be as low as possible.

Throughput

The throughput depends also on the type of the application in addition to the number of simultaneous users. Although the density of the population in rural areas is low, we should note that this population is not distributed throughout the entire region; it is rather concentrated in some sparse locations. Estimation of throughput should consider the number of potential users in the areas to be covered.

Table 3.1 provides requirements in terms of throughput and latency according to the type of application ([Butler et al. 2013], p. 178). The throughput indicated in this table is the requirement for one user.

Location	Designation	Elevation (m)	Estimated area (m²)
H1	St. Joseph Hospital	1022	60.000
H2	Protestant Hospital of Garoua-Boulaï	1034	50.000
H3	MSF (doctors without borders)	1029	40.000
M	Market place	1034	360.000*
MCT	Telecentre	1031	70.000
PS1	Sub-prefecture	1027	100.000
PS2	Town hall	1033	360.000*
SC1	Franco-Arabic School	1025	100.000
SC2	Public Primary School	1032	360.000*
SC3	Bilingual High School	1024	60.000
SC4	CETIC of Garoua-Boulaï	1012	80.000
* Represent the same area			

Table 3.2 – Characteristics of areas of interest in Garoua-Boulaï.

3.2.4 Coverage constraints

Network planning in rural areas has been about planning long-distance links to connect distant points of interest for a long time. So a suitable technology should be able to establish long-distance links. But the meaning of "long-distance links" is relative and depends on areas to cover or the distant points to be linked. In addition, the transmission range depends on the type of antenna. Directional antennas are suitable for point to point communication but they require LOS. In contrary to directional, omnidirectional antennas are used for point to multipoint communication but afford shorter range transmission. Therefore, a transmission range of a wireless technology could be short in a scenario, but long enough in another one.

Figure 3.3 presents the location of areas of interest in Garoua-Boulaï. In this scenario, a link from the telecentre (MCT) to the farthest area of interest (SC4) should be at least 2 Km. Table 3.2 provides some characteristics such as the elevation profile and the total areas of interest.

3.2.5 Legal framework

The spectrum that a wireless equipment is using is regulated by a regulatory body, depending on each country.

The industrial, scientific and medical (ISM) radio bands have been internationally reserved

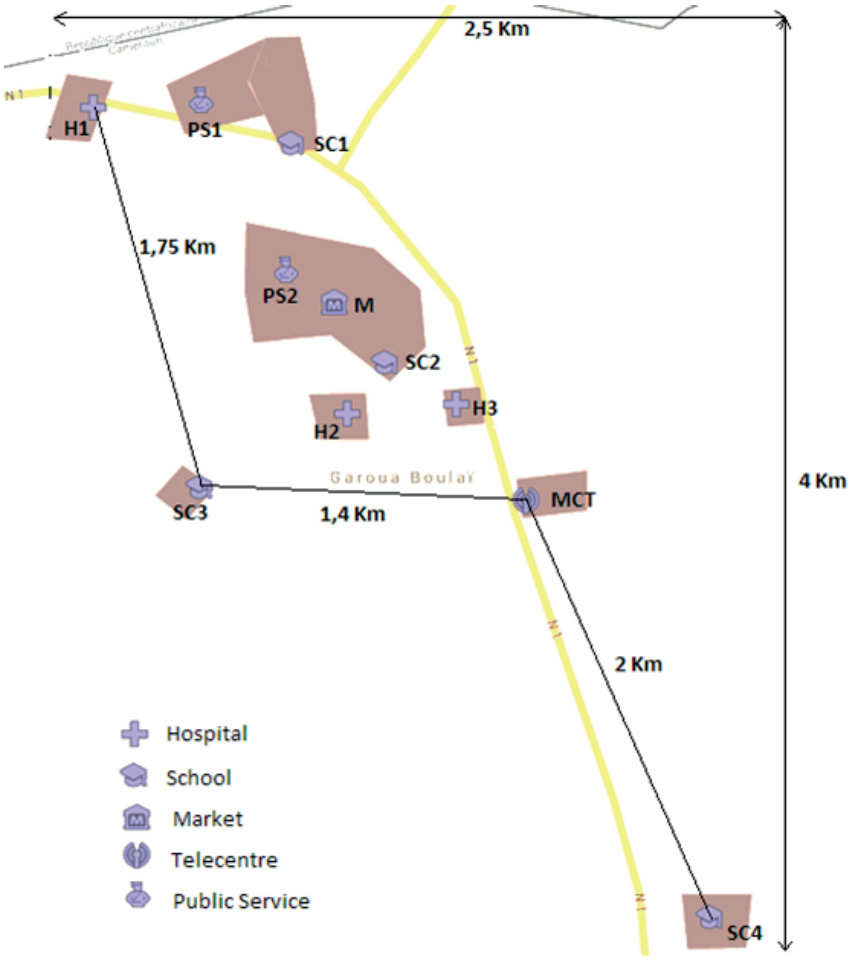
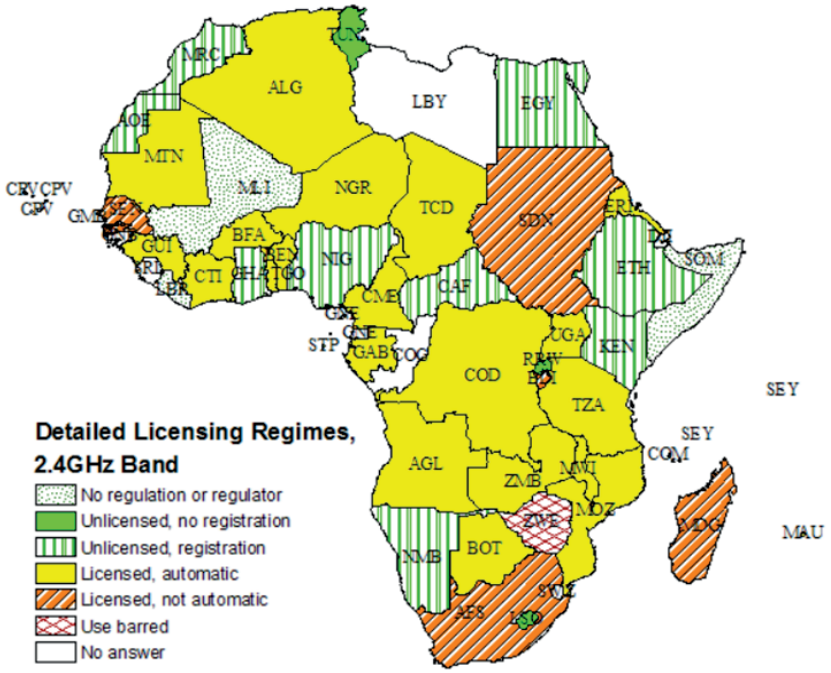


Figure 3.3 – Areas of interest in Garoua-Boulaï (Google Maps 2014).

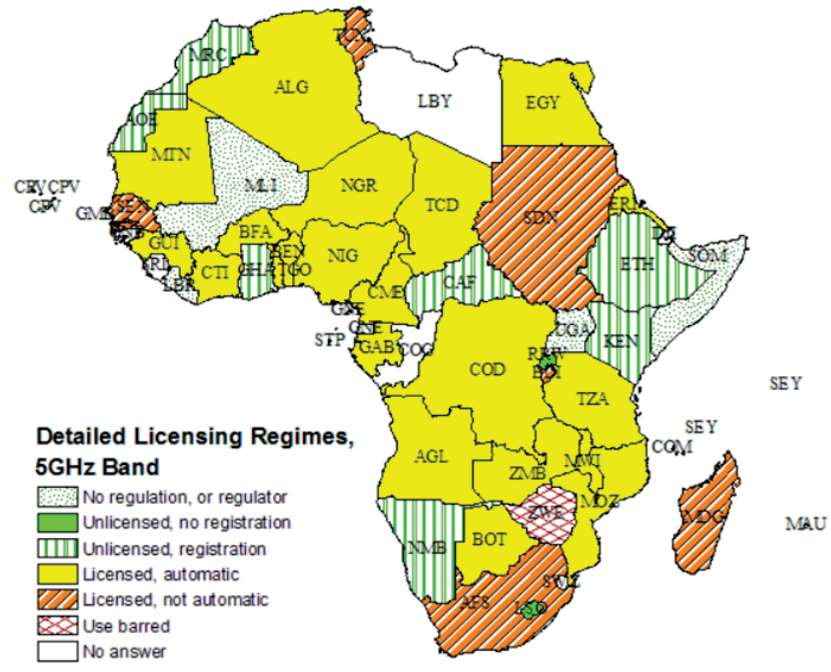
for the use in industry, science and medicine. If these frequencies are unlicensed because of a regulatory vacuum in some countries, ISM bands are subject to some restrictions or a license in other countries. Figure 3.4a and Figure 3.4b provide the map of licensing regimes for respectively the 2.4 GHz and 5 GHz bands in Africa.

In their study about license-exempt wireless policy in Africa, Neto et al. found that more technical restrictions are applied to unlicensed bands. The main technical restrictions in using a particular unlicensed band are the limitation of power output or the circumscription of the allowed transmission range ([Neto/Best/Gillet 2005], p. 77).

Article 36 of the Decree n° 2012/1638/PM of 12 June 2012 states that electronic communication networks opened to the public in rural areas are subject to a license ([Decree1638 2012], p. 10) in Cameroon. Article 37 in the same decree states that experimental or temporary networks are also subject to a license. But this license of second category is more restrictive.



(a)



(b)

Figure 3.4 – Map of licensing regimes for the 5 GHz band: (a) 2.4GHz band; (b) 5GHz band. Adapted from ([Neto/Best/Gillet 2005], pp. 78f.)

All these constraints are mutually dependent and the respect of some constraints may imply the dissatisfaction of others. For example the technology that uses less power will satisfy the energy constraint and may respect also the legal framework, but the range of transmission could be not long enough to satisfy the coverage constraint. Therefore, a compromise should be found between the constraints by defining priorities.

3.3 Wireless network technology

The Institute of Electrical and Electronics Engineers (IEEE) comprises several working groups aiming to define different standards for wireless network technologies. Besides these IEEE working groups, some industry groups certify the product based on these standards. Two relevant examples of these industry groups are the Wi-Fi Alliance for IEEE 802.11 standard and WiMAX Forum for IEEE 802.16 standard.

Wireless Network technologies are generally classified by their transmission range. Thus we have a Wireless Personal Area Network (WPAN), a Wireless Local Area Network (WLAN), a Wireless Metropolitan Area Network (WMAN), and a Wireless Regional Area Network (WRAN). We will present standards that are most implemented in the market of wireless network technologies in the following sections.

3.3.1 Wireless Personal Area Network (WPAN)

WPAN is based on the 802.15 family of standards that are developed with the aim of providing connectivity in short range. The most used standards in this category are 802.15.1 (Bluetooth) and 802.15.4 (ZigBee).

802.15.1 (Bluetooth)

Bluetooth is a specification published by the Bluetooth special interest group. Bluetooth has been designed for small devices requiring low power consumption.

The first version of Bluetooth (v1.0) has been released in 1999. Hence, 802.15.1 has known a real improvement and is present in most recent portable or mobile devices. The latest version v4.2 has been released in December 2014. Bluetooth standard is operating in the 2.4 GHz band. To avoid interference with other technologies operating in the same band, Bluetooth is using a different signalling method ([Tjensvold 2007], p. 1).

Common Bluetooth devices on the market provide medium performance with a data rate up to 3 Mb/s and a short-range transmission not exceeding 100 metres. Consequently, they are not able to cover a great region or to establish long links to connect distant locations.

802.15.4 (ZigBee)

The IEEE 802.15.4 standard is known as ZigBee. But in reality, ZigBee is an enhancement of this standard and operates in the 868 MHz, 915 MHz, and 2.4 GHz ([Tjensvold 2007], p. 2). ZigBee is promoted by the ZigBee alliance and offers low power and short to medium range transmission in the 2.4 GHz band ([Geier 2010], p. 32). ZigBee offers low performance with a data rate of 250 kb/s at 2.4 GHz, 40 kb/s at 915 MHz, and 20 kb/s at 868 MHz. Its transmission range varies between 10 and 75 meters. ZigBee requires very low power and is more cost-effective than Bluetooth for low performance applications such as telemetry.

3.3.2 Wireless Local Area Network (WLAN)

WLAN technologies also called Wi-Fi are based on the 802.11 standards and offer coverage capacity ranging from the size of a building to a citywide environment. The IEEE 802.11 working group has defined different standards since almost two decades.

Initial 802.11

The initial WLAN standard has been ratified in 1997. It specifies the use of both Direct-Sequence Spread Spectrum (DSSS) and Frequency-Hopping Spread Spectrum (FHSS) for the transmission of data in 2.4 GHz. This standard specifies an expected data rate of 1 Mb/s for DSSS and 2 Mb/s for FHSS.

Products based on this initial standard did not know a real success because of their high price and the fact that some wireless data collector vendors were reluctant to move from proprietary wireless technologies to devices based on the initial 802.11 standard ([Geier 2010], p. 20).

802.11a

Two years after the initial 802.11 standard, the IEEE 802.11 working group ratified the 802.11a standard. This standard specifies the use of Orthogonal Frequency-Division Multiplexing (OFDM) with a data rates up to 54 Mb/s in the 5 GHz band.

The main advantage of this standard is the improvement of the data rates compared to the initial 802.11 standard. This improvement comes from the fact that the 5 GHz band is mostly free from sources of RF interference (compared to 2.4 GHz) and this band defines a greater number of RF channels that do not overlap in frequency. However, the specified transmission range is of 20 meters in indoor and 100 meters in outdoor.

802.11b

The IEEE 802.11 working group ratified the 802.11b physical layer with the aim to provide higher data rates when operating in 2.4 GHz still in 1999. Thus, the DSSS physical layer has been enhanced to include additional 5.5 Mb/s and 11 Mb/s data rates.

But 802.11b users experienced important degradation in throughput because of the great deal of RF interference in the 2.4 GHz band ([Geier 2010], p. 22). Moreover, 802.11b offers only up to three non-overlapping channels. So to avoid inter-access point interference, each 802.11b-based access point must be set to a specific channel when operating in the same area.

802.11g

The IEEE 802.11 working group ratified the 802.11g standard in 2004. This standard offers higher performance than 802.11b with a data rate up to 54 Mbps. However, since it operates in the 2.4 GHz band, it cannot offer more than three non-overlapping channels. Consequently, systems based on the 802.11g standard provide less capacity than 802.11a, which is operating in the 5 GHz band.

802.11n

The IEEE 802.11 working group ratified the 802.11n standard in 2009. This standard offers higher performance than previous standards with multiple-input multiple-output (MIMO) technology. This technology overcomes interference issues, and consequently improves the reliability. It provides also data rates up to 258 Mbps when using four antennas.

802.11n is backward compatible to the previous standards 802.11a and 802.11g and it can operate in both the 2.4 GHz and 5 GHz bands ([Geier 2010], p. 23).

802.11s

802.11s is an amendment of IEEE 802.11 standard that defines how multiple wireless devices can connect with each other to form a mesh network. It is not an independent standard and it is associated to one of the previous mentioned standards.

802.11ac

802.11ac has been ratified by the IEEE 802.11 working group in 2013. This recent standard is an evolution of 802.11n. It enhances the provided data rates by offering eight data streams, compared to four offered by 802.11n. Nevertheless, it does not improve the transmission range since it is operating only in 5 GHz band.

3.3.3 Broadband Wireless MAN (WMAN)

IEEE has set up the 802.16 standards working group in 1999. Two years later, the first 802.16 standard was approved.

The IEEE 802.16 standards family is commercialised under the name WiMAX (Worldwide Interoperability for Microwave Access) and recognised as an IMT 2000 standard in 2007. Today, most of the WiMAX systems are based on two specific IEEE standards: 802.16d and 802.16e. However, a more recent standard 802.16m is already approved.

802.16d WiMAX release 1.0

Also known as 802.16-2004, this standard has been released in 2004. It aims at fixed wireless applications and is described by the WiMAX forum as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL" [Radio-electronics.com 2015a].

Although it is suitable for DSL replacement applications, it is more used for backhaul where the final data may be distributed further to those using Wi-Fi.

802.16e WiMAX release 1.5

Released in 2005 and known as 802.16-2005, this standard is an amendment to 802.16d for supporting mobility. The aim to define this standard was to provide high data rates to users on the move at a cost less than what is provided by cellular services.

With a data rate lower than 802.16d, 802.16e provides the ability for users to connect to a WiMAX cell from a variety of locations; there are future enhancements to provide cell handover [Radio-electronics.com 2015b].

802.16m WiMAX release 2.0

IEEE802.16m has been officially designated by ITU as IMT-Advanced 4G technology in 2010 and approved in 2011 by the WiMAX Forum ([Ayvazian/Schwartz 2012], p. 5). WiMAX 2.0 is based on this standard that operates in frequencies less than 6 GHz. It offers a data rate of around 100 Mbps for mobile applications and 1 Gbps for fixed.

In contrary to WPAN and WLAN technologies that require only a transmitter and a receiver, WiMAX networks offer a more complex architecture. The major entities in the architecture of a WiMAX network are:

- Remote or mobile stations that represent the user equipment that may be mobile or fixed. This equipment is called customer premise equipment (CPE).

- Access Service Network (ASN), which is that area of the WiMAX network that forms the radio access network at the edge. The more visible part of ASN are WiMAX towers similar in concept to towers used for cellular networks.
- Connectivity Service Network (CSN), which provides the IP connectivity and all the IP core network functions [Radio-electronics.com 2015c].

Most WiMAX solutions offer data rates at tens of megabits with a theoretical transmission range of 50 Km. But in reality, the range is between 5 and 20 Km depending on the density obstruction between the transmitter and the receiver. WiMAX can operate both in the licensed and unlicensed spectrum ranging from 2 to 66 GHz by using Scalable Orthogonal Frequency Division Multiplexing (SOFDM) technique. However, most deployments are using the 2.5 and 3.5 GHz licensed band and the 5.8 GHz unlicensed band ([Geier 2010], p. 27).

The deployment cost of a WiMAX network is high even when operating in unlicensed bands because of the relative expensive hardware comprised in the architecture.

3.3.4 Wireless Regional Area Network (WRAN)

Also called Super Wi-Fi, the IEEE 802.22 is a standard defined for the Wireless Regional Area Network (WRAN). This standard uses the unused spectrum within the television bands. This unused spectrum also called television white space (TVWS) ranges from 54 to 862 MHz. The transmission range of 802.22 is between 17 and 30 Km radius. In good conditions, the transmission range can reach 100 Km. But this is achieved at the expense of the data rate that is theoretically not more than 10 Mbps. In reality, the offered downlink is 1.5 Mbps and the uplink 384 Kbps.

IEEE 802.22 is a point to multipoint technology (P2MP) requiring a base station (BS) for transmitter and customer premise equipment (CPE) as WiMAX installed at each end point.

Products based on the IEEE 802.22 standard are not yet available, however the first BS and CPE based on the IEEE 802.22 standard operating in the TVWS ranging from 470 to 710 MHz has been developed by the NICT [NICT 2013].

Figure 3.5 summarises the characteristics of wireless networks; Table 3.3 provides a summary of common wireless standards. In this table, the data rate of the 802.11n standard considers two streams (four antennas) ([Rakesh/Dalal 2010], p. 3).

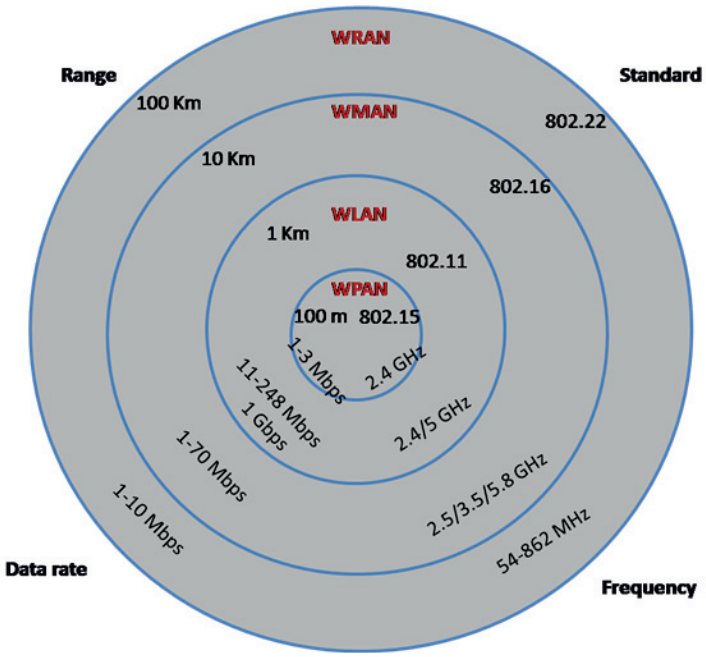


Figure 3.5 – Characteristics of wireless networks.

Standard	Frequency	Data Rate	Range	Type
802.11a	5 GHz	54 Mbps	120 m	WLAN
802.11b	2.4 GHz	11 Mbps	140 m	WLAN
802.11g	2.4 GHz	54 Mbps	140 m	WLAN
802.11n	2.4 / 5 GHz	248 Mbps	250 m	WLAN
802.11ac	5 GHz	1.3 Gbps	-	WLAN
802.15.1	2.4 GHz	3 Mbps	100 m	WPAN
802.15.4	868/915 MHz 2.4 GHz	20/40 Kbps 250 Kbps	75 m	WPAN
802.16d	2 – 11 GHz	63 Mbps	50 Km	WMAN
802.16e	2.3, 2.5-2.7, 3.5 GHz	15-30 Mbps	5-10 Km	WMAN
802.16m	< 6 GHz	100 Mbps (Mobile) 1 Gb/s (Fixed)	3, 5-30, 30-100 Km	WMAN

Table 3.3 – Characteristics of common wireless standards.

3.3.5 Selecting a suitable technology

After presenting rural constraints to the selection of wireless network technologies and the technologies themselves, it is necessary to discuss, which technology is fitting our scenario.

The first constraint we will consider is the coverage. In Table Table 3.2 presenting the characteristics of the areas of interest from our scenario, the total estimated area is about

one Km². This area could double if we consider also residential locations. In this case, WPAN technologies that offer very limited ranges are not suitable. In addition, although they are power-efficient, they are not designed to work in a continuous mode. Moreover, even if they could be meshed to cover a large area, they will require a huge number of elements. Finally, their low data rates cannot serve a great number of users. Therefore, WPAN is not suitable in this scenario. Since WRAN technologies are not yet commercialised, a choice should be made between Wi-Fi and WiMAX technologies.

Wi-Fi technologies have a shorter transmission range than WiMAX. However, by meshing Wi-Fi routers, a larger area could be covered. But choosing a Wi-Fi mesh or WiMAX should be applied on a case-by-case basis.

3.3.6 Wi-Fi mesh or WiMAX?

A great number of routers in a mesh network could degrade its performance. This is due to the fact that the number of hops decreases considerably the data rates. In addition, meshing implies the need to roam from one cell to another. This may be harmful for some connected applications such as voice and could result in service disruption.

Using WiMAX could reduce the rate of roaming and the risk of service disruption. But this happens only when connected applications with frequent use are expected being supported by the network. However, to provide high performance, WiMAX should operate in the licensed spectrum. It requires higher transmitting power to achieve a long transmission range ([Geier 2010], p. 26). These constraints imposed by WiMAX networks increase significantly the cost of this technology: the way of powering and the license for spectrum utilisation. Moreover, even when operating in an unlicensed spectrum, WiMAX requires relatively expensive materials. One of these materials is the tower required to reach a long distance. In irregular terrain with mountains and valleys, a higher tower is generally required. But in our scenario, the profile provided in Table Table 3.2 shows an elevation variation of about 10 m. This means that the tower could be avoided and a long link could be established by using directional antennas with the condition to find a LOS. A last but not the least point to consider is the fact that WiMAX technology requires users to afford a CPE in order to access the network. This is a disadvantage of WiMAX over Wi-Fi, since the latter does not require additional material because it is already embedded in a lot of mobile and portable devices.

After the comparison of WiMAX and Wi-Fi technologies, it appears that the use of Wi-Fi technology is more suitable for our scenario.

3.3.7 Why 802.11n?

A 802.11n-based network is what we should deploy for many reasons today:

1. 802.11n can work either in the 2.4 or the 5 GHz band or in both. This is a great advantage of 802.11n over 802.11ac, which operates only in the 5 GHz band. Providing two bands is an interesting point since in the planning of the network, backhaul could work in 5 GHz while access points that serve clients could work in 2.4 GHz.
2. 802.11n is backward compatible to 802.11g and forward compatible to 802.11ac. That means every 802.11g/n/ac-based device could access the network.
3. The range of 802.11n is twice the range of 802.11g. That means the coverage capability of 802.11n is four times the one of 802.11g. This reduces the number of routers and consequently the number of hops and handoffs due to roaming.

We discussed the selection of wireless technologies in rural regions in this chapter. According to our scenario, the suitable technology is Wi-Fi, especially based on the 802.11n standard.

To plan the wireless network using this technology optimally, it is important to predict how the signal is propagating in an environment similar our scenario. This shows the necessity of a suitable prediction model.

4 Path loss models

Wireless networks can provide very bad performance if they are not well planned. The difficulty is to predict the quality of links by estimating the path loss of the signal. Also called signal attenuation, the signal path loss is essentially the reduction in power density of an electromagnetic wave or signal as it propagates through the environment in which it is travelling [Radio-electronics.com 2015].

To predict the quality of the signal, empirical path loss models are generally used. But they are usually tied to a particular environment with particular configurations such as the equipment, the frequency of the signal, the height of the antenna and the distance between the transmitter and the receiver. Despite the plethora of path loss models [Egli 1957], [Okumura 1968], [Hata 1980], [Erceg et al. 1998], [Medeisis/Kajackas 2000], just few are considering propagation at 2.4 GHz [Tummala 2005], [Liechty 2007].

In this chapter, we are interested in providing a more accurate empirical model for predicting signal path loss at 2.4Ghz using off-the-shelf 802.11n in outdoor. Thus, we do a measurement campaign in three different scenarios: free space, wooded area and built-up area. Afterwards, we compare the results with the path loss predicted by selected models. Finally we improve the best one.

4.1 Prediction models for wireless networks

The prediction of signal attenuation between a transmitter and a receiver is an important task in wireless network planning. But this task is always challenging. Several works trying to predict path loss in wireless networks exist in the literature. They can be grouped into two sets: deterministic models and empirical ones.

Deterministic models, also called theoretical methods, are based on the physical phe-

nomena of radio wave propagation. There are different types of theoretical methods: geometric methods also called multi-ray models taking into account reflected and transmitted rays [Tan/Tan 1995], [Sun/Tan/The 2005], and digital or discrete models based on solving Maxwell's equations [Taflove/Hagness 2005], [Rana/Mohan 2012]. But in practice, their implementation usually requires a huge knowledge of the environment, which is sometimes difficult or impossible to obtain. Algorithms used by deterministic models are usually very complex and require a lot of computation because the more we want to be accurate, the more the computational load increases. Because of this reason, the use of deterministic models is limited to indoor environments or to well-defined and small size outdoor environments.

The development of statistics and probability helped to design a different approach by making observations and measurements in the field without an exact knowledge of the environment. In this approach, the calculation of the signal path loss is made along a single radius shown by the line connecting the transmitter and the receiver. These methods help to reduce the computational complexity and increase the prediction accuracy of signal attenuation. This second class of models is called empirical model.

4.1.1 Characteristics of path loss models

The path loss of a signal is expressed as the ratio in decibels between the transmitted power and the received power using the following expression (4.1).

$$PL = 10\log_{10}\frac{P_t}{P_r} \tag{4.1}$$

Where:
PL: Signal path loss (dB)
Pt: Transmitted Power (dBm)
Pr: Received Power (dBm)

By using the Friis equation [Friis 1946], we obtain (4.2)

$$PL_{fs} = 10\log_{10}\frac{(4\pi d)^2}{G_t G_r \lambda^2} \tag{4.2}$$

By considering antennas as isotropic; that means G_t=G_r=1, we obtain (4.3)

$$PL_{fs} = 20\log_{10}\frac{(4\pi d)}{\lambda} \tag{4.3}$$

With $c = \lambda f$, f frequency in Hz and $c = 3.10^8 m.s^{-1}$, we finally obtain (4.4)

$$PL_{fs} = -147.56 + 20\log_{10} d \ + 20\log_{10} f \tag{4.4}$$

By changing the unit of frequency and the distance of equation (4.4) we finally obtain (4.5).

$$PL_{fs} = \begin{cases} 92.4 + 20\log_{10} d + 20\log_{10} f & \text{with } d \text{ in Km and } f \text{ in GHz} \\ 32.4 + 20\log_{10} d + 20\log_{10} f & \text{with } d \text{ in Km and } f \text{ in MHz} \end{cases} \tag{4.5}$$

Path loss models are built from the basic model (4.4) or (4.5). Their key parameters are:

- Distance: We note that the path loss is increasing at a logarithmic rate depending on the distance between the transmitter and the receiver.
- Frequency: Expression (4.4) depends on the wavelength, which means that two waves of different frequencies do not fade in the same way.
- Gain of the antennas: The higher the antenna gain, the higher the received signal will be.

The calculation of signal path loss between the transmitter and the receiver considers in practice other factors such as:

- Obstacles: In outdoor as well as in indoor environments, a signal may encounter several elements that absorb part of its power such as walls, trees, buildings, mountains and even rain in an outdoor environment. When there is no obstruction between the transmitter and the receiver, the transmission is said to be in Line of Sight (LOS); when there is at least one obstacle, the transmission is said to be in Non-Line of Sight (NLOS).
- Height of antennas: Heights of transmitter and receiver antennas also influence the signal since they depend on the field where antennas are deployed, especially because of the Fresnel zone. This zone is an elliptical region surrounding the line-of-sight path between the transmitting and receiving antennas [Newplans.net 2015].

4.1.2 Propagation environment

An important parameter in signal path loss prediction is the size of the cell in which the signal can be predicted. That means the maximal distance between the transmitter and the receiver. According to this parameter, path loss models can be grouped into different categories [Pahlavan/Krishnamurthy 2002].

Mega-cellular areas

In mega-cellular areas communication is taking place over hundreds of kilometres. Because of their large size these areas are mainly served by mobile satellites usually LEO and GEO. The free space path loss model is generally used to predict the signal attenuation, but with different fading characteristics.

Macro-cellular areas

Communication in macro-cellular areas is taking place over a few kilometres to tens of kilometres. That corresponds to the coverage area of a common mobile telephony base transceiver station. Extensive measurements of signal path loss have been performed in numerous cities in the world, resulting in different empirical path loss models for macro-cellular areas in the literature. Usually these models consider signal frequency around 900MHz, 1800MHz, and 1900MHz. The most popular empirical path loss model for macro-cellular areas is the Okumura model established in 1968 [Okumura 1968].

Micro-cellular areas

In micro-cellular areas the distance between the transmitter and the receiver ranges from hundreds of metres to one or two kilometres and the height of the transmitting antenna is below the average level of building roofs. Some deterministic models have been developed for micro-cellular areas, taking into account diffraction theory with multiple reflections along street wall sand diffractions around street corners [Tan/Tan 1995], [Sun/Tan/The 2005]. However, since deterministic models are very complex and require a deep knowledge of the environment, empirical models are usually preferred.

Pico- and Femto-cellular areas

A typical size of a Pico-cellular area ranges from 30 to 100 metres, corresponding to a building or to a part of a building. Models usually observe path loss inside buildings. These models make use of the penetration loss factors of partitions and floors in a building. These factors are determined empirically by observing the signal going through a partition (soft or hard partition) or from a floor to the next one. Most common path loss models for indoor attenuation are the ITU Model for indoor attenuation [ITU 1997] and the Log-distance

path loss model [Seidel/Rappaport 1992].

Communication in Femto-cellular areas is taking place over a few tens of metres using low power devices with limited range transmission.

Most of the path loss models have been developed in macro- and micro-cellular areas. The list of most common path loss models is presented in Table 4.1 and their expressions are given in Appendix D. Figure 4.1 provides a dependency graph between these models.

Models	**Condition**	**Reference**
|-Free space		[Friis 1946]
|-Egli	$f \in]30; 3000[$	[Egli 1957]
|-One Slope		[Seidel/Rappaport 1992]
|-Dual Slope		[Seidel/Rappaport 1992]
|-Log Normal Shadowing		[Andrade/Hoefel 2010]
|-Partitioned		[Andrade/Hoefel 2010]
|-Liechty	f $\approx$ 2400	[Liechty 2007]
|-Okumura	$f \in]150; 1920[$; $d \in]1; 100[$; $h_{tx} \in]30; 200[$; $h_{rx} \in]3; 10[$	[Okumura et al. 1968]
|-Okumura-Hata	$f \in]150; 1500[$; $d \in]1; 10[$; $h_{tx} \in]30; 200[$; $h_{rx} \in]1; 10[$	[Hata 1980]
|-COST 231 Hata	$f \in]150; 2000[$; $d \in]1; 20[$; $h_{tx} \in]30; 200[$; $h_{rx} \in]1; 10[$	[Cichon/Kürner 1993]
|-Hata-Davidson	$f \in]150; 1500[$; $d \in]1; 300[$; $h_{tx} \in]30; 200[$; $h_{rx} \in]1; 10[$	[Brown/Gregory 1997]
|-Rural	$f \in \{160; 400; 900\}$	[Medeisis/Kajackas 2000]
|-ITU-R	$1.5 < f < 2$; $1 < d < 10$; $30 < h_{tx} < 200$; $1 < h_{rx} < 10$	[NIST 2006]
|-ECC-33	$700 = f = 3500$; $1 < d < 10$; $20 < h_{tx} < 200$; $1 < h_{rx} < 10$	[ECC 2003]
|-Green Obaidat		[Green/Obaidat 2002]
|-Erceg	$f \approx 2000$; $1 < h_{rx} < 2$	[Erceg et al. 1998]
|-SUI	$2500 < f < 2700$; $0.1 < d < 8$; $20 < h_{tx} < 80$; $2 < h_{rx} < 10$	[Erceg 2001]
f: frequency (MHz); d: distance between the transmitter and the receiver (Km) h_{tx}: height of transmitter antenna (m); h_{rx}: height of the receiver antenna (m)		

Table 4.1 – List of the most common macro-cellular path loss models.

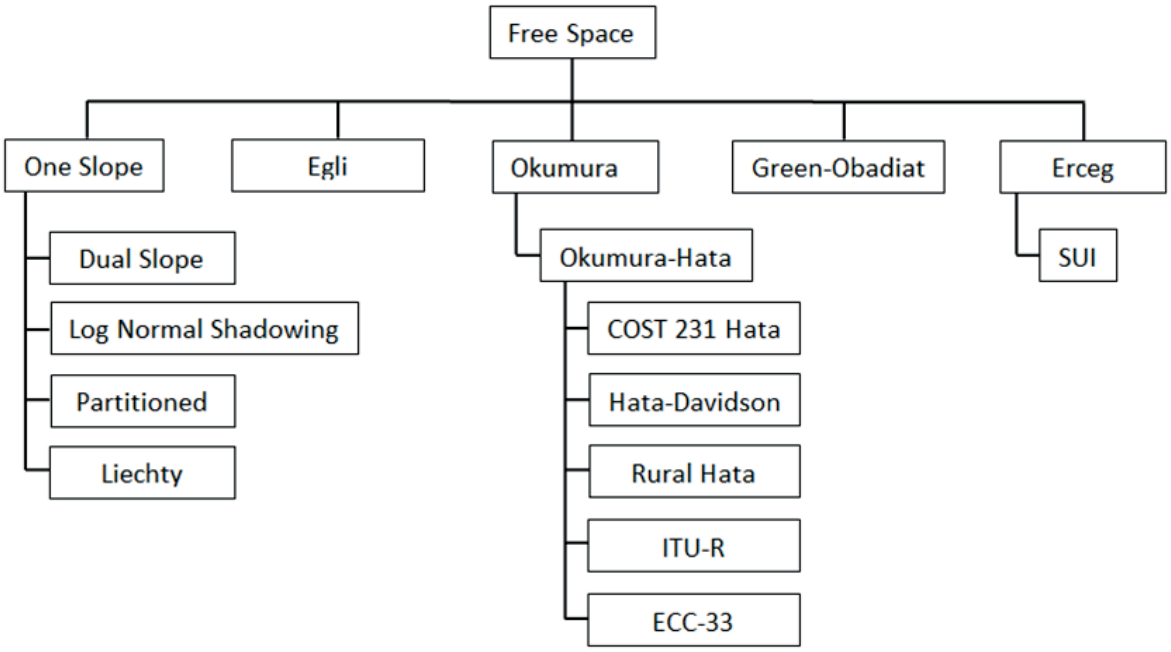


Figure 4.1 – Relation between most of the common path loss models.

4.1.3 Selected models

In the framework of this study, we selected five prediction models usually used in micro-cellular environments: One Slope, Dual Slope, Log Normal Shadowing, Partitioned, and Liechty.

One Slope Model

The One Slope model also called Log Distance Model allows the prediction of the signal at any distance. Some authors [Seidel/Rappaport 1992] show how the attenuation of the signal weakens with the distance. They highlight the attenuation exponent to indicate how the path loss increases rapidly with distance. The path loss is given by (4.6).

$$PL_{1Slope} = PL_{fs}(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) \tag{4.6}$$

Where:
$PL_{fs}(d_0)$: Signal path loss in free space at distance d_0 (dB)
d: Distance between the transmitter and the receiver (m)
d_0: Distance of reference (m)
n: Path loss exponent of the environment
The path loss exponent of the environment indicates how the attenuation increases with the distance. The expression of $PL_{fs}(d_0)$ is given by (4.4).

This model also requires prior measurements to calibrate the parameter n by using the least squares method [Tummala 2005]. Since this model does not consider obstacles between the transmitter and the receiver, it has been improved.

Dual-slope Model

This model is an extension of the One Slope model [Andrade/Hoefel 2010]. It predicted the signal path loss not only in Line Of Sight (LOS) but also in Non-Line Of Sight (NLOS). The expression of the path loss is given by (4.7).

$$PL_{2Slope} = PL_{fs}(d_0) + \begin{cases} 10n_1 \log_{10} d & \text{for } 1\text{m} < d \leq d_{bp} \\ 10n_2 \log_{10} \frac{d}{d_{bp}} + 10n_1 \log_{10} d_{bp} & \text{for } d > d_{bp} \end{cases} \tag{4.7}$$

Where:
$PL_{fs}(d_0)$: Signal path loss in free space at distance d_0 (dB)
d: Distance between the transmitter and the receiver (m)
d_0: Distance of reference (m)
d_{bp}: Distance from the transmitter to the first obstacle (m)
n_1: Pathloss exponent of the environment for $d \leq d_{bp}$
n_2: Pathloss exponent of the environment for $d > d_{bp}$

As in the One Slope model, the expression of $PL_{fs}(d_0)$ is given by (4.4) and values of n_1 and n_2 are determined using the least squares method from field measurements.

Log Normal Shadowing Model

It is also an improvement of One Slope model [Seidel/Rappaport 1992]. This model shows that the signal path loss at a distance is actually a random variable. This is due to the effect of multipath propagation and obstacles encountered by the wave. The path loss in this model is given by (4.8).

$$PL_{LN-Sha} = PL_{fs}(d_0) + 10n \log\left(\frac{d}{d_0}\right) + \chi_\sigma \tag{4.8}$$

Where:
$PL_{fs}(d_0)$: Signal path loss in free space at distance d_0 (dB)
d: Distance between the transmitter and the receiver (m)
d_0: Distance of reference (m)
χ_σ: Shadowing effect (dB)
n: Path loss exponent of the environment for $d > d_{bp}$
As in the One Slope model, the expression of $PL_{fs}(d_0)$ is given by (4.4). ?$_s$ is a log-normal or Gaussian random variable (in dB) with zero mean and standard deviation σ. Values of n

and σ are determined from field measurements [Seidel/Rappaport 1992], [Tummala 2005].

Partitioned Model

Also an extension of the One Slope model, this model has four different equations of signal path loss according to the distance between the transmitter and the receiver. The expression of the path loss is given by (4.9) [Mardeni/Solahuddin 2012].

$$PL_{Part} = PL_{fs}(d_0) + \begin{cases} 20\log d & \text{with } 1\text{m}<d \leq 10\text{m} \\ 20+30\log\frac{d}{10} & \text{with } 10\text{m}<d \leq 20\text{m} \\ 29+60\log\frac{d}{20} & \text{with } 20\text{m}<d \leq 40\text{m} \\ 47+120\log\frac{d}{40} & \text{with } d>40\text{m} \end{cases} \tag{4.9}$$

The expression of $PL_{fs}(d_0)$ is also given by (4.4).

Liechty Model

Christopher Lorne Liechty has created the Liechty model in 2007 [Liechty 2007]. The model also improves the One slope model to consider the attenuation due to obstructions such as trees and buildings. The expression of the path loss is given by (4.10).

$$PL_{Liechty} = PL_{fs}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + \sum_i num_i * a_i \tag{4.10}$$

Where:

$PL_{fs}(d_0)$: Signal path loss in free space at distance d_0 (dB)
d: Distance between the transmitter and the receiver (m)
d_0: Distance of reference (m)
num_i: Number of obstructions of type i
a_i: Attenuation of obstructions of type i (dB)
n: Path loss exponent of the environment
As in all One Slope based models, the expression of $PL_{fs}(d_0)$ is given by (4.4).

4.2 Environment and measurement methodology

To perform a study on signal propagation in rural areas, it is necessary to identify the main factors that could influence the signal propagation in these regions. This section describes the propagation environment, the tools (hardware and software) and the methodology we used to collect data and to analyse them.

4.2.1 Environment of the study

The measurements are carried out within the campus of the University of Ngaoundere. The selected area is mainly characterised by the presence of some small buildings and trees randomly distributed as we can see in Figure 4.2[1]. For measurement sessions three different scenarios have been developed:

1. **Free space**: This part of the selected environment covers a distance of 600 m. Measurements of signal strength are taken straight to each interval of 50 m. Figure 4.3 gives a picture of the environment and shows also the different places where the measurements are taken.
2. **Wooded area**: All trees have an average height of 6,5 m in this part of the selected environment. Measurements of the signal strength are taken at different points as shown in Figure 4.4.
3. **Built-up area**: The average height of the houses is around 3.5 m in this space. Measurements of the signal strength are taken at different points as shown in Figure 4.5.

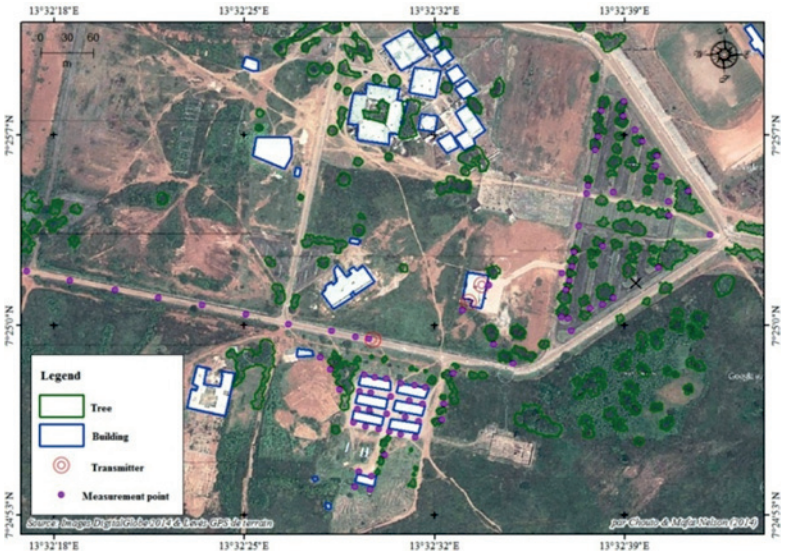


Figure 4.2 – Environment of the study for empirical path loss models.

4.2.2 Description of the hardware and software tools

Alpha Network has manufactured the access point used as the transmitter in all scenarios. This access point is compliant to the IEEE 802.11n standard. It operates at the ISM

[1]Figures 4.2 to 4.5 are created with ArcGIS.
http://www.arcgis.com

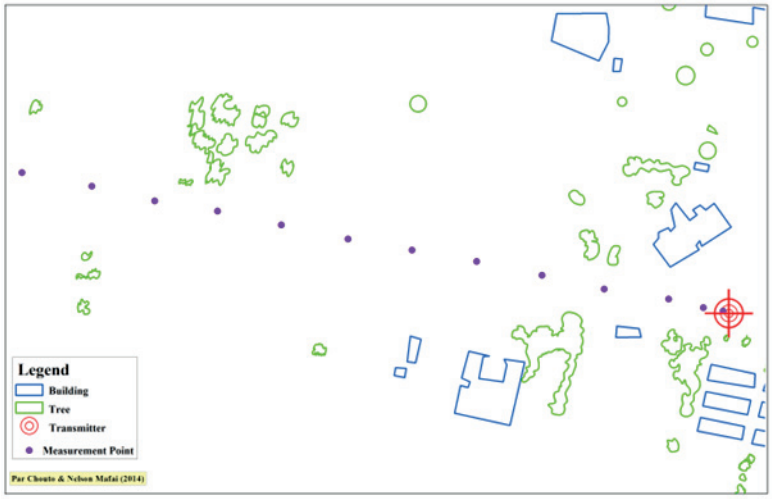


Figure 4.3 – Free space scenario.

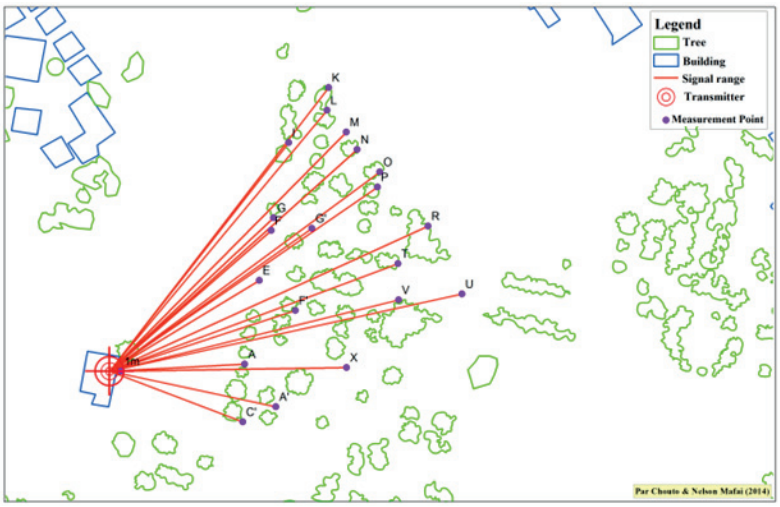


Figure 4.4 – Wooded area scenario.

frequency band 2.4 GHz and provides a bandwidth of 150 Mbps. The transmitting power used by the access point is 30 dBm.

Both wireless USB dongles used as receivers are compliant to IEEE 802.11n, 802.11b and 802.11g standards, operating at 2.4 GHz but providing different bandwidth: 150 Mbps and 300 Mbps.

A USB GPS is used in all scenarios to determine the different locations for measurements. This USB GPS is connected to a laptop, which is driven away from the access point to geographical coordinates (latitude and longitude) determined using the USB GPS.

Several tools exist for wireless signal power measurement such as *WirelessNetView* and

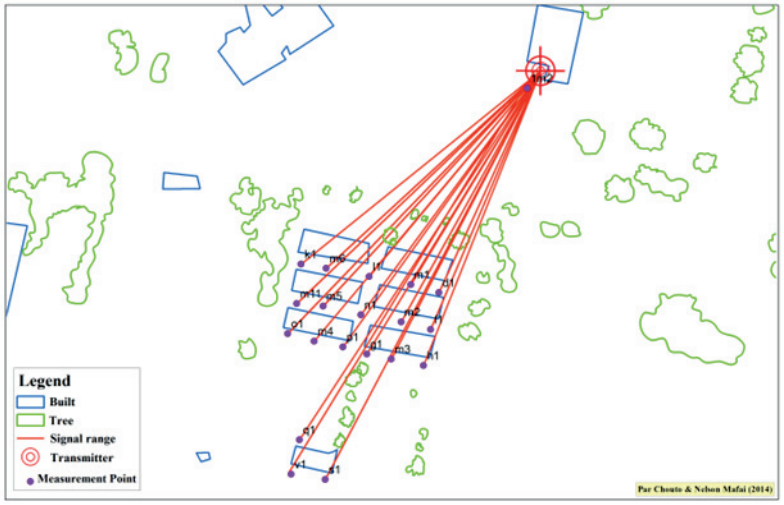


Figure 4.5 – Built-up area scenario.

InSSider. But we choose *Vistumbler* for three reasons: It is free and open source; it supports GPS integration, and it allows live Google Earth tracking of access points. In all scenarios, we used Vistumbler version 9.8 to measure the signal power at each predefined location. Table 4.2 provides the characteristics of the hardware we used.

	Manufacturer: Alpha Network, Model: N2, Power: 30 dBm, Antenna: 12 dBi		Manufacturer: Dodocool Rate: 300 Mbps Chipset: Realtek 8191 Driver: RTL8188SU/ 8191FEB28 Antenna: 2 dBi
	Manufacturer: Dodocool Rate: 150 Mbps Chipset: Ralink RT5370 Driver: RALINK23FEB Antenna: 2 dBi		Manufacturer: Navilock Model: NL-464US 60122 Sensibility: -159 dBm

Table 4.2 – Description of the hardware used for measurements.

4.2.3 Data collection

The USB wireless adapter is connected to the USB port of the laptop during the measurements. Throughout the measurements, the antenna of the wireless USB adapter is oriented towards the sky. In this study, the used positioning mode is the Single Marker Measurements [Liechty 2007]. Measurements are made at each randomly chosen location in this method. This method has been used in all the different previously described scenarios with the help of *Vistumbler*,. Datasheets have been designed for recording the retrieved data. A sample is given in Appendix A.

4.3 Data analysis and interpretation

Data analysis is performed to compare the results from selected empirical models with the data collected in each scenario. This is done in five steps:

1. Calculation of the mean loss of signal measured in the field.
2. Use of the least squares method to determine the fitting curve.
3. Evaluation of the path loss exponent n.
4. Calculation of the σ parameter of Log Normal Shadowing Model.
5. Comparison of the mean loss measured with the values predicted by the selected models.

4.3.1 Determination of parameters

Determination of path loss exponent n

The path loss exponent is used in *One-slope, Dual slope, Log-normal shadowing,* and *Liechty* models. It is determined using the least squares method.

Let us consider a set of points $(x_1,\ y_1)$, $(x_2,\ y_2)$,... $(x_n,\ y_n)$. We can obtain a scatter plot on an orthogonal graph from this set. The idea of the least squares method is therefore to determine the coefficients a and b of a linear equation (4.11).

$$y = ax + b \tag{4.11}$$

$$so\ that \begin{cases} \sum_i (A_i P_i)^2 = \sum_i (e_i)^2 & \text{is minimal} \\ A_i P_i = e_i = y_i - (ax_i + b) & \text{with } 1 \leq i \leq n \end{cases}$$

Obstacle attenuation

The Liechty model requires the estimation of the attenuation caused by each type of obstacle. This is done by calculating the difference between the mean loss of the signal obtained before and after the obstacle.

Parameter σ

The calculation of parameter value σ of the Log-normal shadowing model is determined using (4.12).

$$\sigma^2 = \frac{\sum_i (\overline{P_m} - \overline{P_r})^2}{k} \tag{4.12}$$

With:
$\overline{P_m}$: Power of the measured received signal
$\overline{P_r}$: Strength of the estimated received signal
k: Number of measurement points

4.3.2 Result analysis in free space

Measurements have been done in free space at ten points presented in Figure 4.3. We performed a total number of 100 measurements in free space. The analysis process defined at the beginning of this section is applied:

1. Calculation of the mean loss of the signal measured in the field

The mean loss of the signal at each distance is calculated; Figure 4.6 shows the plot for both USB wireless receivers (300 Mbps and 150 Mbps) depending on the distance TR (Transmitter - Receiver). As expected in Figure 4.6, the mean loss of the signal increases as the distance between the transmitter and the receiver increases.

In addition losses from the 300 Mbps wireless USB receiver are lower than those from the 150 Mbps one.

2. Use of the least squares method to determine the fitting curve

The fitting curves of data for both receivers are represented in Figure 4.7a (for the 300 Mbps receiver) and Figure 4.7b (for the 150 Mbps receiver).

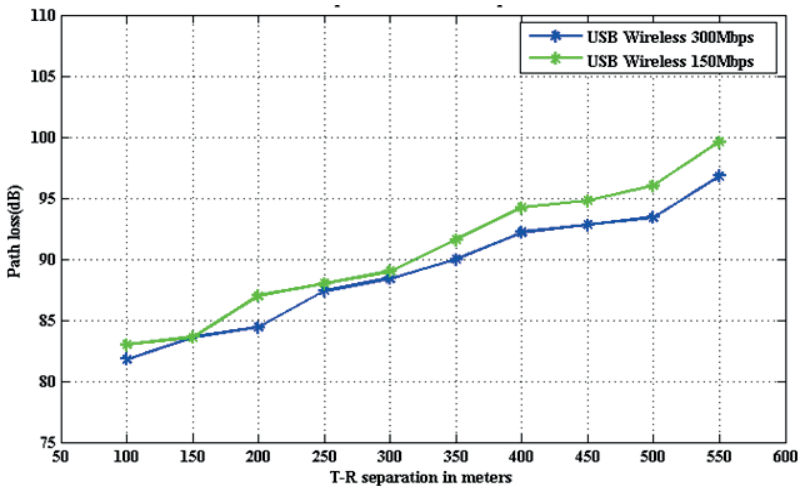
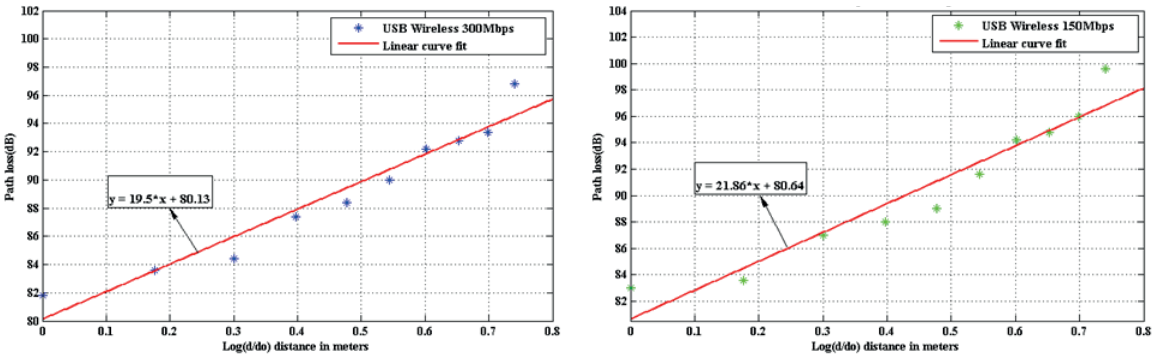


Figure 4.6 – Mean losses in free space.



(a) (b)

Figure 4.7 – Fitting curves in free space: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver.

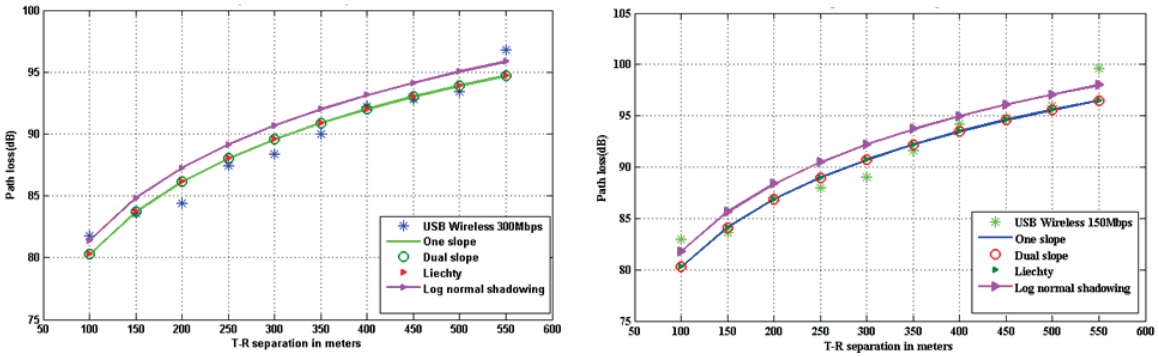
3. Evaluation of the path loss exponent n

The expression of the fitting curve is given by (4.11). The value of the path loss exponent n is determined by identification when comparing the expression (4.11) with (4.6). So, we obtain n=1.95 for the 300 Mbps receiver and n=2.186 for the 150 Mbps one.

4. Calculation of the σ parameter of the Log Normal Shadowing Model

The standard deviation σ is calculated for each receiver by using the expression (4.12). σ = 1.12 for the 300 Mbps receiver and σ = 1.50 for the 150 Mbps one.

5. Comparison of the mean losses to the values predicted by the selected models



(a) (b)

Figure 4.8 – Comparison of the predicted values in free space: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver.

To compare the measured values with the predicted ones, we use two indicators: the mean error and the standard deviation. Table 4.3 summarises the comparison between the models. A graphical comparison between the models and the measured values is given in Figure 4.8a for the 300 Mbps receiver and 4.8b for the 150 Mbps one. The predicted values from One Slope, Dual Slope and Liechty models are quite close to the measured values in these figures. Results from the Partitioned model are not plotted because of the great errors that we obtained.

Models	**300 Mbps**		**150 Mbps**	
	Mean Error (dB)	**Standard Deviation (dB)**	**Mean Error (dB)**	**Standard Deviation (dB)**
One Slope	0.90	1.12	1.12	1.50
Dual Slope	0.90	1.12	1.12	1.50
Lietchy	0.90	1.12	1.12	1.50
Log Normal	1.54	1.68	1.71	1.85
Partitioned	141.03	142.89	103.83	104.06

Table 4.3 – Experimental results in free space.

In Table 4.3, One Slope, Dual Slope, and Liechty models are the best for the prediction of signal path loss in free space with a mean error of 0.90 dB and a standard deviation of 1.12 dB for the 300 Mbps receiver, and a mean error of 1.12 dB and a standard deviation of 1.50 dB for the 150 Mbps receiver.

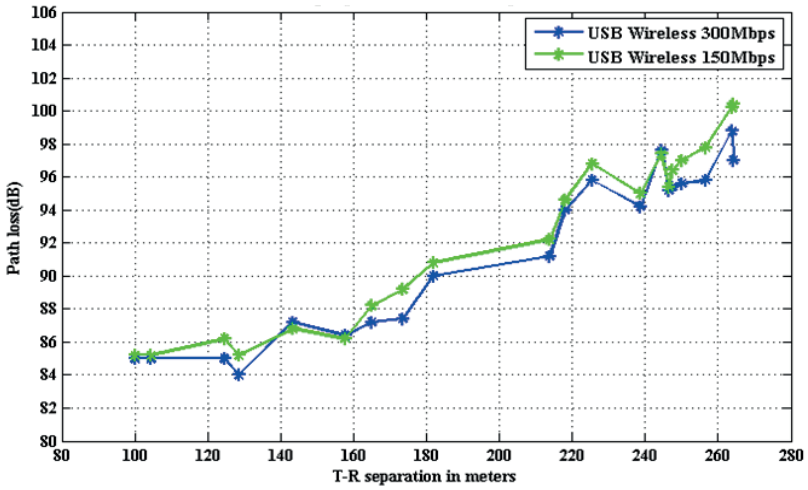


Figure 4.9 – Mean losses in wooded area.

4.3.3 Result analysis in a wooded area

Measurements have been done in a wooded area at 20 points presented in Figure 4.4. We performed a total number of 200 measurements in this space. The analysis process defined at the beginning of this section is applied as in free space:

1. Calculation of the mean loss of the signal measured in the field

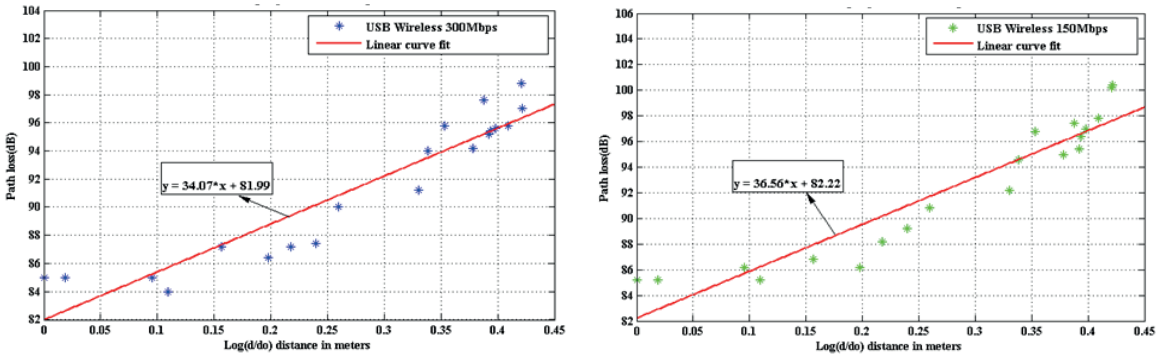
The mean loss of the signal at each distance is calculated; Figure 4.9 shows the plot for both USB wireless receivers (300 Mbps and 150 Mbps) depending on the distance TR (Transmitter - Receiver). In contrary to free space where the curve seems to be linear, Figure 4.9 shows an increasing saw tooth curve. This is due to the presence of obstacles and shows the difficulty to predict the path loss at any point. Nevertheless losses from the 300 Mbps wireless USB receiver are still lower than those from the 150 Mbps one.

2. Using the least squares method to determine the fitting curve

The fitting curves of data for both receivers are represented in Figure 4.10a (for the 300 Mbps receiver) and Figure 4.10b (for the 150 Mbps one).

3. Evaluation of the path loss exponent n

The expression of the fitting curve is given in (4.11). The value of the path loss exponent n is determined by identification when comparing expression (4.11) with (4.6). We obtain n=3.407 for the 300 Mbps receiver and n=3.656 for the 150 Mbps one.



(a) (b)

Figure 4.10 – Fitting curves in the wooded area: (a) 300Mbps wireless receiver; (b) 150Mbps wireless receiver.

4. Calculation of the σ parameter of the Log Normal Shadowing Model

The standard deviation σ is calculated for each receiver by using the expression (4.12). σ = 2.41 for the 300 Mbps receiver and σ = 2.61 for the other one.

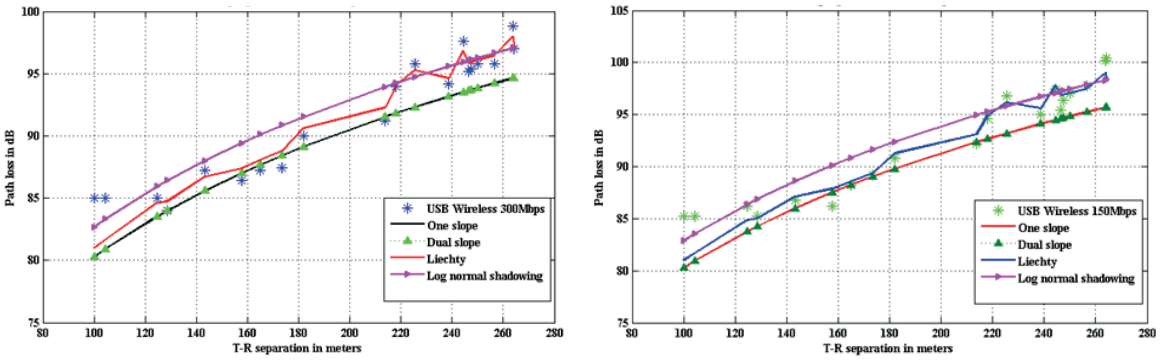
5. Comparison of the mean losses to the values predicted by the selected models

We also used the mean error and the standard deviation as indicators. Table 4.4 summarises the comparison between the models. A graphical comparison between the models and the measured values is given in Figure 4.11a for the 300 Mbps receiver and 4.11b for the other one. The predicted values from the Liechty model are quite close to the measured values as it can be seen in these figures.

Models	**300 Mbps**		**150 Mbps**	
	Mean Error (dB)	**Standard Deviation (dB)**	**Mean Error (dB)**	**Standard Deviation (dB)**
One Slope	1.97	2.41	2.03	2.61
Dual Slope	1.97	2.41	2.03	2.61
Lietchy	0.94	1.35	1.04	1.50
Log Normal	1.54	1.81	1.59	1.86
Partitioned	116.73	117.32	115.82	116.38

Table 4.4 – Experimental results in the wooded area.

The Liechty model provides the best results with a mean error of 0.94 dB and a standard deviation of 1.35 dB for the 300 Mbps receiver, and a mean error of 1.04 dB and a standard deviation of 1.50 dB for the other one (Table 4.4).



(a) (b)

Figure 4.11 – Comparison of the predicted values in the wooded area: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver.

4.3.4 Result analysis in a built-up area

Measurements have been done in a built-up area at 20 points presented in Figure 4.5. We performed a total number of 200 measurements in this space. The analysis process defined at the beginning of this section is applied as in the free space and the wooded area.

1. Calculation of the mean loss of the signal measured in the field

The mean loss of the signal at each distance is calculated; Figure 4.12 shows the plot for both USB wireless receivers (300 Mbps and 150 Mbps) depending on the distance TR (Transmitter - Receiver). Figure 4.12 shows a non-monotonic increasing curve as it is the case in the wooded area,. This is due to the presence of obstacles and shows the difficulty to predict the path loss in this type of environment. As expected, losses from the 300 Mbps wireless USB receiver are still lower than those from the 150 Mbps one.

2. Using the least squares method to determine the fitting curve

The fitting curves of data for both receivers are represented in Figure 4.13a (for the 300 Mbps receiver) and Figure 4.13b (for the 150 Mbps receiver).

3. Evaluation of the path loss exponent n

The expression of the fitting curve is given in (4.11). The value of the path loss exponent n is determined by identification when comparing expression (4.11) with (4.6). We obtain n=4.799 for the 300 Mbps receiver and n=4.996 for the other one.

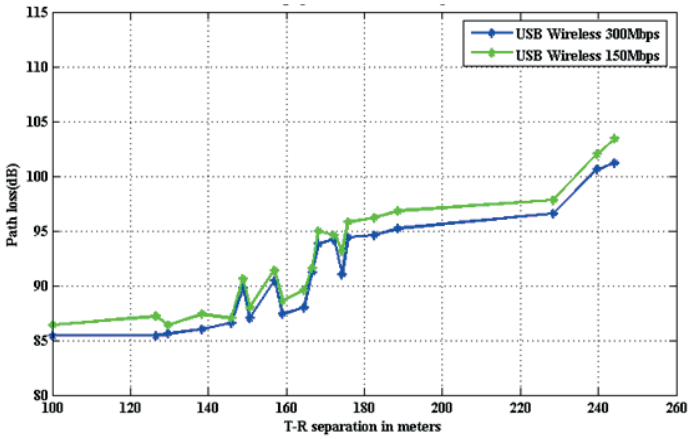
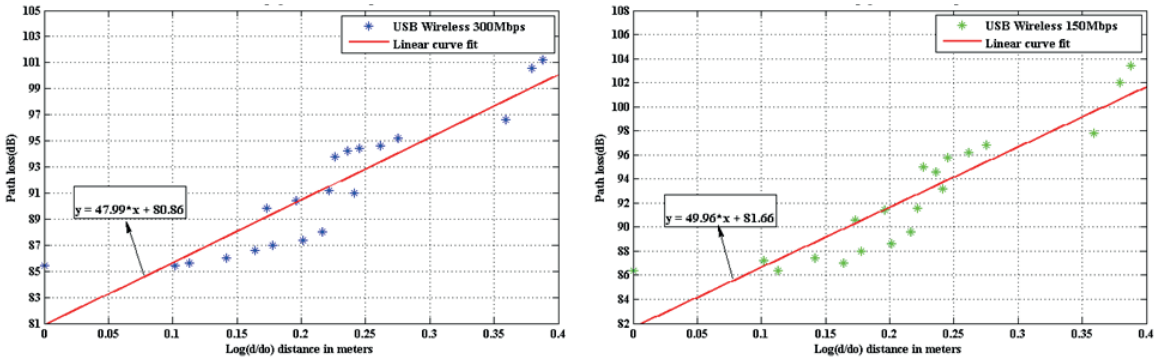


Figure 4.12 – Mean losses in a built-up area.



(a) (b)

Figure 4.13 – Fitting curves in a built-up area: (a) 300Mbps wireless receiver; (b) 150Mbps wireless receiver.

4. Calculation of parameter σ of the Log Normal Shadowing Model

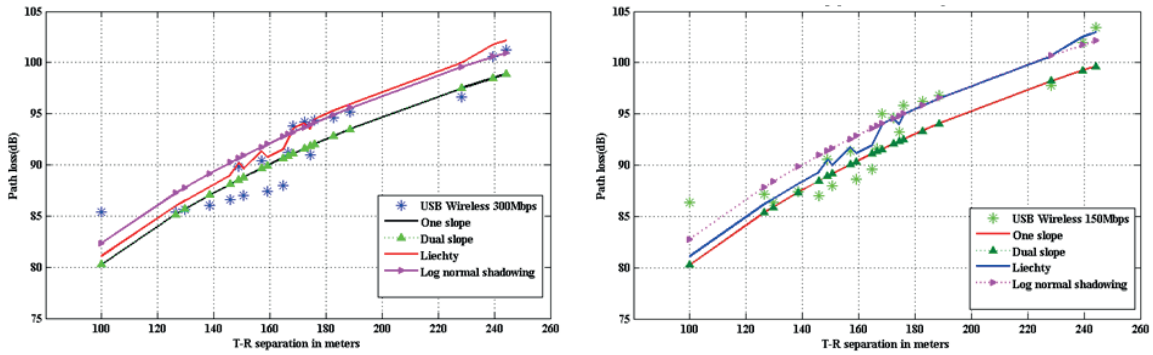
The standard deviation σ is calculated for each of receiver by using the expression (4.12). σ = 2.10 for the 300 Mbps receiver and σ = 2.48 for the other one.

5. Comparison of the mean losses with the predicted values by selected models

We also used the mean error and the standard deviation as indicators. Table 4.5 summarises the comparison between the models. A graphical comparison between the models and the measured values is given in Figure 4.14a for the 300 Mbps receiver and 4.14b for the 150 Mbps one. The predicted values from the Liechty model are quite close to the measured values as it can be seen in these figures.

Models	300 Mbps		150 Mbps	
	Mean Error (dB)	Standard Deviation (dB)	Mean Error (dB)	Standard Deviation (dB)
One Slope	1.73	2.10	2.02	2.48
Dual Slope	1.73	2.10	2.02	2.48
Lietchy	1.60	2.03	1.27	1.78
Log Normal	1.97	2.49	1.85	2.30
Partitioned	109.71	109.93	108.48	108.69

Table 4.5 – Experimental results in a built-up area.



(a) (b)

Figure 4.14 – Comparison of predicted values in wooded area: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver.

The Liechty model provides the best results with a mean error of 1.60 dB and a standard deviation of 2.03 dB for the 300 Mbps receiver, and a mean error of 1.27 dB and a standard deviation of 1.78 dB for the other one (Table 4.5).

4.3.5 Summary of results

Table 4.6 gives the parameters values of the selected models determined empirically in each scenario for each USB wireless receiver. Table 4.7 provides the smallest standard deviation of the selected models in each scenario for each USB wireless receiver. The Liechty model provides the smallest standard deviation in every scenario.

4.4 Proposal for a new empirical model

The Liechty model takes the number of obstacles between transmitter and receiver and their attenuation on the signal into account. But the distance of each attenuation point

		300 Mbps		150 Mbps	
Environment	**Obstruction (dB)**	**n**	σ	**n**	σ
Free Space	0	1.95	1.12	2.186	1.50
Wooded area	0.37	3.407	2.41	3.656	2.61
Built-up area	0.41	4.799	2.10	4.996	2.48

Table 4.6 – Empirical values of the model parameters.

		300 Mbps	150 Mbps
Environment	**Best Model**	**Standard Deviation (dB)**	**Standard Deviation (dB)**
Free Space	One Slope	0.90	1.12
	Dual Slope	0.90	1.12
	Lietchy	0.90	1.12
Wooded area	Lietchy	1.35	1.50
Built-up area	Lietchy	2.03	1.78

Table 4.7 – Best prediction in different scenarios.

influences also the quality of the signal. Considering the distance from the transmitter to those points during the prediction of the signal could improve the accuracy. However, since it is difficult to consider the distance from the transmitter to all those points, we just consider the distance to the first obstacle, the so-called breakpoint. We assume that the attenuation at this point has the greatest impact on the signal.

4.4.1 Path loss expression

The optimisation is done by adding the parameters of the Dual slope model to the Liechty model. This results in equation (4.13).

$$PL_{new} = PL_{fs}(d_0) + \begin{cases} 10n_1 \log_{10} d & \text{with } 1\text{m} < d \leq d_{bp} \\ 10n_2 \log_{10} \frac{d}{d_{bp}} + 10n_1 \log_{10} d_{bp} + \sum_i num_i * a_i & \text{with } d > d_{bp} \end{cases} \quad (4.13)$$

Where:
$PL(d_0)$: Attenuation of the signal at distance d_0 (dB)
d: Distance between transmitter and receiver (m)
d_0: Reference distance (m)
d_{bp} : Distance from the transmitter to the first obstacle (m)
num_i : Number of obstacles of type i
a_i : Attenuation of obstacle of type i (dB)
n_1 : Path loss exponent for $d \leq d_{bp}$

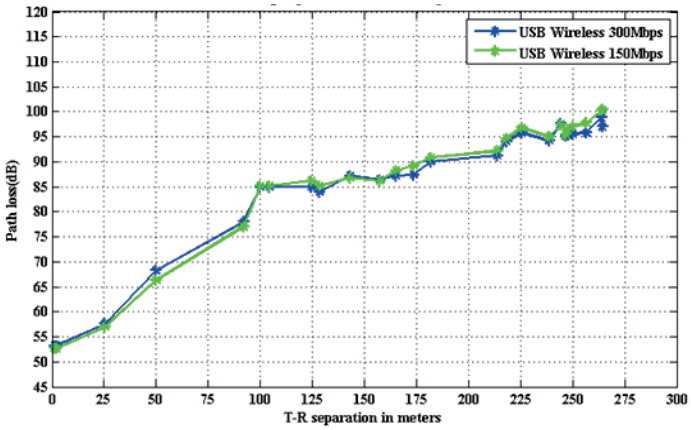


Figure 4.15 – Mean losses in the wooded area for accuracy analysis.

Models	300 Mbps		150 Mbps	
	Mean Error (dB)	Standard Deviation (dB)	Mean Error (dB)	Standard Deviation (dB)
Liechty	4.22	5.12	4.00	5.09
New model	2.33	4.02	2.67	4.21

Table 4.8 – Results of the accuracy analysis in the wooded area.

n_2 : Path loss exponent for $d > d_{bp}$

4.4.2 Analysis of the accuracy of the new model

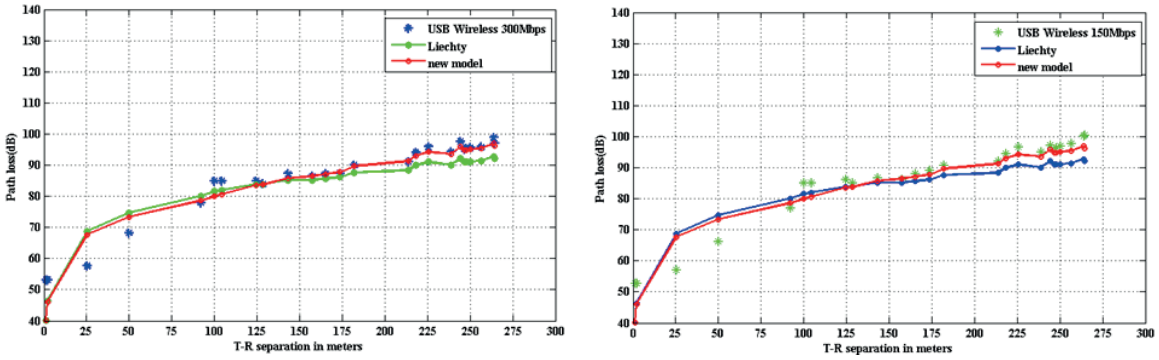
To analyse the accuracy of the new model, we consider the measurements in both LOS and NLOS in wooded and built-up areas. The consideration of both LOS and NLOS is materialised by using different path loss exponents, as it is the case in the new model: n_1 in LOS and n_2 in NLOS.

Wooded area

Figure 4.15 shows the mean values of signal losses measured in the wooded area.

A comparison is made between the prediction of the Liechty and the new model. Figures 4.16a and 4.16b give a graphical comparison between the two models and the measured data in the wooded area respectively for the 300 Mbps wireless receiver and the 150 Mbps wireless receiver. From these figures it becomes clear that the Liechty and the new model give very similar results. Nevertheless, the new model is closer to the measured data than the Liechty model.

The new model provides the best results with a mean error of 2.33 dB and a standard



(a) (b)

Figure 4.16 – Accuracy of models in the wooded area: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver.

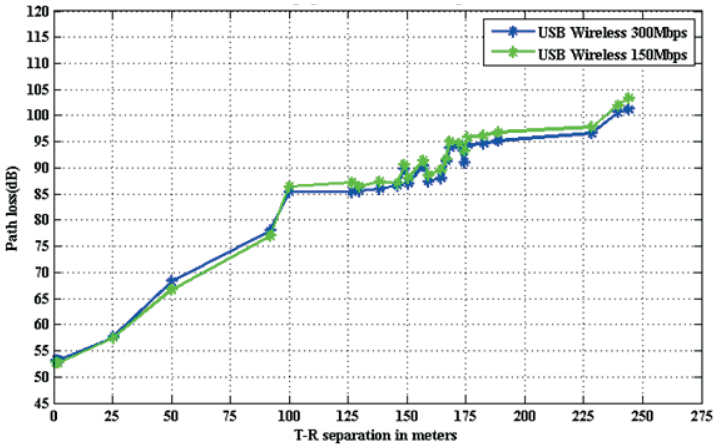


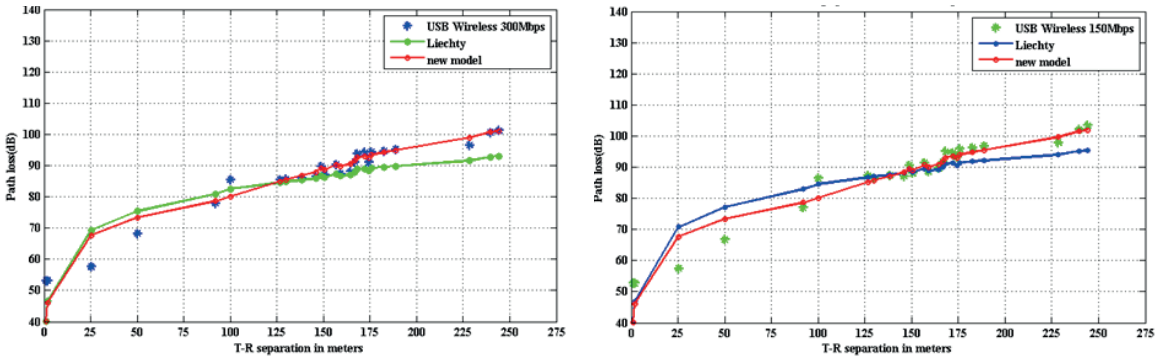
Figure 4.17 – Mean losses in the built-up area for accuracy analysis.

deviation of 4.02 dB for the 300 Mbps receiver, and a mean error of 2.67 dB and a standard deviation of 4.21 dB for the 150 Mbps receiver (Table 4.8).

Built-up area

Figure 4.17 shows the mean values of signal losses measured in the field for the built-up area.

A comparison is made between the prediction of the Liechty and the new model. Figures 4.18a and 4.18b give a graphical comparison between the two models and the measured data in the built-up area respectively for the 300 Mbps wireless receiver and the 150 Mbps one. From these figures it is also clear that the Liechty and the new model give very similar results. The new model is closer to the measured data than the Liechty model as in the wooded area.



(a) (b)

Figure 4.18 – Accuracy of models in the built-up area: (a) 300 Mbps wireless receiver; (b) 150 Mbps wireless receiver.

The new model provides a better prediction of the path loss of the signal in the built-up area with a mean error of 2.36 dB and a standard deviation of 4.01 dB for the 300 Mbps receiver, and a mean error of 2.61 dB and a standard deviation of 4.19 dB for the 150 Mbps receiver (Table 4.9).

Models	**300 Mbps**		**150 Mbps**	
	Mean Error (dB)	**Standard Deviation (dB)**	**Mean Error (dB)**	**Standard Deviation (dB)**
Liechty	4.35	5.46	4.00	5.45
New model	2.36	4.01	2.61	4.19

Table 4.9 – Results of the accuracy analysis in the built-up area.

We defined three scenarios tied to rural regions, and we conducted a measurement campaign in this chapter. We compared five path loss models and we found that the Liechty model has been more accurate than others. Further, we improved this model by considering the distance to the breakpoint and we obtained a better prediction model both in the wooded and the built-up area. We did not just provide a new model, but we also empirically determined the parameter values of the models such as the path loss exponent and the value of the attenuation due to trees and buildings (Table 4.6).

Path loss models are useful in network planning to predict the position of the receiver in point to point communication. However, since we want to build a mesh network, we need suitable approaches to determine the position of mesh routers in the network besides the path loss models.

5 Wireless mesh networks: The planning problem

Communities and neighbourhoods are increasingly deploying their own networks. Most of the users in communities with a high density of obstacles due to trees or hills cannot be served because of the lack of line of sight ([Sichitiu 2005], p. 1). Using base stations tend to be an expensive solution in this case. A low cost solution that could skirt obstacles is the wireless mesh network (WMN). We discussed the suitability of Wi-Fi mesh networks over WiMAX in our scenario in chapter 4. Although providing an accurate prediction model is an important step for network planning, it is not enough when planning WMNs. This type of networks brings a lot of particularities and constraints that are not present in point-to-point networks. Their planning requires efficient approaches to deal with constraints and to optimise the objectives of the planning, which are in contradiction most of the time.

We summarise what a WMN is and its different types of architecture in this chapter. Since the planning problem in general is an optimisation problem, we recall some notions about optimisation techniques. Then we talk about the planning issue in WMN: usually handled constraints and types of planning. Finally we present the WMN planning problem in rural regions.

5.1 Wireless mesh networks

Recent advances in wireless networks foster the development and deployment of WMNs. This type of networks extends the limited coverage of WLANs and overcomes the LOS required by WMANs by providing connectivity in a multi-hop fashion. WMNs, based on Wi-Fi technologies, reveal themselves as an efficient solution to bridge the digital divide between rural and urban regions. The success of this kind of network is due to the low cost of the Wi-Fi technology and the continuous capacity improvement in terms of throughput and transmission range.

WMNs are self-organising and self-healing networks with nodes communicating without requiring a central switch point, as it is the case in traditional wireless networks. More than a simple host, a node also operates as router by forwarding packets on behalf of other nodes that may not be able to directly communicate ([Akyildiz/Wang/Wang 2005b], p. 446). Node addition and maintenance are still rare events in this type of network ([Benyamina et al. 2007], p. 1).

A comprehensive survey of WMNs can be found in [Akyildiz/Wang/Wang 2005b]. The authors present different aspects of WMNs and also discuss the open research issues in all protocols and algorithms for this type of network.

5.1.1 Network architecture

A WMN is mainly composed of two types of nodes: mesh routers and mesh clients. Similar to a normal router, a mesh router incorporates some routing functions to support mesh networking. Usually, it is equipped with multiple wireless interfaces to improve the flexibility of the architecture ([Akyildiz/Wang/Wang 2005b], p. 447). In contrary, a mesh client typically has a unique wireless interface and provides much simpler software than a mesh router; even if it may also provide mesh capability. Akyildiz and Wang classified the architecture of WMNs into three categories ([Akyildiz/Wang 2005a], p. 23 f.).

Infrastructure/backbone WMN

In this architecture, the backbone is composed of mesh routers representing an infrastructure for clients as illustrated in Figure 5.1. Some mesh routers can be connected to the Internet by gateway functionality. Clients using an Ethernet interface or the same radio technologies as the mesh router can directly communicate with the WMN. Gateway/bridge functionalities in mesh routers enable internetworking between a WMN and existing wireless networks. Therefore, clients using radio technologies different from mesh routers can communicate with the WMN via their base stations, which are connected via an Ethernet interface to the WMN.

Client WMN

This architecture does not require a mesh router, because the client devices are connected in a peer-to-peer mode, in which each client device can perform self-configuration and routing as well as providing application(s) to other devices. The devices usually communicate among themselves with a type of radio as it is the case in conventional ad-hoc networks.

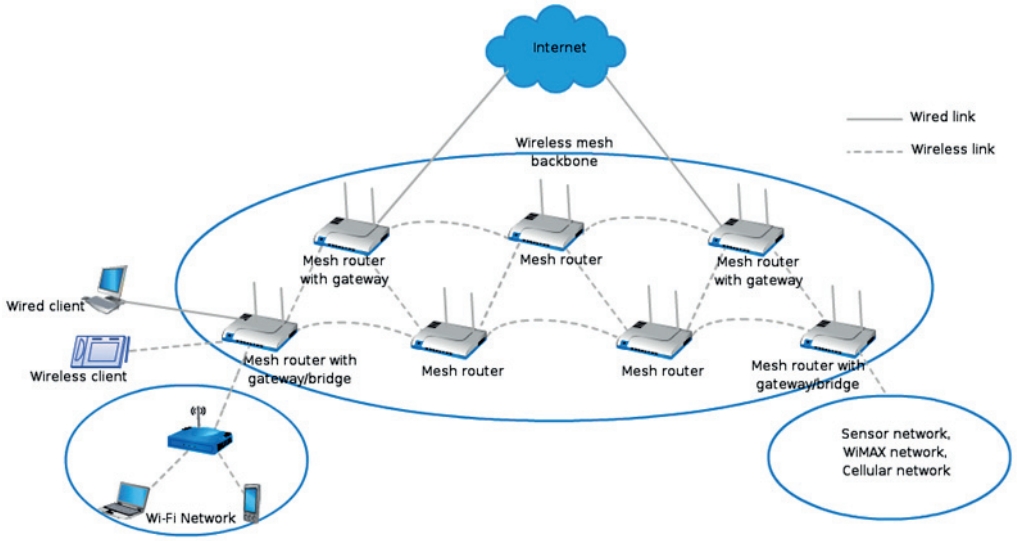


Figure 5.1 – Infrastructure/backbone WMN adapted from ([Akyildiz, 2005a], p. 24).

Hybrid WMN

This architecture is the combination of the two previous ones where the infrastructure/backbone architecture insures connectivity with other wireless networks; mesh clients improve the connectivity by enabling direct communication between clients.

5.1.2 Characteristics of WMNs

The characteristics of WMNs are unique; some are derived from their mesh topology. Some of these characteristics are:

- Multi-hop communication: A node in the network can communicate with other nodes, which are out of its transmission range through its neighbour nodes. This multi-hop fashion allows to extend the coverage of the network and moreover to provide connectivity in a NLOS scenario by skirting obstacles.
- Self-organisation: WMNs are self-organised, allowing self-forming and self-healing. When a node is down, the traffic is routed via another path to reach the destination.
- Mobility: Mesh clients in a WMN are usually mobile or stationary in contrary to mesh routers, which have a reduced mobility.
- Multiple radios: To improve the performance of a WMN, each node is usually equipped with multiple radios in order to separate the traffic of the backbone and

the local traffic of mesh clients. This separation is performed by assigning different channels to each radio.

5.1.3 WMN applications

The cost of WMNs as well as their easy deployment even in difficult-to-wire regions makes them suitable for a wide-range of scenarios. They find different applications ranging from a simple building networking to a metropolitan area networks. WMNs are underlying different types of systems such as transportation, security, and health. Because of their self-organisation, they are particularly suitable for the deployment of emergency systems in the case of disasters.

The performance of WMN depends on the way they are planned. To ensure minimum performance of a WMN, optimisation techniques are used during the planning phase. Good general literature on optimisation techniques are found in [Weise 2009] and [Talbi 2009].

5.2 Optimisation techniques

We are frequently facing optimisation problems in daily life. How to spend fewer resources, less time, or less effort to achieve a goal or a project? How to optimise the output of a particular process?

The aim of the optimisation is to find the best possible elements x* from a set $\mathbb{X}$ according to a set of criteria $F = \{f_1, f_2, .., f_n\}$. Each criterion is expressed as a mathematical function called objective function ([Weise 2009], p. 21).

Definition 5.1 (Objective Function): An objective function f: $\mathbb{X} \longmapsto Y$ with $Y \subseteq \mathbb{R}$ is a mathematical function, which is subject to optimisation.

$\mathbb{X}$ is the domain of f and is called search space or problem space. The type of elements $\mathbb{X}$ can represent depends on the problem to solve. An objective function is not always a mathematical expression and could be an algorithm that involves several simulations. Different techniques have been developed to optimise the function f. They are grouped under the name “Global optimisation techniques” and be classified as illustrated in Figure 5.2. In continuous optimisation, elements of $\mathbb{X}$ can take a continuous range of values, usually real numbers ([Wright 1999], p. 1). This is not the case in combinatorial optimisation in which elements of $\mathbb{X}$ use discrete values such as binary, integer, or more abstract objects from a finite set.

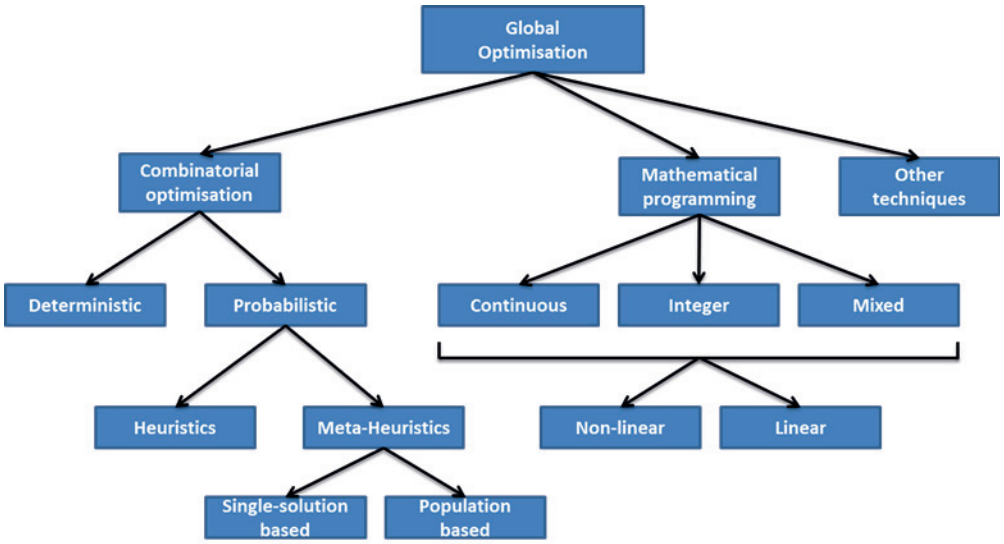


Figure 5.2 – Global optimisation techniques.

Combinatorial optimisation techniques (or algorithms) can be classified according to their method of operation (deterministic or probabilistic) and their properties (speed and number of criteria) ([Weise 2009], p. 22 f.).

5.2.1 Method of operation

Optimisation can be done only if there is a relation between the characteristics of candidate solutions and their utility for a given problem. When this relation is obvious or not complicated and if the search space is small enough to be efficiently explored, then deterministic algorithms are preferred. But when this relation is too complicated or the dimensionality of the search space is very high, probabilistic algorithms are used. Most of the probabilistic methods are based on Monte-Carlo criteria. These methods provide a good trade-offs between the quality of the solution and the time of execution. They approach the best solution while spending much less time than the time required finding the best solution using a deterministic algorithm (if there exists one). Monte Carlo-based optimisation algorithms are given in Figure 5.3.

Optimisation techniques process by examining different solutions in order to find the optimum. During the process, some functions are used to determine the next candidate solution to examine. These functions are called heuristics.

Definition 5.2 (Heuristic): A heuristic ([Weise 2009], p. 22) is a part of an optimisation algorithm that uses the information currently gathered by the algorithm helping to decide which solution candidate should be tested next or how the next individual can be produced.

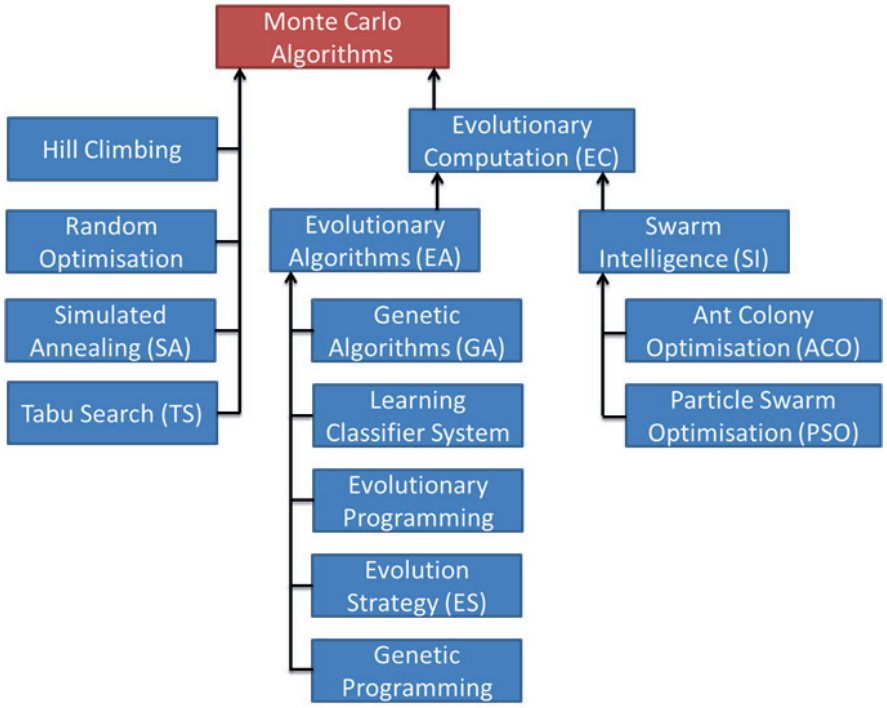


Figure 5.3 – Monte Carlo-based optimisation algorithms adapted from ([Weise 2009], p. 23).

Definition 5.3 (Meta-heuristic): A meta-heuristic is a method for solving general classes of problems. It combines objective functions or heuristics in an abstract and hopefully efficient way, usually without utilising a deeper insight into their structure, i.e., by treating them as black-box-procedures ([Weise 2009], p. 23).

While solving optimisation problems, meta-heuristics are generally based on two types of solutions: single-solution and population. Single-solution based meta-heuristics (**S-meta-heuristics**) improve a single solution while population-based meta-heuristics (**P-meta-heuristics**) improve a population of solutions ([Talbi 2009], p. 87, 190).

5.2.2 Properties

Optimisation algorithms, especially probabilistic algorithms are appreciated depending on their speed and precision. But these objectives are conflicting since the accuracy is obtained at the expenses of the speed. Some problems have a strong time constraint and require a solution in very short time, usually not more than few minutes. This category is called **online optimisation problems**. In contrary to this category, other problems are looking for an accurate solution even if this solution will be found after days. This second category is called **offline optimisation problems**; it provides a long-term solution and

encompasses problems such as network planning.

Another important property of optimisation algorithms is the number of functions to optimise. Usually, optimisation algorithms are divided into two groups: single-objective optimisation and multi-objective optimisation.

5.2.3 Single-objective optimisation

Single-objective optimisation is looking for the optimum of an objective function f, which is either the maximum or the minimum of this function.

Let $\mathbb{X} = (X_1, X_2)$ a dimensional space, and $f : \mathbb{X} \longmapsto \mathbb{R}$ an objective function.

Definition 5.4 (Neighbourhood): A neighbourhood function N is a mapping $N : \mathbb{X} \rightarrow 2^{\mathbb{X}}$ that assigns to each $x \in \mathbb{X}$ a set of elements $N(x) \subset \mathbb{X}$.

Definition 5.5 (Local minimum): A local or relative minimum $\check{x}_l \in \mathbb{X}$ of f is an element of $\mathbb{X}$ with $f(\check{x}_l) \leq f(x)$ for all x within the neighbourhood of $\check{x}_l$.

Definition 5.6 (Global minimum): A global or absolute minimum $\check{x} \in \mathbb{X}$ of f is an element of $\mathbb{X}$ with $f(\check{x}_l) \leq f(x) \ \forall \ x \in \mathbb{X}$.

Definition 5.7 (Local maximum): A local or relative maximum $\hat{x}_l \in \mathbb{X}$ of f is an element of $\mathbb{X}$ with $f(\hat{x}_l) \geq f(x)$ for all x around $\hat{x}_l$.

Definition 5.8 (Global maximum): A global or absolute maximum $\hat{x} \in \mathbb{X}$ of f is an element of $\mathbb{X}$ with $f(\hat{x}) \geq f(x) \ \forall \ x \in \mathbb{X}$.

Definition 5.9 (Local optimum): A local or relative optimum $x_l^* \in \mathbb{X}$ of f is either a local minimum or a local maximum.

Definition 5.10 (Global optimum): A global or absolute optimum $x^* \in \mathbb{X}$ of f is either a global minimum or a global maximum.

Local and global optima of a two-dimensional function are illustrated in Figure 5.4. To reach the global optimum, single-objective optimisation is based on S-meta-heuristics, which explore the neighbourhood of the current solution in order to produce the next solution to be examined. The efficiency of an S-meta-heuristic depends on the structure of the neighbourhood.

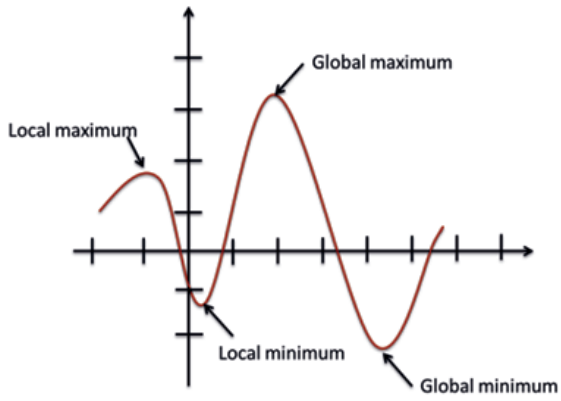


Figure 5.4 – Optima of a two-dimensional function.

5.2.4 Multi-objective optimisation

In reality, most of the concrete problems that are subject to optimisation encompass more than one objective. They are applied to a set of objective functions $F = \{f_i : \mathbb{X} \mapsto Y_i\}$, with $1 \leq i \leq |F| \ \wedge \ Y_i \subseteq \mathbb{R}$.

A trivial solution is to define a priority order and to optimise objective functions one after another. But this approach is not a real multi-objective approach because the search of the optimal solution of the next objective function(s) is local to the neighbourhood of the optimal solution of the previous objective function(s). An easier way to simultaneously consider all the objective functions is to linearly aggregate them.

Weighted sums

It is an approach based on linear aggregation that assigns to each objective function f_i a weight w_i depending on its importance in the problem. These weighted functions are summed into a new function $g(x)$ which is the new one to optimise. Weights are usually signed: a negative weight will be assigned to a function to minimise while a positive weight will be assigned to a function to maximise.

The difficulty in implementing this approach is the determination of an adequate weight for each function. It is usually difficult to objectively determine the weights. Even if it is possible, this approach still presents a drawback when functions rise and fall with different speeds ([Weise 2009], p. 29).

Pareto Optimisation

In most scenarios, objective functions are conflicting; that means the improvement of one function is done at the expenses of others. An example is illustrated in Figure 5.5 where two

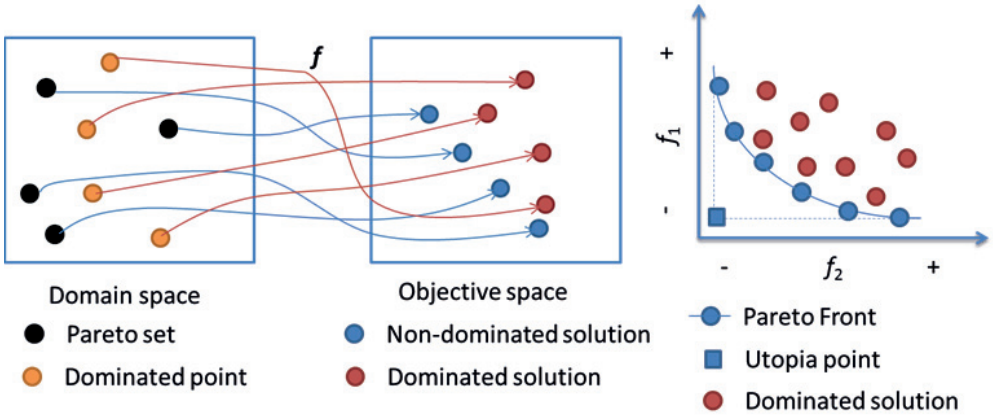


Figure 5.5 – Example of Pareto optimisation.

objective functions f_1 and f_2 are minimised. Rather than aggregating objective functions into a new one, Pareto optimisation consists of trading-off conflicting objective functions in order to determine a set of optimal solutions. The *Optimality* in a Pareto optimisation is tied to the concept of *Dominance*.

Definition 5.11 (Pareto Dominance): $x_1 \in \mathbb{X}$ dominates $x_2 \in \mathbb{X}$ (with $x_1 \neq x_2$) if x_1 is better than x_2 in at least one objective function and not worse with respect to all other objectives.

Definition 5.12 (Pareto Optimality): $x^* \in \mathbb{X}$ is a Pareto optimum if and only if it is non-dominated by any other element of $\mathbb{X}$. The set of Pareto optima is called *Pareto set*.

Definition 5.13 (Pareto Front): The Pareto Front is the set of all Pareto optimal solutions (non-dominated solutions).

The utopia point illustrated in Figure 5.5 corresponds to the optimal but unattainable solution of both objectives.

Optimisation techniques are widely used in daily life. One useful application of optimisation techniques is found in the planning of wireless networks.

5.3 WMN planning

A lot of work has been conducted in the planning of WMNs. All these works aim to optimise some criteria of the network planning or operating. A good survey on the planning of WMNs can be found in [Benyamina/Hafid/Gendreau 2012] where the planning problem is classified according to the flexibility of the network topology: unfixed (not-predefined) and fixed (predefined). The planning problem in WMN is summarised in Figure 5.6.

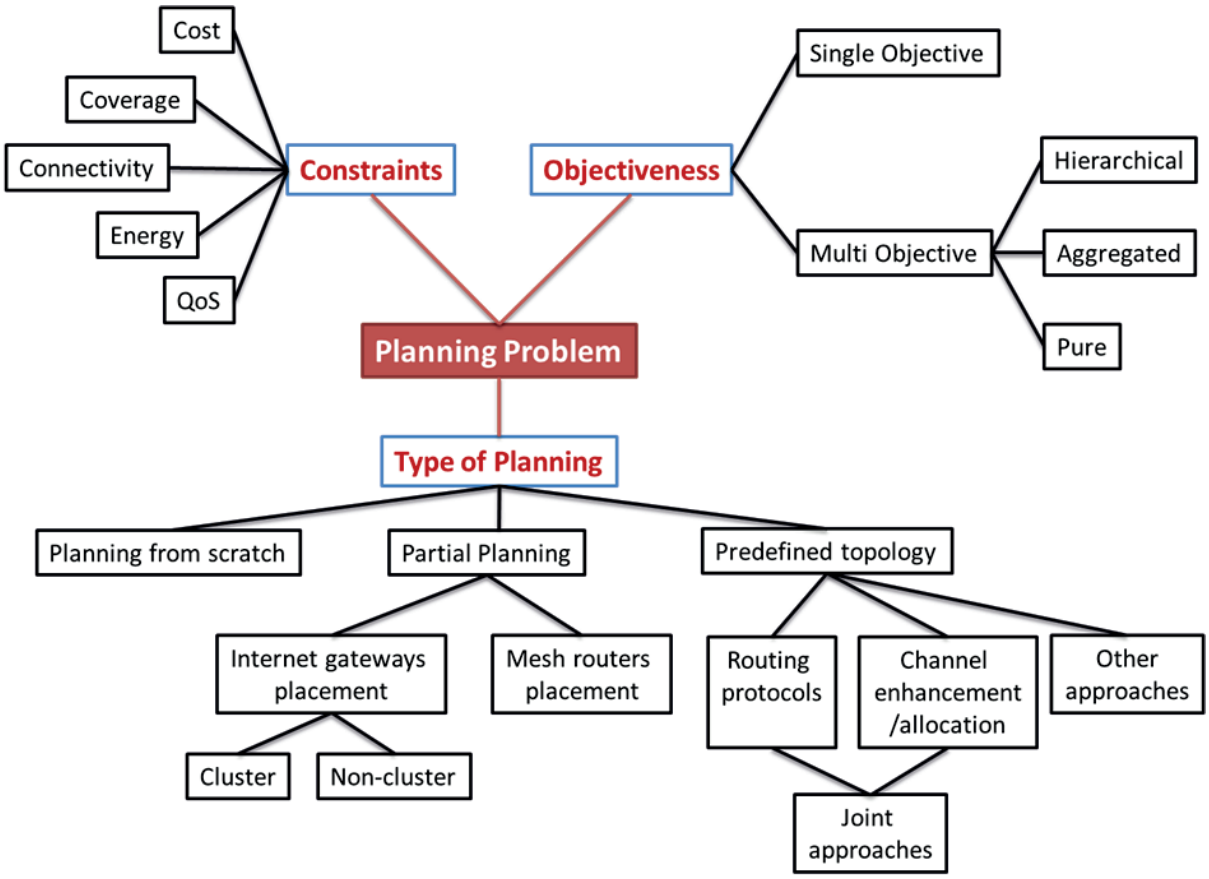


Figure 5.6 – Planning problem in wireless mesh networks.

5.3.1 Predefined topology

In a predefined topology, each mesh router is installed in a predefined location and cannot be moved elsewhere. So, previous works aimed to improve the capacity of the network while preserving its topology. The way how each node in a network is sending and receiving information influences the performance of the network; because an inefficient use of transmission channels could result in a lot of interferences, decreasing the capacity of the network ([Gupta/Kumar 2000], p. 388). Many approaches have been proposed to improve the performance of predefined-topology networks:

- New MAC protocols to handle multi-channel and to resolve multiple access for multi-channel wireless networks [Garces 2000], [Darties/Theoleyre/Duda 2009];
- Multi-channel routing algorithms; channel assignment schemes [Arindam et al. 2005], [Ramachandran et al. 2006], [Chaudhry et al. 2010]; and joining approaches. An interesting survey is found in [Pathak/Dutta 2011];

- Other approaches like the channel bonding technique [Liang et al. 2008]; cross-layer design [Akyildiz/Wang 2008], [Fu et al. 2014]; network topology control design [Tang/Xue/Zhang 2005], [Marina et al. 2010]; and network virtual backbone construction [Wang/Thai/Du 2009].

In contrary to predefined-topology networks, the performance can be considered during the planning of a WMN by carefully placing and characterising each node of the network. This placement is subject to some constraints, depending on the problem.

5.3.2 Planning constraints

Five types of constraints are frequently considered in WMN planning: cost, coverage, connectivity, quality of service (QoS) and energy. Usually some of these constraints are defined as objective function(s) in order to optimise with respect of other constraints.

Cost

One of the major constraints in network planning is the cost of the designed solution. An optimal planning should reduce the cost of the architecture as low as possible. A trivial assumption is to consider that all network nodes have the same cost. In this case, the cost of the network is optimised by reducing the number of nodes. Another assumption could differentiate the cost according to the type of nodes. Each mesh node has a cost c_m and each gateway a cost $c_g$with $c_m < c_g$. In this way, an optimal solution should provide an as less number of nodes as possible with the fewest number of gateways. The last assumption, and not the least, is to associate an installation cost to each candidate location for network nodes. Therefore, an optimal solution should use low cost locations as many as possible with respect of other constraints such as coverage.

In most planning problems, the cost is defined as an objective function to be optimised. But there are some cases like in [Chen/Chekuri 2007] where the cost is set as a constraint whose value is not allowed to exceed a defined ceiling.

Coverage

To maximise the coverage is almost always an objective in the planning of unfixed topology WMNs. The coverage could be expressed as a set of locations of traffic spots (also called traffic concentration and representing a set of mesh clients) to cover and a set of potential mesh router locations. This case supposes that the number and the locations of traffic spots are predefined and eventually also their QoS requirements (especially the aggregated throughput). This definition of the coverage is the most used in the literature, since the planning problem can be reduced to the facility location problem with mesh clients

representing locations to serve and mesh routers representing the facilities.

Supposing a predefined set of traffic spots is just to alleviate the difficulty of the problem. In most cases in reality, the set of predefined traffic is not given. A more realistic approach is to express this constraint as a geographic circumscription to cover and to assign a function for throughput requirements. [Wang et al. 2007] considered the region to cover as a two-dimensional disk of radius R. They associated a function $\mu(a)$ to the disk to characterise the traffic demand for each given infinitesimal traffic area a.

Connectivity

Connectivity is a strong requirement in WMN planning. Each mesh router should communicate at least with one router. A bad planning or a node failure after the deployment of the network could result in independent or separated sub-networks. In case of a sole Internet gateway, only one sub-network will reach the Internet. To ensure some robustness of a WMN the number of neighbours each mesh router can communicate with should increase. A great number increases the robustness of the network, but the drawback is the complexity of channel assignment, resulting in a prone to interference network. A good trade-off is found in a bi-connected WMN as it is designed in [Benyamina/Hafid/Gendreau 2009a]. Bi-connected WMNs are based on a bi-connected undirected graph wherein any single vertex could be removed without prejudicing the connectivity of the graph.

Quality of Service (QoS)

The QoS constraint in the network is usually expressed in terms of throughput [Xin/Wang 2009], [Li et al. 2008], [Zhou et al. 2010], or the delay that depends on the number of hops to an Internet gateway [Beljadid/Hafid/Gendreau 2007]. The throughput is maximised by maximising the ratio between the flow on a link and the capacity of this link. The delay is minimised by reducing the number of hops from a node to an Internet gateway.

QoS is mainly influenced by interference. In several works, to optimise the QoS consists of either mitigating interference or maximising the ratio between flow and capacity of each wireless link in the network.

Interferences are mitigated by a good channel assignment, allowing communication between nodes only on non-interfering channels. In ([Benyamina/Hafid/Gendreau 2008a], p. 3) an interference level metric has been defined: Balanced Channel Repartition (BCR); allowing a fairly allocation of channels to avoid the disparity in the number of channels used in each node of the network.

Energy and rate adaptation

Rate adaptation could be another factor to be considered in order to improve the network performance. The idea is to adapt the transmission rate to the condition of the transmitting channel; so that channels with good transmission conditions send data with a high speed. This is done by minimising the power output and consequently the transmission range in order to reduce interference. [Beljadid/Hafid/Gendreau 2007] provided an approach to incorporate an energy constraint in the design of WMNs. This approach consists of defining different energy levels and of associating a transmission range to each level. [Zheng et al. 2011] considered jointly power control and rate adaptation at access points to improve the network performance, based on different user demands and charging capabilities of the access points.

5.3.3 Objectiveness in planning

Earlier WMN planning problems considered just one of the above constraints as single objective to optimise, mainly the cost of the solution. But by its nature, the problem of mesh node placement requires a multi objective approach; since all constraints in the planning problem are interdepending. For instance, when trying to reduce the cost by reducing the number of mesh nodes, the coverage also decreases. Most of the time, these objectives seem to be contradictory as an example can illustrate. In multi-objective WMN planning, there are three types of multi-objective planning:

- Hierarchical: objectives are considered in priority order;
- Aggregated: objectives are combined to form only one objective to be considered;
- Pure: objectives are considered simultaneously and a set of trade-offs between objectives is provided.

Depending on the type of node, the problem of placement usually consists of determining either the position of the Internet gateway(s) or the position of mesh router nodes in partial design. But when designing the network from scratch, this problem consists of finding optimal locations for both Internet gateway(s) and mesh router nodes.

5.3.4 Partial planning

Partial planning aims to optimally place only one type of network nodes: Internet gateway(s) or mesh routers; the second type of node is supposed to be fixed.

Internet gateway(s) placement

The Internet gateway(s) placement problem receives a lot of attention, since it is the main mechanism for internetworking and also because it is more expensive than simple mesh routers. The number of Internet gateway(s), their location and the number of hops in the network have a direct incidence on the performance, the scalability, and the overall cost of the network. Planning approaches in the literature can be categorised in two main classes: cluster-based approaches where the network is partitioned into subsets of nodes, each subset being served by one Internet gateway, and non-clustering approaches, which consider the network as a whole.

[Aoun et al. 2006] proposed a cluster-based approach to address the problem of gateway placement in a WMN, aiming to place a minimum number of gateways, while ensuring the QoS requirements in terms of throughput, which was reduced to the load of congested intermediate wireless links. [Tang 2009] proposed an incremental clustering algorithm to solve the problem of gateway placement in a backbone WMN with respect of QoS including a delay constraint, a relay load constraint and a gateway capacity constraint. [Benyamina/Hafid/Gendreau 2009b] proposed a cost effective and cluster-based approach for the gateway placement that guarantees end-to-end bounded delay communication with a good handling of network scalability. [Waharte/Boutaba/Anelli 2009] investigated the performance of several heuristics for routers-to-gateways association in relation with different gateway placement algorithms. The proposed clustering algorithms (Voronoi, Force-based, and Potential-based) have been evaluated using the network topology of the already-deployed network of the city of Chaska in USA. Taking the Beijing Wangjing zone as an example [Ding/Xu/Zheng 2009] provided another cluster-based approach for the placement of an Internet gateway with respect of QoS.

In non-cluster-based approaches, [Li et al. 2008] proposed a grid-based deployment approach aiming to optimise the throughput in a WMN subject to interference. The goal is to place an Internet gateway in such a way that the throughput is maximised while ensuring a certain fairness among all mesh nodes. [Zhou et al. 2010] proposed also a square grid-based deployment approach. Their gateway placement scheme is based on a metric called multi-hop traffic-flow weight (MTW), which considers the number of mesh clients and routers. In their performance study about deployment factors in WMNs, Robinson and Knightly [Robinson/Knightly 2007] found that the square grid topology is more efficient than triangular, hexagonal, and random topologies. But in a real deployment, using a regular pattern to place network nodes is not feasible because network planners are looking for safe and low cost locations and the client distribution may not be uniform ([Franklin/Murthy 2007], p. 1). [Xin/Wang 2009] used a cross-layer approach to optimally select among mesh router nodes those to be equipped with gateway functionality with the aim of improving the total throughput of the network and ensuring a certain fairness among all mesh nodes. Another work [Wu/Luo/Yang 2009] aimed to ensure load balancing

in the network when placing the gateways.

Although there are different objectives in gateway placement problems, they all consider the placement of mesh routers.

Mesh router placement

In this placement problem, Internet gateways are supposed to be fixed. Therefore, the aim is to find the locations for mesh routers, which optimise the objective(s) with respect of constraints.

An earlier work related to mesh router placement is found in [Sen/Raman 2007]. From a landline node, considered as the Internet gateway, the authors proposed a low-cost solution to connect neighbour villages. The cost affected by the height of the antenna towers and the multi-hop topology is minimised with respect of the throughput, power and interference constraints.

[Chen/Chekuri 2007] considered the planning of a robust and fault-tolerant urban WMN composed of mesh routers that are using directional antennas. The aim in this planning problem has been the maximisation of the deployment profit, expressed in terms of amount of services while maintaining the cost within the budget.

Another work that can be categorised as partial planning is found in [Roh/Lee 2010]. The authors considered a wireless network that consists of multiple fixed nodes and a single relay node that has controllable mobility. Therefore, they formulated the optimisation problem with the aim to maximise the weighted throughput of a node that achieves the lowest weighted throughput among all nodes.

Usually, the mesh router placement problem is not considered independently, but associated to the problem of gateway placement. Therefore we talk about planning the network from scratch.

5.3.5 Planning from scratch

A network well planned from scratch could provide extra capacity with the same infrastructure cost of a fixed or partially fixed topology. Planning from scratch consists not only of finding the optimal location and the type of nodes in the network but also of determining a judicious number of interfaces and channel assignment for each node while minimising the cost and ensuring the connectivity, the required coverage and a minimum QoS.

Several works aiming to plan WMN from scratch, have tried to optimise different objectives subject to particular constraints. [Wang et al. 2007] provided an approach for nodes placement where a set of candidate positions are pre-decided. The aim was to determine a minimum set of positions satisfying the network coverage, the connectivity and the Internet traffic demand. [Beljadid/Hafid/Gendreau 2007] addressed this problem with the objective of minimising the overall cost of the network. They provided a generalised model for the design of a WMN, considering all-important parameters such as interference, transmission power, and multi-channel. But their model does not consider user's coverage.

[Amaldi et al. 2008] formulated the planning model of a WMN considering the coverage and topology planning for real size networks (60 nodes). They used a mixed integer linear programming model to solve their placement problem.

[Wu/Luo/Yang 2010] defined the WMN placement problem as an integer linear programming issue. They proposed a method for the determination of mesh access point locations, Internet gateway selection and mesh router addition with the aim of minimising the cost of the network. Three corresponding heuristic algorithms are proposed.

Previous works in WMN planning used deterministic methods to solve the node placement problem, after formulating it as a single-objective linear programming problem. The main drawback of this formulation is the restriction of the network size, especially when the number of constraints is important. Therefore, to consider real size networks, probability techniques are used among which are: genetic algorithms (GA) [De Marco 2009], [Xhafa/Sánchez/Barolli 2010]; particle swarm optimisation (PSO) [Benyamina/Hafid/ Gendreau 2008a], [Benyamina/Hafid/Gendreau 2008b], [Benyamina/Hallam/Hafid 2008a]; simulated annealing (SA) [Xhafa et al. 2011]; ad hoc and neighbourhood search methods Sánchez/Barolli 2009].

Some works provide a multi-objective formulation for the WMN planning problem. In [Xhafa et al. 2011], the problem is defined as a hierarchical multi-objective optimisation problem; that means a priority is defined between the two objectives: coverage and size of the giant component (connectivity). As stated earlier, the optimal solution of the next objective function(s) is local to the neighbourhood of the optimal solution of the previous objective function(s) in this approach. A pure multi-objective formulation based on Pareto optimisation is provided in [Benyamina/Hafid/Gendreau 2008a] and [Benyamina/Hafid/Gendreau 2008b]. The authors tried to simultaneously minimise the cost of the network while either maximising the throughput or minimising interference in these works. A set of non-dominated solutions between objectives are provided at the end.

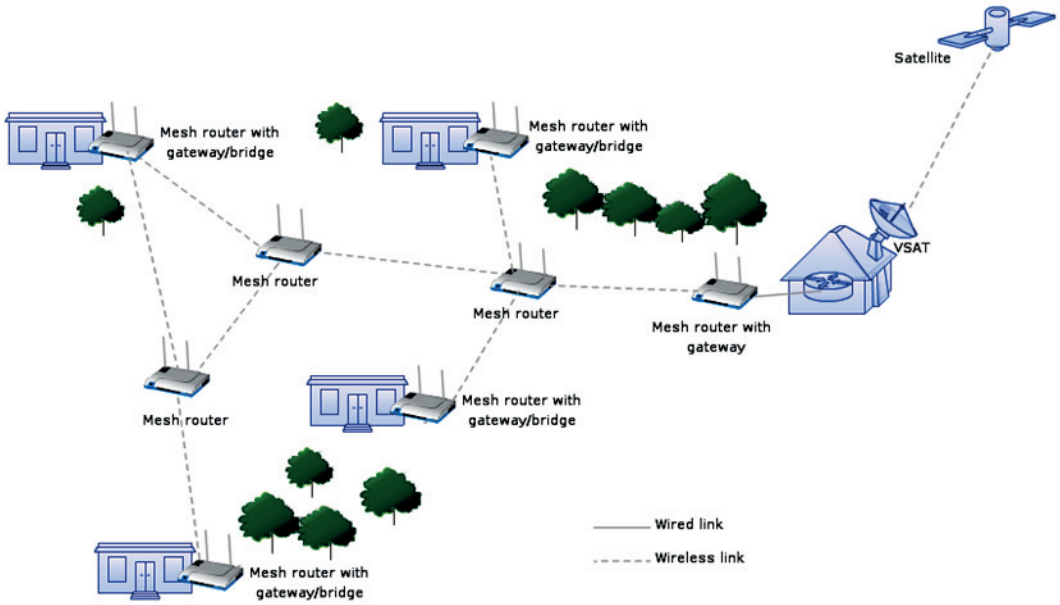


Figure 5.7 – Rural application of a wireless mesh networks.

5.4 WMN planning in rural regions

WMN planning in rural regions is considered as a partial planning problem like in [Sen/Raman 2007] wherein different villages are connected from a landline node. A WMN in a rural region is usually composed of a set of mesh routers and a sole gateway, which connects the network to the Internet via a last mile solution such like VSAT as illustrated in Figure 5.7. This is the case of the Macha network in Zambia and the Peebles network in South Africa.

Rural regions generally present hostile environments with obstacles like trees, mountains or emplacements like a lake where we cannot install something. Previous works were focused on technical challenges when planning a WMN; but a realistic planning approach for rural regions should also consider environmental constraints.

The main constraint when planning a rural WMN is the cost of the solution. The fact that the population is sparsely distributed in the region drives the planers to satisfy only regions presenting some interests. The first approach to reduce the cost is considering therefore only areas of interest in the coverage constraint. We usually can suppose neither the existence of a traffic spot nor its location as it is the case in almost all previous works. The coverage constraint could be expressed as a circumscription of an area rather than a set of clients to serve. The planning problem is in this configuration more looking like planning from scratch with only the location of the Internet gateway (IGW). In contrary to urban regions where the planning of networks is typically capacity-driven, the planning of networks in rural regions is rather coverage-driven ([Bernardi et al. 2011], p. 1 f.). This

means, we are more concerned with the area to cover than the capacity to provide. In other terms: The number of mesh routers is determined by the area to cover rather than the capacity required by a set of clients in the case of a wireless mesh network planning. The suitability of coverage-driven planning in rural regions is truer when most of the applications accessible through the network are mainly text- not audio- or video-based. Although a low cost network with limited QoS could be acceptable in rural regions, a mitigation of interference by a good channel assignment could improve the QoS in the network.

6 Mesh router nodes placement in rural areas

As said in the previous chapter, the planning of WMNs in rural areas is subject to more than technical constraints. We have also to deal with the environment, which is most of the time very hostile. These constraints have to be modelled and considered during the planning process.

This chapter starts by describing the mesh router nodes placement problem in rural regions. A statement of the problem is presented as well as the network model. The second section presents and discusses the efficiency of simulated annealing, the optimisation method used to solve the problem. In the next section, this algorithm is particularised to solve the problem of the mesh router nodes placement. Different trade-offs are proposed between the coverage percentage and the number of routers. The last section deals with the cost optimisation of the solution. The aim is to relocate mesh routers to cost effective emplacements. A new approach is proposed to tackle this redefinition of the problem: Pareto archived reverse simulated annealing (PARSA).

6.1 Placement problem formulation

In contrary to urban regions, there is no need to cover a whole region in rural ones. Because the greater the region to cover is, the more we need router nodes, and the overall cost is higher. To focus only on important part of a given region is a good approach.

6.1.1 Region description

In our placement problem, a given region is composed of:

- Areas of interest like a market, a school, a hospital, that are usually sparse, but need

to be connected. When an area is not of interest, the coverage of this region is considered as optional. Regions with optional coverage could be great farms for example;

- Prohibited areas where a node cannot be placed for example a lake, a river or a road. However, a node can be placed in an optional area because an optional area is not necessary a prohibited one;
- A set of obstacles with different attenuation factors on a signal;
- A set of low cost locations that can reduce the cost of node installation.

6.1.2 Network model

The area to cover is modelled as a two-dimensional irregular form in a two-dimension coordinate plane. We consider the smallest rectangle that can contain the irregular form. Therefore, we assume that this rectangle is decomposed in small square forms. Each discrete point is called elementary area (EA). Each EA can be of one or more types:

- EAI: Elementary Area of Interest;
- NEA: Non-line-of-sight (NLOS) Elementary Area;
- CEA: Cost effective Elementary Area;
- PEA: Prohibitive Elementary Area.

When an EA is not an EAI, it is automatically an optional EA (OEA). IGW is the Internet gateway. Figure 6.1 illustrates the result of a decomposition of a region into a set of EA.

Thinking like that, we can define different two-dimensional matrices to characterise each EA. Let us consider the following matrices:

- *Cover* defining whether an EA requires coverage;
- *Place* defining whether we can place a node in an EA;
- *CoverDepth* defining the number of routers covering an EA;
- *Pathloss* defining whether an EA contains an obstacle;
- *LowCost* defining whether an EA is cost-effective.

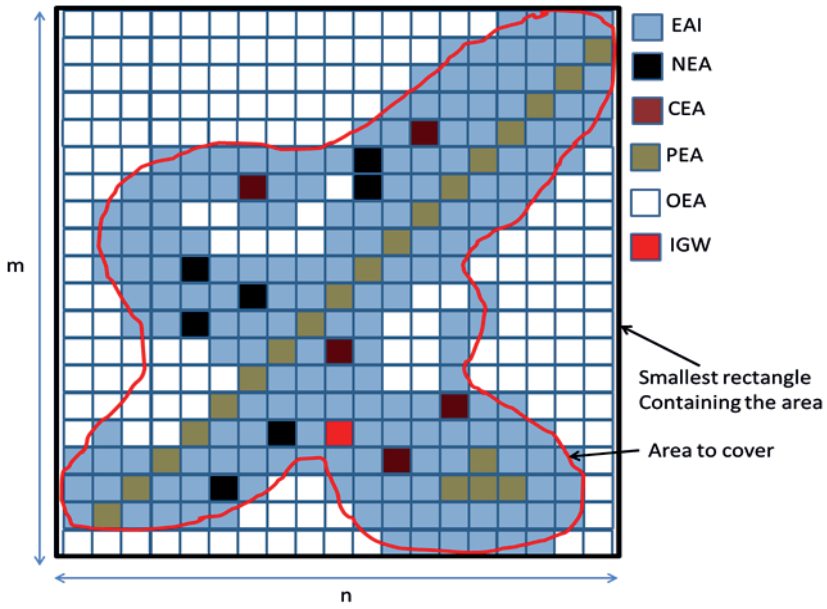


Figure 6.1 – An example of a region decomposed in EA.

Therefore, an EA at position (x, y) can be characterised by (6.1)-(6.5).

$$Cover(x,y) = \begin{cases} 0 \rightarrow \text{ coverage not required} \\ 1 \rightarrow \text{ coverage required} \end{cases} \tag{6.1}$$

$$Place(x,y) = \begin{cases} 0 \rightarrow \text{ cannot place a node} \\ 1 \rightarrow \text{ can place a node} \end{cases} \tag{6.2}$$

$$CoverDepth(x,y) = \begin{cases} 0 \rightarrow \text{ no coverage} \\ n \rightarrow \text{ covered by } n \text{ routers} \end{cases} \tag{6.3}$$

$$Pathloss(x,y) = \begin{cases} 0 \rightarrow \text{ no obstacle} \\ p \rightarrow \text{ attenuation factor=} p \end{cases} \tag{6.4}$$

$$LowCost(x,y) = \begin{cases} 0 \rightarrow \text{ no cost effective} \\ 1 \rightarrow \text{ cost effective} \end{cases} \tag{6.5}$$

Since the population is not so dense like in urban regions, we consider a uniform repartition of clients in EAIs. That means each EAI has the same number of clients. We assume, to alleviate the complexity of the problem, that the attenuation factor of any obstacle in the line of sight between two routers is high enough to prevent a wireless link between those routers. We also assume that all routers are equipped with an omnidirectional antenna all having the same coverage radius (r). Hence we represent a router as a circle. The radius is expressed as the number of EAs. For example $r = 6$ means that the radius stretches over 6 EAs.

Let l be an EA at position (x, y). If a mesh router is located in l, then the set of EAs covered by this mesh router is given by (6.6).

$$\forall\,(a,b)\,,\ (x-a)^2+\left(y-b\right)^2 < r^2 \tag{6.6}$$

6.1.3 Problem statement

The mesh router placement problem in rural regions can be described as the determination of a minimum set of positions, which maximises the coverage of areas of interest, minimises the coverage of optional areas while maximising the use of cost effective locations and ensuring the connectivity.

Let us consider an area of n*m EAs containing p PEAs. Let us consider also n_{eai} be the number of EAIs and n_{peai} the number of EAIs where we can place a router. The value of n_{peai} is given by (6.7).

$$n_{peai} = n_{eai} - p \tag{6.7}$$

The basic placement problem of nr routers in this area requires the evaluation of the number of combinations given by (6.8) for checking the optimal coverage.

$$C_{nr}^{n_{peai}} = \frac{n_{peai}!}{nr!(n_{peai}-nr)!} \tag{6.8}$$

We suppose n=m=50, nr=60 and p=100 for a real life scenario. We also suppose that half of the region is optional in terms of coverage. Thus

$$n_{eai} = \frac{50*50}{2} = 1250 \quad \text{then} \quad n_{peai} = 1250 - 100 = 1150$$

The number of combinations to examine is therefore:

$$C_{60}^{1150} = \frac{1150!}{60!(1090)!}$$

(6.8) increases exponentially when the number of routers or the size of the area increases. Since the number of combinations is too high, a deterministic algorithm cannot solve this problem in a polynomial time. Therefore, a meta-heuristic should be used.

6.2 Simulated annealing

The simulated annealing (SA) algorithm is a probabilistic global optimisation technique for approaching the global optimum of a given objective function in a large search space, by accepting non-improving solutions in order to escape local optima.

The SA algorithm has been developed independently by [Kirkpatrick et al. 1983] and by [Cerny 1985]. It is inspired from the annealing process in metallurgy and material science, whereby a substance is heated to a specific temperature and then slowly cooled to reduce the defects and to obtain a strong crystalline structure reaching a minimal (optimal) energy level. The energy changes in the cooling process of a system are simulated by the SA algorithm until an equilibrium state (an optimum) is reached. The first development of an optimisation technique based on an annealing process dates back to Metropolis [Metropolis et al. 1953].

6.2.1 Basic SA algorithm

The SA algorithm proceeds as follow: First, an initial solution is generated; several iterations are performed from this solution. A new random solution is generated at each iteration. If the solution improves the value of the objective function, it is directly accepted. Otherwise, this non-improving solution is accepted with a probability depending on the current temperature and the difference E between the value of its objective function and the one of the previous solution. Since the temperature decreases progressively, the probability of accepting non-improving solutions also decreases. Usually, the probability in the SA algorithm follows the Boltzmann distribution (6.9) ([Talbi 2009], p. 127).

$$P(\triangle E, T) = e^{-\frac{\triangle E}{T}} \tag{6.9}$$

With $\triangle E = f(s') - f(s)$

Algorithm 6.1 Simulated annealing

Input: f : the objective function to be minimised
Output: s: the best solution found

```
1   Begin
2   | T := T_initial
3   | s := InitialSolution()
4   | v := f(s)
5   | while (stopping condition not met) do
6   |   | while (equilibrium condition not met) do
7   |   |   | s' := GenerateSolution()
8   |   |   | v' := f(s')
9   |   |   | ΔE := v' − v
10  |   |   | if ΔE ≤ 0 then s := s'
11  |   |   | else accept s' with probability e^(−ΔE/T)
12  |   | Update(T)
13  | return s
14  End
```

The basic version of the SA algorithm is given in Algorithm 6.1.

6.2.2 Parameter setting

Several parameters determine the efficiency of the SA algorithm. Each of them should be carefully defined in order to obtain good results and to optimise the computational time. The main parameters are: the initial temperature, the equilibrium state, the temperature update, the acceptance probability, and the stopping condition ([Talbi 2009], pp. 130-133).

Initial temperature

The initial temperature should not be too high in order to avoid the cooling process to be time consuming in the SA algorithm. But it should also not be too low to escape from the local optimum of the initial solution.

Equilibrium state

An equilibrium state should be reached at each temperature; then the temperature is decreased. Two strategies are defined to reach an equilibrium state: a static and an adaptive one. The number of moves to perform at each temperature in the static strategy is predefined while in the adaptive strategy, this number of moves is dynamic. For instance, moves can be performed until an improvement is known. The temperature is therefore updated.

Temperature update

Each update of the temperature decreases its value such as:

$T_i > 0,\ \forall i$ and $\lim_{i\to\infty} T_i = 0$

The decrease of the temperature can be based on different schemes. The most current schemes of updates are:

- Linear: $T_i = T_0 - i \times \beta$
- Geometric: $T = \alpha T$ with $0 < a < 1$
- Logarithmic: $T_i = \frac{T_0}{\log(i)}$

Stopping condition

The most used stopping condition is reaching a current temperature less than a minimal temperature.

$T_i < T_{min}$ with $T_{min} \approx 0$

Another proposed stopping condition is to perform a number of moves without improving the best solution found.

6.3 Mesh router placement approach using the SA algorithm

The basic SA algorithm is an S-meta-heuristic that approaches the global optimum of a single objective function. It is usually used in a single-objective optimisation problem. But in our problem, the objective is twofold: maximising the coverage and minimising the cost while ensuring the connectivity of the solution. The first approach to tackle this problem is to define a priority between objectives and to optimise the second one after the first while preserving a minimal quality of the first one (hierarchical MOOP). We assume the number of routers to be placed to be unknown at the beginning in this placement approach. We therefore have also to determine a set of choices depending on the number of routers.

6.3.1 Algorithm particularisation

We use a multi-start SA algorithm in the proposed scheme. It consists of running the SA algorithm many times to keep the best result at the end. This is more time consuming, but since we are in offline optimisation, the quality of the solution has a great priority.

Nevertheless, the computational time should be acceptable. The basic SA is modified according to the flowchart given in Figure 6.2.

Initialisation

The first step is to determine the initial number of routers for a given region. For that, we need to determine the minimum number of routers that allows full coverage of the EAIs first. This is calculated by dividing the total required area by the area covered by a router. Let r be the radius of a router, the minimum number of routers is given by (6.10).

$$nr_{min} = \left\lceil \sum Cover\left(x, y\right) \ / (r^2 * 3.14) \right\rceil \tag{6.10}$$

Because this minimal number of routers may not ensure the coverage and the connectivity of the required areas, since routers should overlap to ensure the connectivity, and because the form of the region is irregular, we use a greater number so that the coverage and the connectivity can be ensured. This number is reduced later while trying to keep the same coverage. However, a too great number at the beginning is not efficient. We choose an initial number of routers given by (6.11).

$$1.4 * nr_{min} < nr_{init} \leq 2 * nr_{min} \tag{6.11}$$

$Best$ keep the best solution for each number of routers. $nRun$ is the number of times the SA algorithm will be executed. Routers are placed randomly in the region during the initialisation phase of the SA algorithm, but only in areas of interest. We randomly select an EA for each router. We check if Cover(EA)=1, and Place(EA)=1, and, if a router is not already set at this location then the current router can be placed there. Otherwise, we continue by selecting another EA. The initialisation ends when all routers are placed.

Cooling schedule

The initial temperature $T = 10$ has been determined empirically. At this temperature the coverage percentage is more than 80% as shown in Figure 6.3a, when considering a number of routers $nr = 1.4 * nr_{min}$. We select a geometric update scheme with $\alpha = 0.5$. When the temperature is less than $T_{min} = 0.001$, the coverage percentage of the area of interest is more than 99% as shown in Figure 6.3a. Figure 6.3b shows the coverage of the router placement in the area; blue areas are covered by one router, red by two and white by three.

Move

We define a set of movements with moving only one router at the same time randomly. We define three hops: r ; $r/2$; 1EA in different directions. We select randomly a distance

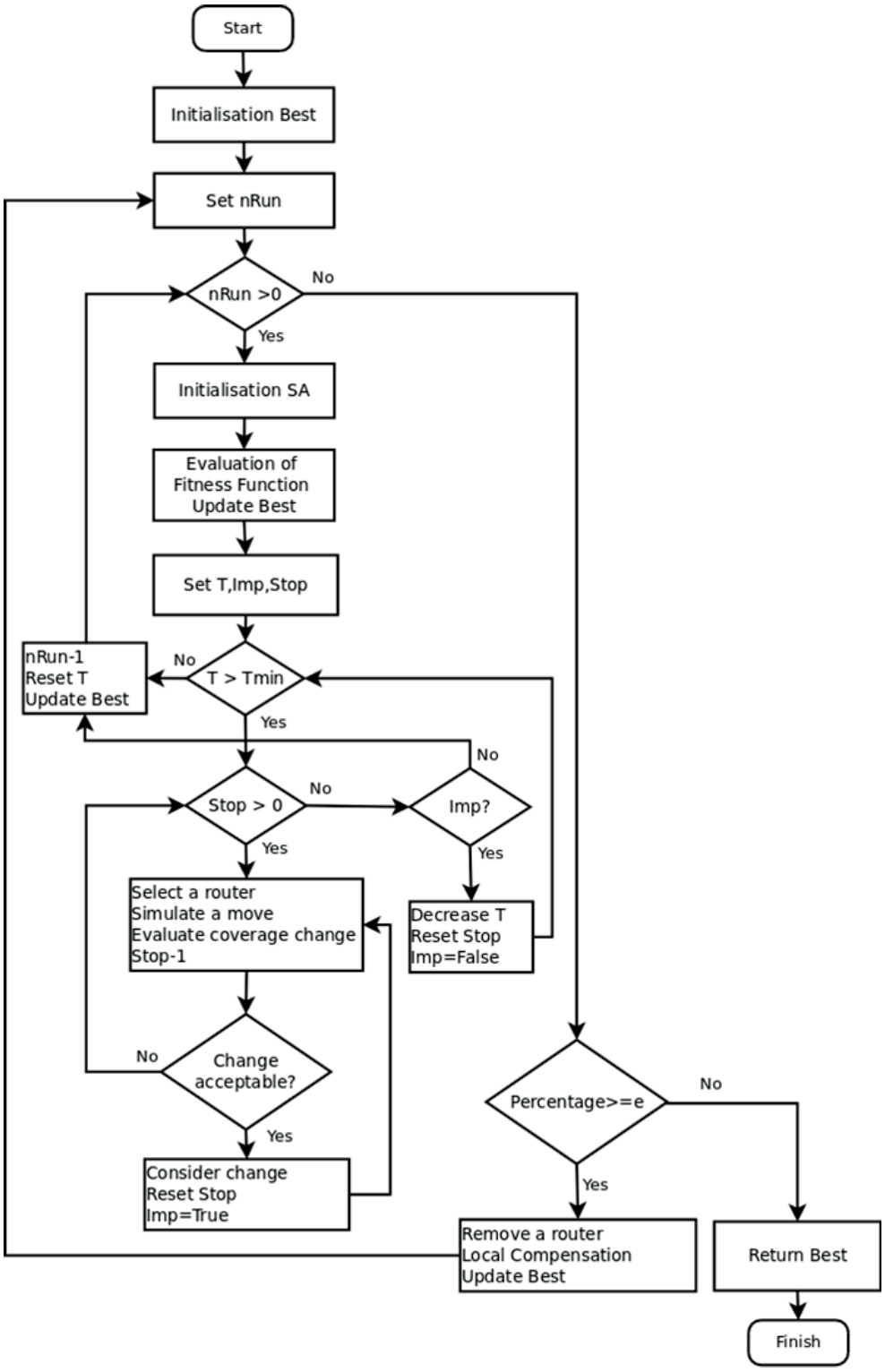
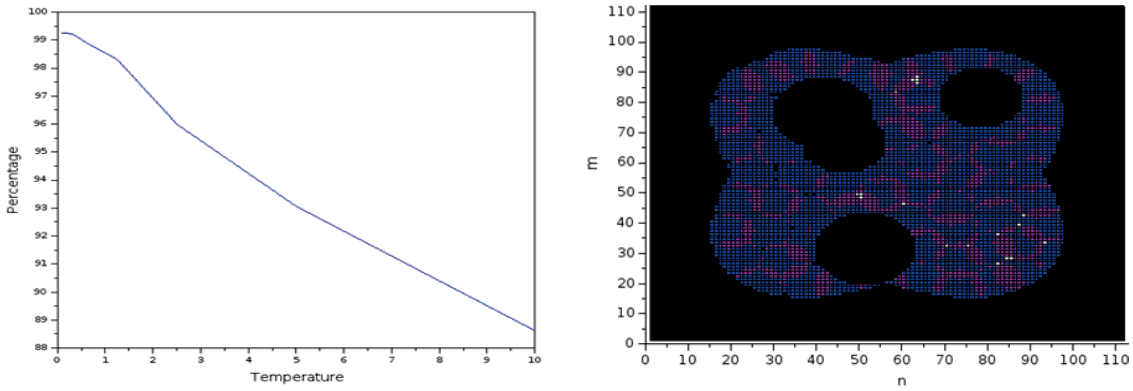


Figure 6.2 – Flowchart of the modified SA algorithm for solving the mesh router placement.



(a) (b)

Figure 6.3 – Cooling process:(a) Variation of the temperature; (b) Corresponding router coverage.

and a direction; the movement from the current EA_a to the new EA_b is simulated if and only if Cover(EA_b)=1 and Place(EA_b)=1. This is always done to avoid placing a router in an optional area and consequently to reduce their coverage and to increase the coverage of areas of interest. The size of the hop when moving a router has a direct influence on the improvement of the solution. Initially great moves are selected to allow a rapid convergence. The size of moves decreases with the temperature; when the temperature is close to T_min, the size of moves is one EA.

Fitness function

We count the number of EAIs that are covered to evaluate the fitness function. This is done by (6.12) after the initialisation.

$$f = \sum \text{sign}(CoverDepth . * Cover) \tag{6.12}$$

To be more efficient in the iteration phase, we calculate only the change in the coverage. Since we move only one router at the same time, we consider also only the EAs which are concerned by the movement. For example in Figure 6.4, when moving a router from a to b, we decrease the coverage depth of the router in position a and we increase the coverage depth of that one in position b. Let f_i be the value of the fitness function of the configuration i, C_a the coverage of the selected router in previous position a, and C_b the coverage of the selected router in the new position b, the fitness function in configuration $i+1$ is given by (6.13).

$$f_{i+1} = f_i + C_b - C_a \tag{6.13}$$

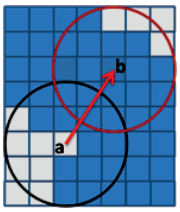


Figure 6.4 – Considering only EAs affected by a movement of a router.

Acceptance criterion

When $C_b \geq C_a$, the coverage change is directly accepted. But when the coverage change is negative, the change is accepted with a certain probability influenced by the temperature T to avoid local optimum. The acceptability criterion is given in (6.14).

$$\text{rand}(x) < e^{\frac{C_b - C_a}{T}} \tag{6.14}$$

With $0 < \text{rand}(x) < 1$

Equilibrium state and stopping condition

We combine the static and the adaptive strategy to determine the equilibrium state. The equilibrium state is supposed to be reached if after a number (stop) of moves no solution has been accepted. The stopping condition depends on Imp and on the minimal temperature. At each temperature T_i, Imp indicates whether the solution has improved. When the equilibrium state at a temperature T_i is reached, before decreasing the temperature we check whether the solution has improved. In case of an improvement, we decrease the temperature and move to the next iteration. But if there is no improvement or the temperature is less than the minimal temperature (T_{min}), we stop the search process and suppose having reached an optimum.

At the beginning nr_{init} routers are used. The SA algorithm is running $nRun$ times at each stage. If the required coverage is satisfied, we remove one router and restart until the coverage can no longer be satisfied.

Nodes connectivity

The network is connected if for two pair of routers there exists a non-empty set of links that allows a communication between those two routers. At this step we check if each router is connected to at least one router while verifying that there exists no sub-network. This task is more complicated with the presence of obstacles in the model. We must not only check that the router radiuses are overlapping, but also the existence of the line of sight between the routers. The three routers are overlapping in Figure 6.5. Because of obstacles (NEA in

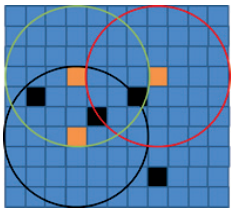


Figure 6.5 – Influence of obstacles in the connectivity of routers.

black) between the centre of the red router and the black one, these routers cannot directly communicate. Nonetheless, they are connected via the green router.

The algorithm for checking the connectivity of the network is given in Algorithm 6.2. In this algorithm we consider $NotConnected$ as the list of not connected routers, $Connected$ the list of connected routers, $NumConnected$ the number of connected routers, nr the number of routers, f_g a flag. The two lists $NotConnected$ and $Connected$ are subject to change.

We consider initially that the first router belongs to $Connected$ and the rest belongs to $NotConnected$. We check that each router is connected to at least one router in $Connected$. When it is the case, the current router is removed from $NotConnected$ and added to $Connected$, then $NumConnected$ is incremented. To check the connectivity between two routers, two functions are used: distance(x, y) that checks whether the two routers are overlapping and LOS(x, y) that checks the line of sight between two routers. distance(x, y) makes use of the Pythagoras theorem to calculate the distance between the centres of two routers x and y, and checks if it is not greater than twice the radius. LOS(x, y) determines the line segment between routers x and y and checks if there is no NEA.

Reducing the number of routers

After $nRun$ for a given number of routers nr, we select the run, which provides the best coverage of the area of interest and we remove one router. To remove a router, three strategies can be used:

1. Remove the router with the minimum single-coverage: the orange router in Figure 6.6 covers alone only one EAI (blue cells), the red router covers alone two EAIs and the black one covers alone five EAIs. So, the orange router should be removed;
2. Remove the router with the minimum coverage of EAI: the black router in Figure 6.6 covers six optional EAs (white cells), the orange router covers four optional EAs and the red one does not cover any optional EA. Therefore, the black router should be removed.

Algorithm 6.2 Checking the connectivity of the network

Input: Ctr : Set of router locations
Output: Connectivity of the network

```
1   Begin
2   | NotConnected := [0 ones(1,nr-1)]
3   | Connected := [1 zeros(1,nr-1)]
4   | NumConnected := 1
5   | for ii := 1 to nr do
6   |   | fg := 0
7   |   | for jj := 1 to nr do
8   |   |   | if (NotConnected(jj)=1) then
9   |   |   |   | for kk := 1 to NumConnected do
10  |   |   |   |   | if (distance(Ctr(:,jj), Ctr(:,Connected(kk))<=2r) then
11  |   |   |   |   |   | if (LOS(Ctr(:,jj), Ctr(:,Connected(kk)) then
12  |   |   |   |   |   |   | fg := 1
13  |   |   |   |   |   |   | NumConnected := NumConnected+1
14  |   |   |   |   |   |   | Connected(NumConnected) := jj
15  |   |   |   |   |   |   | NotConnected(jj) := 0
16  |   |   |   |   |   |   | break
17  |   |   | if (NumConnected==nr or fg==0) then
18  |   |   |   | break
19  |   | return NumConnected==nr
20  End
```

3. Remove the circle with the maximum over-coverage: the black router has ten EAIs over-covered in Figure 6.6, the orange router has 16 EAIs over-covered and the red one has 21 EAIs over-covered. So the red router should be removed.

The first appears to be the best among these three strategies.

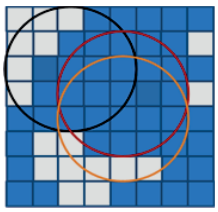


Figure 6.6 – Strategies for removing routers.

Local compensation

When removing one router - if its single coverage is not null - we try to compensate it locally. The idea is to check if by moving its neighbours the compensation can be achieved.

Algorithm 6.3 Local compensation

Input: $CtrToRemove$: the removed router
s: solution without $CtrToRemove$
Output: s: solution with compensation

```
1   Begin
2   | if SingleCoverage(CtrToRemove)>0 then
3   |   | ListNeighbours:= findNeighbours(CtrToRemove)
4   |   | if length(ListNeighbours) >0 then
5   |   |   | for i:=1 to maxIteration do // maxIteration is a static value
6   |   |   | CtrTmp:= Random neighbour in ListNeighbours
7   |   |   | s':= generateSolution(CtrTmp) // Move from 1EA in one direction
8   |   |   | if f(s') − f(s) > 0 then
9   |   |   |   | s := s'
10  | return s
11  End
```

So, when removing the router, we keep its coordinates. Then we determine its neighbours and we simulate small moves. We accept a move only if it improves the coverage. The algorithm for local compensation is given in Algorithm 6.3.

6.3.2 Experimentation

To evaluate our proposed algorithm, we consider a grid of 100x100 with the radius of a router r=6. The unit is the size of an EA. If size (EA)=20m, the grid will be 2Km x 2km=4km² and the radius r=120m. This is realistic since 802.11a routers have a theoretical outdoor transmission range of 120m, 802.11b 150m and 802.11n routers 250m. The global parameters for the experimentation phase are given in Table 6.1.

We generate three regions with different areas of interest, obstacles and prohibited areas as in Figure 6.7. Blue regions represent the area of interest that should be covered and black regions represent optional areas in this figure. Prohibited areas are not directly seen in Figure 6.7 because some areas of interest and optional areas can also be prohibited areas. Obstacles are placed randomly on regions.

The SA algorithm and all following algorithms have been implemented in Scilab, which is an open-source software for numerical computation [Ramchandran/Nair 2011].

Results and interpretation

The proposed algorithm has been run with each region instance. Table 6.2, Table 6.3, and

$nRun$=3	nr_{init}=1.5nr_{min}
T_{init}=10	$Region$= 100x100
T_{min}=0.001	$NumberOfNEA$=50
$Stop$=500	r=6

Table 6.1 – Parameter values for experimentation (adapted SA algorithm).

Table 6.4 provide results respectively for instance 1, 2, and 3. In these tables:

- AI is the coverage percentage of the area of interest;
- OA is the coverage percentage of the optional area;
- Connect is indicating whether all routers are connected.

The first line of data represents the results for an initial number of routers nr= nr_{init}=nr_{min}*1.5; and the last line for a number of routers nr=nr_{min}. Complete results about the coverage percentage of the area of interest are plotted in Figures 6.8a, 6.8b, and 6.8c, respectively for instance 1, 2, and 3.

In Table 6.2 related to instance 1, all the three runs provide a coverage percentage of the area of interest close to 100% with nr_{init}=65. All routers are connected and the coverage of the optional area is around 20%. We observe that with nr= 63 or nr=62, no run provided a connected network. But with nr between 61 and 58, we get at least one connected network from each run. This is due to the presence of obstacles between routers. That means, in presence of obstacles, augmenting the number of routers is not an efficient strategy to ensure the connectivity of the network. We also observe that with nr=59 (1.34*nr_{min}), we obtain a coverage percentage of the area of interest greater than 99%, with all the routers connected. This number could be considered as the optimal number to achieve a coverage percentage of the area of interest close to 100%. This number of routers starts an horizontal asymptote as shown in Figure 6.8a. Augmenting the number of routers will not improve the coverage, since it is close to 100%. The smallest number of routers that provides a connected network is nr=48 (1.09*nr_{min}) with a coverage of 92.44%.

Related to instance 2, Table 6.3 shows, with the initial number of routers nr_{init} =68, a coverage percentage of the area of interest close to 100%; all routers are connected. As in the first instance, the locations of obstacles in the region influence the connectivity of the network. With nr=63 or 64, no run provided a connected network. A good trade-off between the number of routers and the coverage percentage of the area of interest is found with nr=61 (1.32*nr_{min}) with a coverage of 98%. The smallest number of routers that provides a connected network is nr=48 (1.04*nr_{min}) with a coverage of 91.40%.

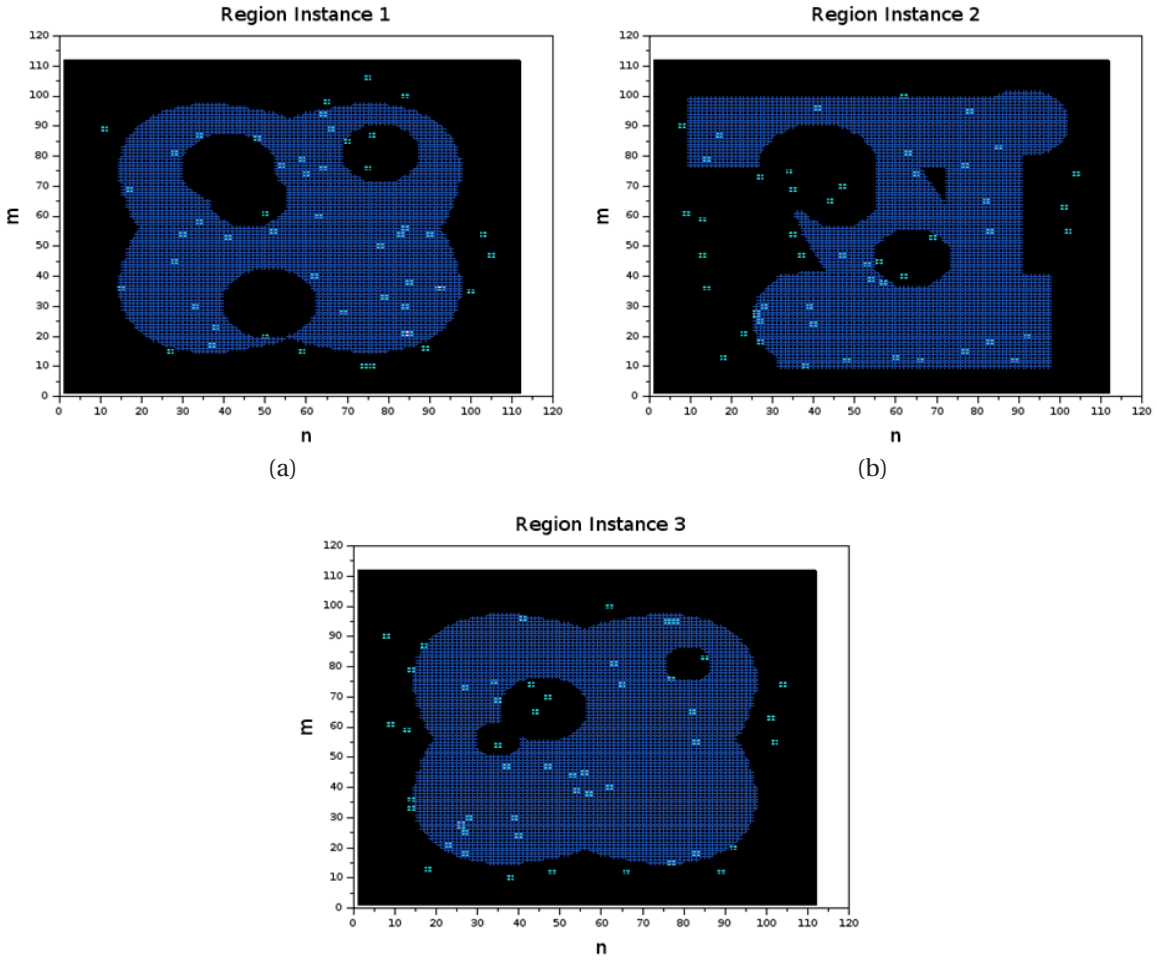


Figure 6.7 – Areas to cover with random obstacles: (a) instance 1; (b) instance 2; (c) instance 3.

In Table 6.4 from instance 3, as it is the case in both previous instances, the initial number of routers nr_{init} =75 achieves a coverage percentage of the area of interest close to 100%. The impact of obstacles is not as important as in previous instances. This is due to the form of the area of interest and the small size of optional areas inside. Since the algorithm is looking for covering the area of interest, a small number of obstacles in the region can be easily skirted. With a number of routers nr=65 (1.3*nr_{min}), the algorithm still achieves a coverage percentage of the area of interest of 99.27%. A good trade-off is found with nr=61 (1.22*nr_{min}) providing a coverage of 98%.

Figures 6.8a, 6.8b, and 6.8c compare the best and the worst coverage percentage of the area of interest for instance 1, 2, and 3 respectively.

	Run1			Run2			Run3		
nr	**AI (%)**	**OA (%)**	**Connect**	**AI (%)**	**OA (%)**	**Connect**	**AI (%)**	**OA (%)**	**Connect**
65	99,81	23,32	Yes	99,83	20,18	Yes	99,63	21,61	Yes
64	99,81	20,10	Yes	99,86	22,56	Yes	99,71	20,55	No
63	99,52	20,26	No	99,75	20,70	No	98,76	19,21	No
62	99,52	19,91	No	99,32	21,15	No	99,65	19,58	No
61	99,55	19,58	No	98,68	19,25	Yes	97,71	18,82	Yes
60	99,34	17,93	No	99,63	18,57	Yes	98,45	18,28	Yes
59	99,34	17,15	Yes	98,93	17,60	Yes	98,14	14,89	No
58	98,55	16,67	Yes	98,60	17,52	No	95,27	15,18	No
57	98,39	17,31	No	97,42	15,27	No	97,71	16,67	No
56	97,85	16,73	No	97,91	17,29	No	96,53	14,96	Yes
55	97,65	15,70	No	94,98	13,67	No	96,36	15,39	Yes
54	97,03	15,70	No	93,91	14,71	Yes	96,96	14,42	No
53	96,22	14,96	No	95,70	13,96	No	96,47	14,85	Yes
52	95,68	13,34	Yes	95,62	12,23	Yes	95,17	10,49	Yes
51	94,86	12,91	Yes	95,37	12,46	Yes	95,46	12,95	No
50	94,32	12,29	No	90,66	9,83	Yes	95,04	11,67	No
49	93,93	11,67	No	93,97	10,56	Yes	91,74	10,93	Yes
48	93,47	9,58	No	92,44	10,49	Yes	92,42	9,96	No
47	92,32	8,72	No	91,68	10,39	No	91,51	9,89	No
46	91,12	8,32	No	91,32	8,63	No	90,62	7,85	No
45	90,13	7,95	No	89,71	7,66	No	89,55	6,75	No
44	88,82	7,42	No	87,85	7,33	No	89,57	6,22	No

Table 6.2 – Partial results of the router placement in instance 1.

The sawtooth form of the curve representing the worst coverage percentage (minimal) shows the probabilistic property of the algorithm in all the three figures: a greater number of routers does not imply automatically a greater coverage. The almost monotonically increasing curve of the best coverage percentage (maximal) is obtained by keeping the best previous configuration after removing one router and making the local compensation. It should be compared later with the results of the next series of three runs; the best will be kept. Apart from some low peaks with a decrease of 5% from the best, other numbers of routers provide a variation less than 4% between the best and the worse percentage coverage of the area of interest in Figures 6.8a, 6.8b, and 6.8c. That means, even though the approach is probabilistic, the results are similar.

Figures 6.9, 6.10, and 6.11 show router locations (a), links and obstacles (b), respectively in instance 1, 2, and 3. In Figure 6.11a, blue, red, and white colours represent areas covered respectively by one, two, and three routers. In Figure 6.11b, lines represent links between

	Run1			Run2			Run3		
nr	**AI (%)**	**OA (%)**	**Connect**	**AI (%)**	**OA (%)**	**Connect**	**AI (%)**	**OA (%)**	**Connect**
68	99,31	17,48	Yes	99,15	18,35	Yes	99,09	23,04	Yes
67	98,98	22,39	Yes	98,84	18,67	Yes	98,41	19,39	No
66	98,78	22,15	Yes	99,39	18,43	Yes	99,19	16,01	No
65	99,23	17,86	Yes	98,62	16,07	No	98,76	18,04	No
64	99,09	17,56	No	98,90	16,34	No	97,97	16,28	No
63	98,80	17,13	No	97,76	16,07	No	98,72	15,53	No
62	98,19	16,64	No	98,66	13,49	No	97,24	15,99	Yes
61	98,37	13,07	No	98,60	16,20	No	97,97	16,09	Yes
60	97,99	15,14	No	97,66	13,39	Yes	98,03	15,95	No
59	97,50	14,85	No	98,19	12,46	No	97,60	14,14	No
58	97,74	12,44	No	96,48	12,48	No	97,66	12,58	No
57	96,91	11,91	No	97,24	13,15	Yes	96,91	12,19	Yes
56	96,59	13,15	Yes	97,52	13,23	No	96,59	12,66	No
55	97,01	11,97	No	96,93	11,16	No	96,69	11,36	Yes
54	96,26	10,89	No	95,47	9,79	Yes	95,16	10,81	Yes
53	95,59	9,96	No	94,55	9,67	Yes	94,96	8,92	No
52	94,68	9,27	No	94,45	9,06	No	93,33	9,02	Yes
51	93,80	8,49	No	94,13	9,63	No	93,98	8,01	No
50	93,15	8,62	No	88,92	8,21	No	93,13	8,11	Yes
49	92,12	8,13	No	90,82	7,91	No	89,82	7,56	No
48	91,04	7,23	No	91,40	7,27	Yes	87,89	9,51	No
47	90,67	6,73	No	90,86	6,60	No	90,49	6,50	No
46	89,88	5,61	No	88,80	4,92	No	89,19	7,01	No

Table 6.3 – Partial results of the router placement in instance 2.

routers that are represented as white squares. Obstacles are represented as green squares.

59 routers are used in Figure 6.9; that corresponds to 1.34*nr_{min}. 61 routers are used in Figure 6.10 (1.32*nr_{min}), the same number in Figure 6.11 (1.22*nr_{min}).

In Figures 6.10a and 6.11a, we can observe some very small dead spots represented by black space between routers. That are areas supposed to be covered, but they are not due to the misplacement of routers. A smaller number of routers could provide a greater number of dead spots even if the network is connected as shown in Figure 6.12a (green areas are covered by one router, while white areas are covered by two).

From these three dissimilar instances and different runs of the algorithm, we can generalise some results. The first result is the efficiency of the approach to solve this problem of mesh

	Run1			Run2			Run3		
nr	**AI (%)**	**OA (%)**	**Connect**	**AI (%)**	**OA (%)**	**Connect**	**AI (%)**	**OA (%)**	**Connect**
75	99,89	14,69	Yes	99,27	13,57	Yes	99,93	14,73	Yes
74	99,84	14,35	Yes	99,95	15,39	Yes	99,88	11,84	Yes
73	99,91	14,46	Yes	94,87	18,02	No	97,95	13,44	Yes
72	99,73	14,24	Yes	99,61	13,12	Yes	99,38	14,48	Yes
71	99,47	14,24	Yes	98,72	12,93	Yes	99,95	12,64	No
70	99,52	14,30	No	99,45	12,11	Yes	99,39	11,87	Yes
69	99,00	14,30	No	99,66	13,75	Yes	99,63	11,80	No
68	99,16	12,80	Yes	99,70	13,26	Yes	98,88	11,02	No
67	99,20	12,19	Yes	99,39	13,48	Yes	98,88	12,52	No
66	99,02	13,48	Yes	98,36	11,64	Yes	98,41	10,14	No
65	98,57	13,18	Yes	99,27	10,41	Yes	98,73	9,65	Yes
64	98,95	10,41	Yes	98,40	11,27	Yes	98,65	9,50	Yes
63	98,22	9,66	Yes	98,57	9,66	Yes	97,54	10,38	Yes
62	98,36	9,66	Yes	98,29	8,58	Yes	97,91	9,07	Yes
61	97,99	9,47	Yes	97,59	8,56	Yes	98,06	8,68	Yes
60	97,34	9,07	Yes	97,13	7,81	Yes	94,62	8,43	No
59	96,59	8,74	Yes	96,76	6,90	Yes	96,02	7,92	Yes
58	95,85	6,90	Yes	95,06	5,88	Yes	96,58	5,87	Yes
57	95,88	7,92	Yes	95,47	7,72	Yes	94,97	6,74	Yes
56	95,40	7,61	Yes	94,67	7,10	Yes	93,08	6,97	Yes
55	94,60	7,18	Yes	93,81	5,49	No	92,58	5,10	No
54	93,78	6,67	Yes	93,87	6,01	Yes	93,60	4,92	Yes
53	92,96	5,33	Yes	91,07	4,33	No	92,82	6,01	Yes
52	92,01	5,13	Yes	90,66	3,44	Yes	91,50	3,57	Yes
51	90,85	5,13	Yes	91,75	3,01	No	90,09	5,87	No
50	90,62	2,85	No	89,77	3,64	Yes	88,23	3,51	No

Table 6.4 – Partial results of the router placement in instance 3.

router nodes placement in regions with different forms. In fact, in the three instances the average coverage is close to 100% with nr_{init}= 1.5*nr_{min}. Secondly, we observe that an optimal number is around 1.3*nr_{min}, with a coverage percentage of the areas of interest of at least 98%.

Proposing different trade-offs between the number of routers and the achievable coverage percentage is particularly interesting for decision makers who would like to compare a set of choices before deciding. However, the placement approach proposed in this section does not consider the cost effective elementary areas (CEAs), previously defined in the network model, which can be used to reduce the cost of the solution.

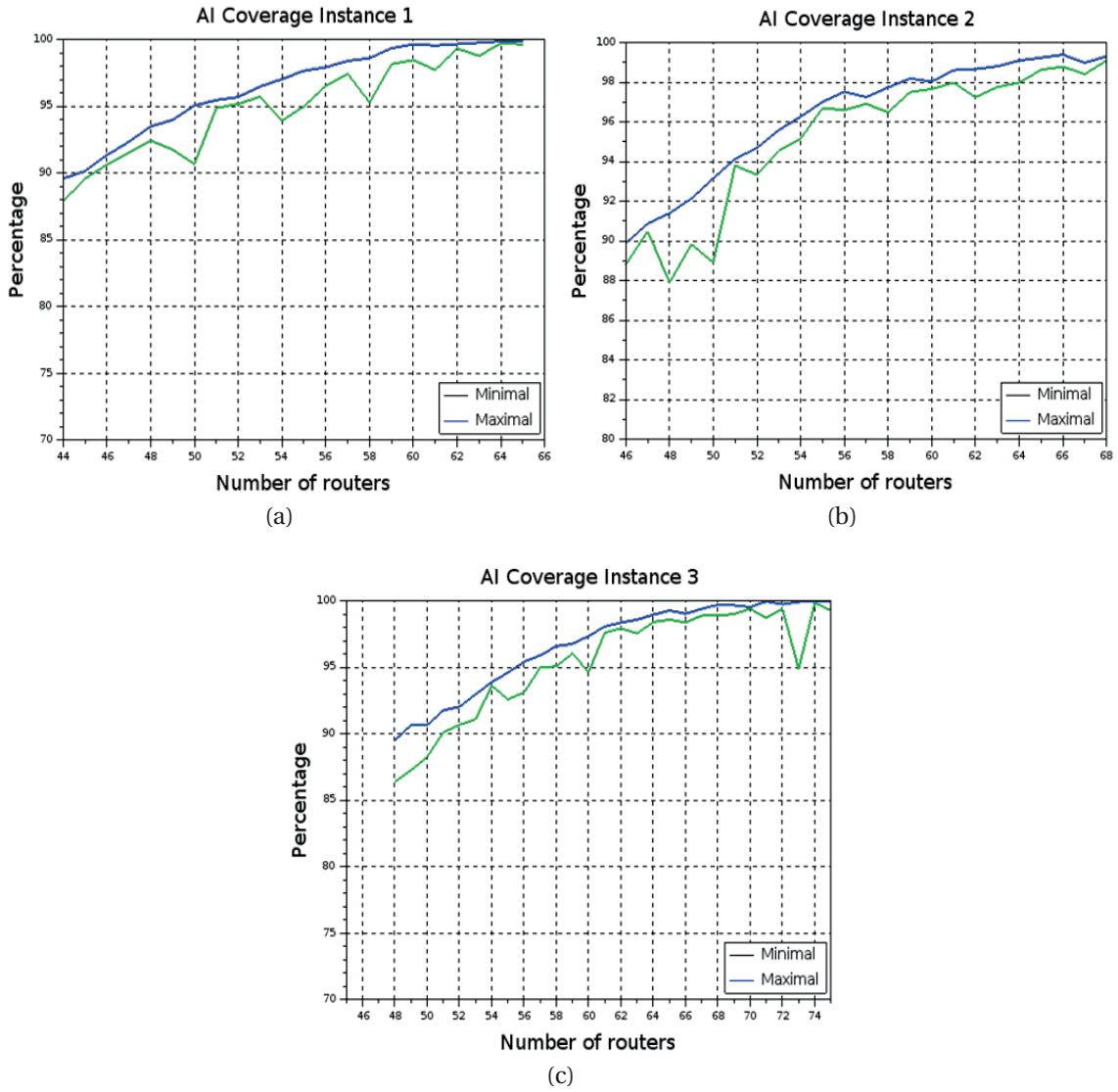
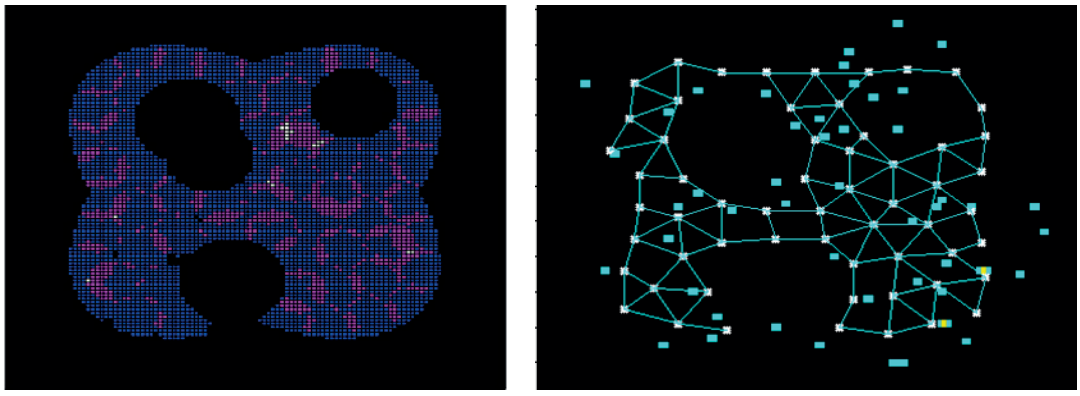


Figure 6.8 – Coverage percentage of the area of interest: (a) instance 1; (b) instance 2; (c) instance 3.

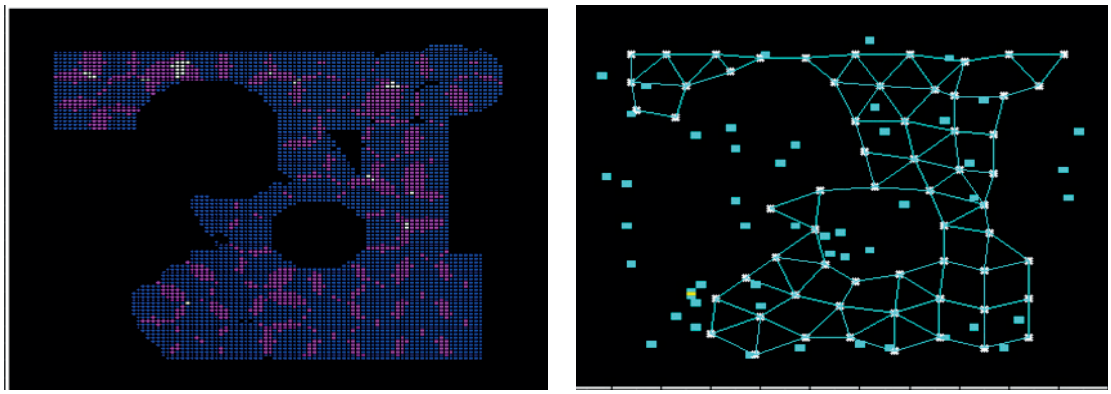
6.4 Cost consideration

In reality, network planners are looking for safe and cost effective emplacements wherein nodes can be placed. Reducing the cost of the solution by relocating nodes as many as possible to CEAs is therefore a new objective to consider simultaneously the previous one of maximising the coverage of the area of interest. In this context, hierarchical MOO can be used to optimise these two objectives. We consider the optimisation of the first objective (coverage) done earlier. Then we try to optimise the cost by relocating nodes, which are not in CEAs to their closest available CEAs. Nevertheless, since those relocations will worsen



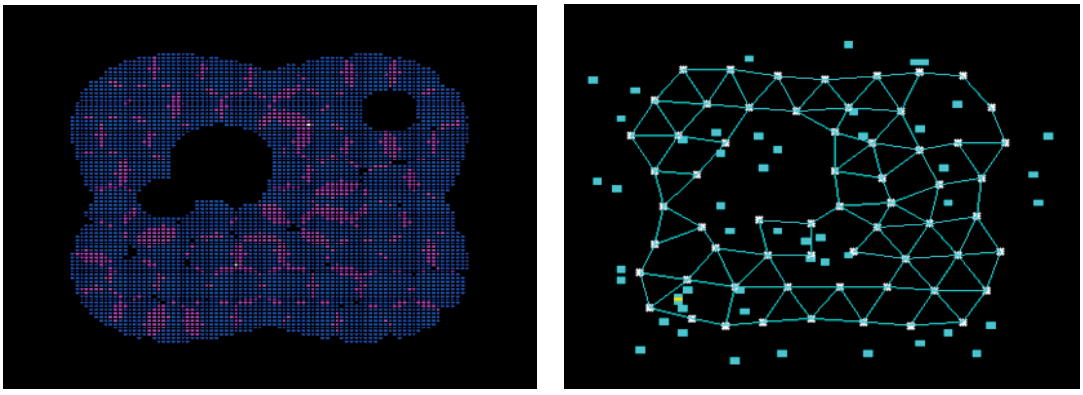
(a) (b)

Figure 6.9 – SA results on instance 1: (a) router locations; (b) router links and obstacles.



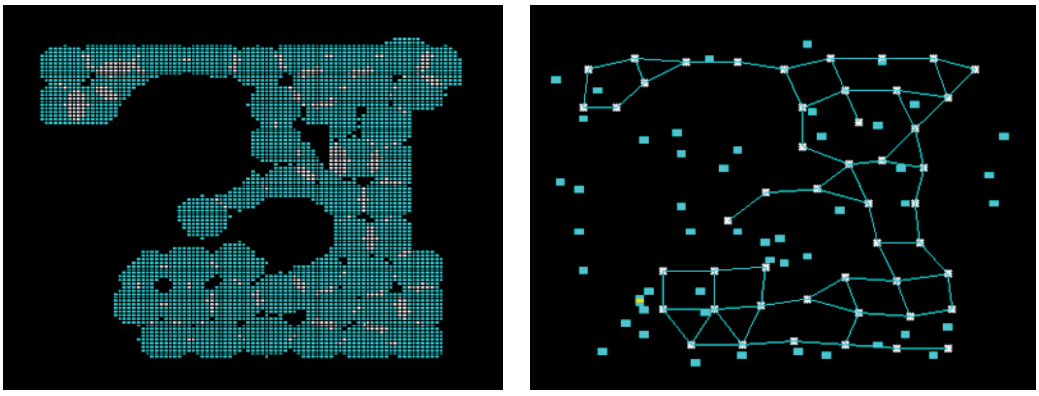
(a) (b)

Figure 6.10 – SA results on instance 2: (a) router locations; (b) router links and obstacles.



(a) (b)

Figure 6.11 – SA results on instance 3: (a) router locations; (b) router links and obstacles.



(a) (b)

Figure 6.12 – Connected configuration with dead spots in instance 2: (a) Router locations; (b) Router links and obstacles.

the coverage percentage (the case of conflicting objectives), it is suitable to determine a set of trade-offs depending on the degradation of the coverage.

6.4.1 Algorithm (PARSA)

The proposed algorithm for solving this new definition of the problem is called Pareto Archived Reverse Simulated Annealing (PARSA). The algorithm is called reverse simulated annealing because it starts with a solution, which is optimised for one objective function (the coverage) and a very low temperature, which is gradually increased in order to reach a new optimum for the two objective functions (the cost and the coverage). The idea is to gradually worsen the optimal solution of the coverage in order to optimise the cost. PARSA is based on Pareto optimally, and it produces an archive of non-dominant solutions (Pareto archive).

During the optimisation process, a solution is accepted only if it optimises the cost and if the variation of the coverage percentage is accepted with a probability $e^{-\frac{\triangle E}{T}}$. In contrary to the normal annealing process, which starts with a high temperature, PARSA starts with a very low temperature. This is for maintaining a coverage percentage close to the initial optimum. The equilibrium state is reached when there is no solution accepted after a number of iterations ($stop$). Then we update the temperature $T = \alpha T$ with $\alpha > 1$.

The algorithm stops after reaching a final temperature T or when the value of the first objective function is less than a minimal value (cov_{min}). PARSA is given in Algorithm 6.4.

Two important functions are defined in the algorithm: NearestFreeCEA() and updateAndPruneOptimalSet(). The first looks for a CEA in the area covered by a router. It performs

Algorithm 6.4 Pareto Archived Reverse SA (PARSA)

Input: s : optimised solution for the first objective function (coverage)
f_{cov}: first objective function (coverage)
f_{cost}: second objective function (cost)
Output: $arch$: Pareto optimal

```
1  Begin
2  | T := T_initial
3  | (cost, cov):= (f_cost(s), f_cov(s))
4  | arch:=createList(1,(cost, cov))
5  | while T<T_final do
6  |   | stop:=Val_init    //Initial value
7  |   | while stop>0 do    //Equilibrium
8  |   |   | stop:=stop-1
9  |   |   | ctrTmp:=selectRouter(s)
10 |   |   | cNew:=NearestFreeCEA(ctrTmp)
11 |   |   | if cNew exists then
12 |   |   |   | s':=MoveTo(ctrTmp,cNew,s)    //Move from ctrTmp to cNew
13 |   |   |   | ΔE:= f_cov(s') − f_cov(s)
14 |   |   |   | if rand_u< e^(−ΔE/T) then
15 |   |   |   |   | s:= s'
16 |   |   |   |   | (cost, cov):= (f_cost(s), f_cov(s))
17 |   |   |   |   | if cov >=cov_min then
18 |   |   |   |   |   | arch:=updateAndPruneOptimalSet(arch, (cost, cov))
19 |   |   |   |   |   | stop:= Val_init    // Reset stop
20 |   | Update(T)
21 | return arch
22 End
```

a local search and returns the nearest CEA to the centre of the router. Since we are looking only for CEAs, each accepted router move will automatically optimise the cost of the solution.

UpdateAndPruneOptimalSet() updates the Pareto archive $arch$. In Pareto optimisation, there are two concepts associated to the archive: elitism and diversity. Since the size of the archive is limited, not all non-dominated solutions can be stored. Therefore, we have to select 'elite' solutions to store in the archive (elitism). When constructing the set of 'elite' solutions, this set should be representative of the front (diversity). That means, solutions should not be located only in some parts of the front.

To ensure the elitism and the diversity of the Pareto front, updateAndPruneOptimalSet() stores for each integer value of the coverage percentage the best cost. For instance, if cov_{min}=80%, the size of the archive will be at least 100-80+1=21. Let us suppose having a

$\alpha = 1.1$	$nr = 61$
T_{init}=0.01	cov_{min}=90%.
T_{final}=10	$NumberOfNEA$=50
$Stop$=500	$NumberOfCEA$ =[50, 100]

Table 6.5 – Parameter values for experimentation (PARSA algorithm).

couple (13, 97.5) in the archive. If a new couple ($cost$, cov) with $97 \leq cov < 98$ is accepted, that implies the number of CEAs used is more than 13 (since we only accept solutions that increase the number of CEAs used). The new couple will replace (13, 97.5) in the archive. By this way, the elitism and the diversity of the front are maintained.

6.4.2 Experimentation

For the experimentation, we choose a configuration of instance 3 defined earlier, with 61 routers and an optimal coverage percentage of the area of interest of about 98%. The parameter values for experimentation are given in Table 6.5. To evaluate the algorithm, we randomly place different numbers of CEAs (50 and 100) in the instance and we run the algorithm twice.

Results and interpretation

Table 6.6 and 6.7 give the Pareto front when randomly placing respectively 50 and 100 CEAs in instance 3. In Tables 6.6 and 6.7, the percentage of routers in CEAs is almost the same for each coverage percentage of the area of interest. We just observed a slight variation ranging from 1.64% (one CEA) to 3.28 (two CEAs) for the coverage percentage of the area of interest comprised between 96% and 93%. The low initial temperature allows accepting only moves that imply small degradations of the coverage percentage of the area of interest. So, very small moves are accepted at the beginning, allowing moving routers only to closest CEAs. With $Stop$=500, the probability of finding such a move, if there exists one, is 1- $(\frac{60}{61})^{500}$=0.99. This probability is high enough and justifies the fact that the percentage of routers in CEAs is always the same for higher coverage percentage of the area of interest. This result is strengthened by the very low augmentation of the temperature after each equilibrium state ($\alpha = 1.1$). From a certain temperature, the number of acceptable moves becomes greater. The order in which acceptable moves are found determines therefore the number of CEAs archived for each range of coverage percentage of the area of interest. This explains the variation observed between the first and the second run in Tables 6.6 and 6.7. The ideal would be to select each time the pair (router, CEA) that generates the smallest variation on the coverage percentage. But the idea of choosing the closest pair each time does not ensure having the smallest variation on the coverage percentage of the area of interest.

In fact, if the CEA of the closest pair (router, CEA) is on an edge, the probability of not having the smallest variation of the coverage percentage is higher. A deterministic method should compute the coverage change for each pair (router, CEA) to keep the smallest one at each stage. But this approach would require high computational time, especially when the number of routers and CEAs are important.

The values of the first run in Tables 6.6 and 6.7 are plotted respectively in Figures 6.13a and 6.13b. These figures show some concavity of the Pareto front, since the two objectives have to be maximised.

Run 1	Routers in CEA (%)	1.64	9.84	16.40	21.32	27.88	32.80	36.08	39.36	41.00
	Coverage of AI (%)	98.00	97.21	96.04	95.13	94.09	93.27	92.28	91.01	90.30
Run 2	Routers in CEA (%)	1.64	9.84	14.76	19.68	24.60	29.52	36.08	39.36	41.00
	Coverage of AI (%)	98.00	97.09	96.13	95.25	94.47	93.02	92.22	91.03	90.47

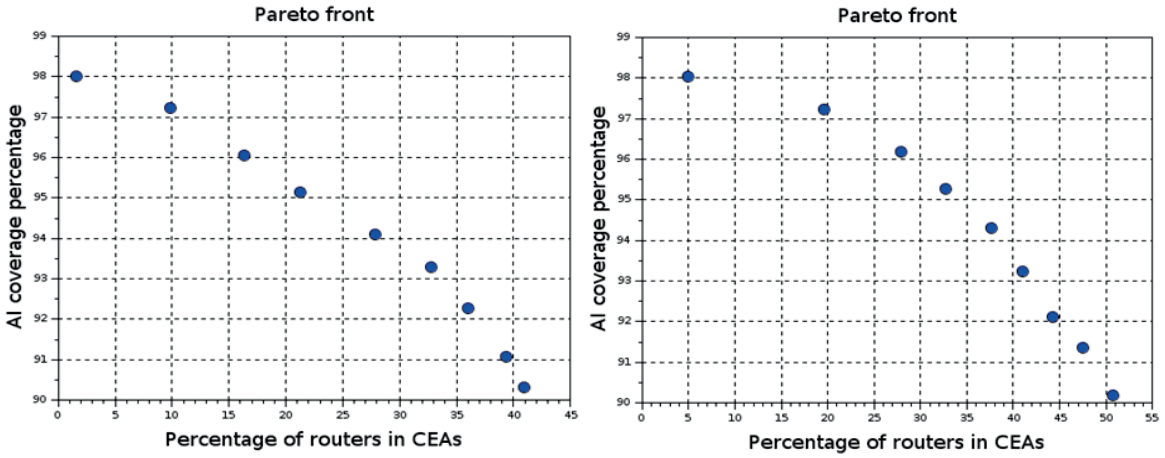
Table 6.6 – Pareto front in instance 3 with 50 CEAs.

Run 1	Routers in CEA (%)	4.92	19.68	27.88	32.80	37.72	41.00	44.28	47.56	50.81
	Coverage of AI (%)	98.03	97.21	96.18	95.27	94.29	93.24	92.11	91.35	90.17
Run 2	Routers in CEA (%)	4.92	19.68	27.88	32.80	36.08	39.36	41.00	47.56	50.81
	Coverage of AI (%)	98.03	97.27	96.18	95.06	94.08	93.25	92.65	91.08	90.03

Table 6.7 – Pareto front in instance 3 with 100 CEAs.

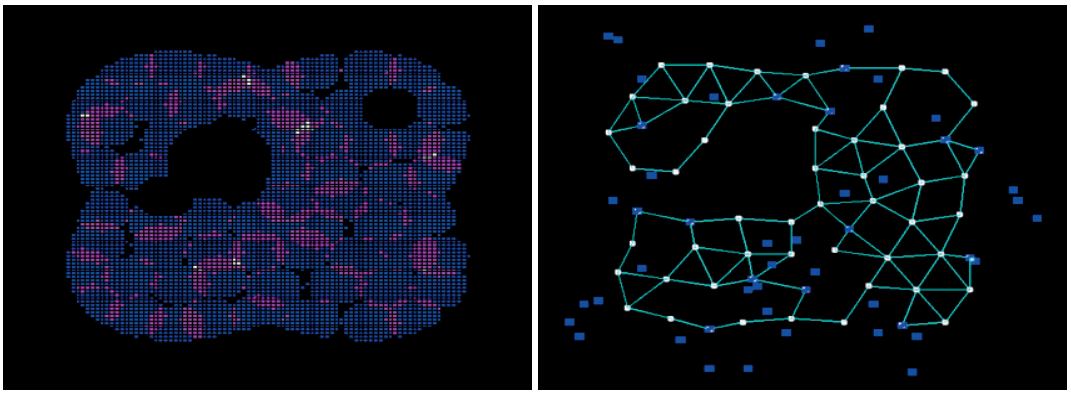
Figure 6.14a shows router locations, and 6.14b shows links and CEAs in instance 3. Blue areas in Figure 6.14a are covered by one router, red by two routers and white by three routers. In this Figure, we observe that relocating routers in CEAs could generate death spots in the coverage. The more routers are relocated in CEAs, the lower is the coverage of the area of interest, and the greater the number of death spots.

The coverage percentage of the area of interest and the number of routers relocated in CEAs are not enough for network planners. They should also appreciate the density of death spots for each trade-off in the Pareto archive.



(a) (b)

Figure 6.13 – Pareto front between the percentage of routers in CEAs and the coverage percentage of the area of interest in instance 3: (a) Pareto front with 50 CEAs; (b) Pareto front with 100 CEAs.



(a) (b)

Figure 6.14 – Result after cost improvement: (a) Router locations after relocation; (b) Router links and CEAs.

The placement approach in this chapter has been tackled by considering the region as a continuous area of interest. In a real scenario, we observe separated areas of interest as illustrated in Figure 3.3 in Chapter 3. This particular case is not handled by the approach. Planning the network in such a scenario using the present approach will result in separated sub-networks. This result could also be observed even in a continuous region. In fact, when the number of obstacles is important, the probability of not getting a connected network at the end is higher. So a new approach should be proposed to deal with these particular cases. A last important point to consider, and not accounted in the present approach, is the definition of a scheme for the channel assignment in the network.

7 Case of disjoint areas of interest and channel assignment

The sparseness of buildings or group of houses usually presents disjoint areas of interest to cover in rural regions. The placement approach presented in the previous chapter cannot ensure connectivity of the network; because this approach is placing routers only in the area of interest. Applying the previous approach in the present configuration will result in a set of non-connected sub-networks, especially when the areas of interest are distant enough. An important number of obstacles in the region could additionally hamper the connectivity of the network, resulting in a non-connected network.

This chapter deals with these particular cases, which are bringing new challenges. How to place optimally routers in this configuration? How to detect sub-networks? How to join them in order to obtain one connected network?

The first section presents the network model and the placement approach composed of three steps: initial placement of routers, sub-network detection, and sub-network joining strategy. The initial placement reusing the approach of the previous chapter is presented in the second section. The third section recalls some notions in graph theory that are used in the following sections about the detection of sub-networks and the sub-networks joining strategy. We also deal with the channel assignment problem in this chapter. We define a strategy with the constraint of having just one gateway in the network.

7.1 Network model and placement approach

We consider a real-life scenario in this new formulation of the placement problem, wherein we could have several areas of interest, which could be quite far from each other, so that placing routers only in these areas will result in a set of non-connected sub-networks. This scenario is the generalisation of the one defined in the preceding chapter. A given region in this scenario is composed of prohibited areas, a set of obstacles, and a set of low cost

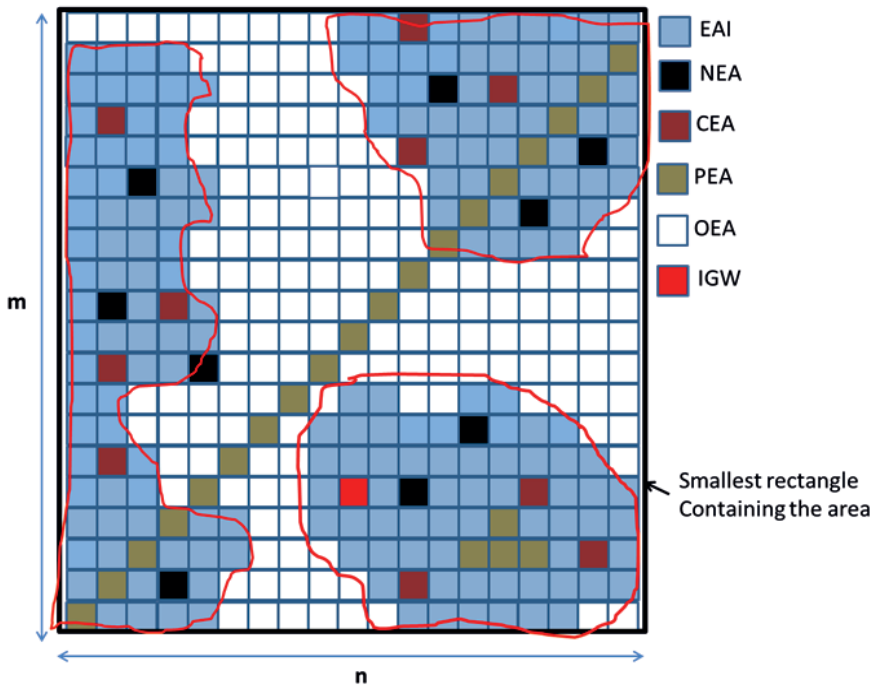


Figure 7.1 – An example of a region decomposed in EA with disjoint areas of interest.

locations, as it is the case in the previous chapter. However, this new scenario differs from the previous one by the fact that the area of interest can be composed of a set of separated areas.

7.1.1 Network model

Figure 7.1 illustrates the result of a decomposition of a region into a set of EAs with three disjoint areas of interest. We are still considering the previous two-dimensional matrices used to characterise each EA.

7.1.2 Placement approach

The new approach for tackling the placement problem in a general scenario is composed of four main steps as described in Figure 7.2.

1. Initial placement based on the placement approach of the previous chapter;
2. Detection of sub-networks;
3. Joining sub-networks;

4. Assigning channels.

Depending on the number of sub-networks after the initial placement step, the third step in the approach can be avoided. These different steps will de detailed in the following sections. Experiments will be conducted and the results will be presented at each step. We still consider a grid of 100∗100 with the radius of a router r=6. We use instances defined in Figure 7.3 to go through the different steps of the approach. Blue regions represent areas of interest that should be covered and black regions represent optional areas in this figure. Obstacles (NEAs) are placed randomly in each instance and prohibited areas are not directly seen because some areas of interest and some optional areas can also be prohibited areas.

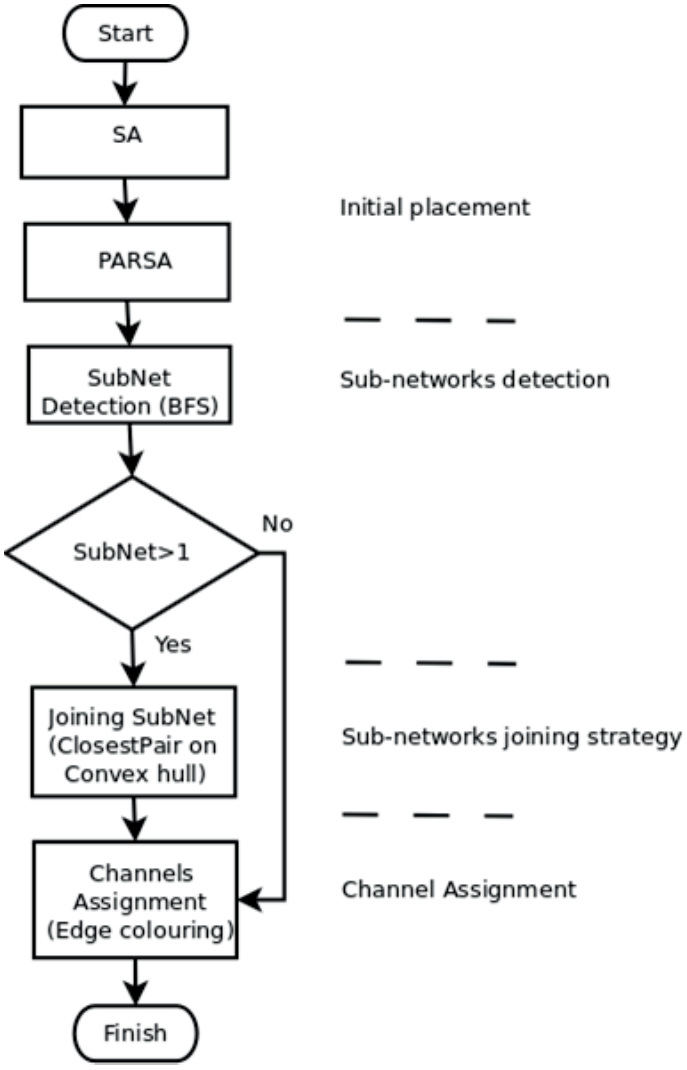
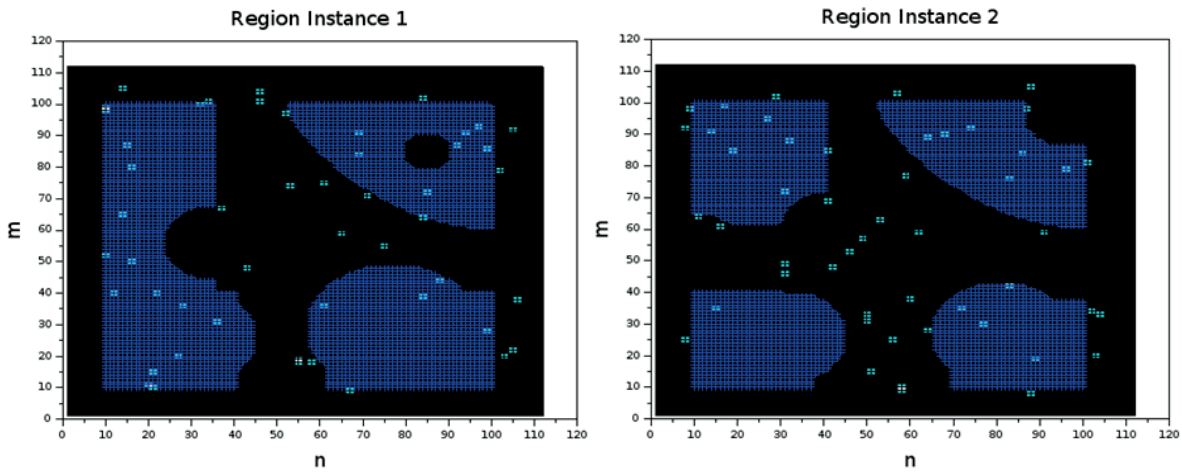


Figure 7.2 – Flowchart of the complete placement approach of mesh routers.



(a) (b)

Figure 7.3 – Region instances with disjoint areas of interest: (a) instance 1; (b) instance 2.

7.2 Initial placement

We follow the approach described in chapter 6 at this step. We start with the SA algorithm to maximise the coverage, then we use PARSA to determine a set of Pareto optimal between coverage and cost.

Routers are placed randomly during the initialisation phase with the constraint of selecting only EAI and avoiding PEA in the prior SA algorithm. By this way we could encounter some problems during this phase when we have separated areas of interest. Routers could not be placed according to the size of the area of interest. That means a greater area could receive a smaller number of routers. The number of routers in each area of interest could not be subject to change during the annealing phase, especially when areas are quite far and router moves are less than the distance between areas. It is important to redefine router moves so that routers can move from one area of interest to another at this stage. Thus, long router moves are used; when the temperature is decreasing, router moves become proportionally smaller.

7.2.1 Experimentation

Values for global parameters for the experimentation phase are given in Table 7.1. For instance 1, nr_{init}=69 and for instance 2 nr_{init}=59. CEAs are placed randomly in each instance.

SA		PARSA	
T_{init}=10	nr_{init} =1.5nr_{min}	T_{init}=0.01	nr = 61
T_{min}=0.001	$NumberOfNEA$ = 50	T_{final}=10	Cov_{min}=90%
$Stop$=500	r=6	$Stop$=500	$NumberOfCEA$ =50

Table 7.1 – Parameter values for experimentation (SA and PARSA).

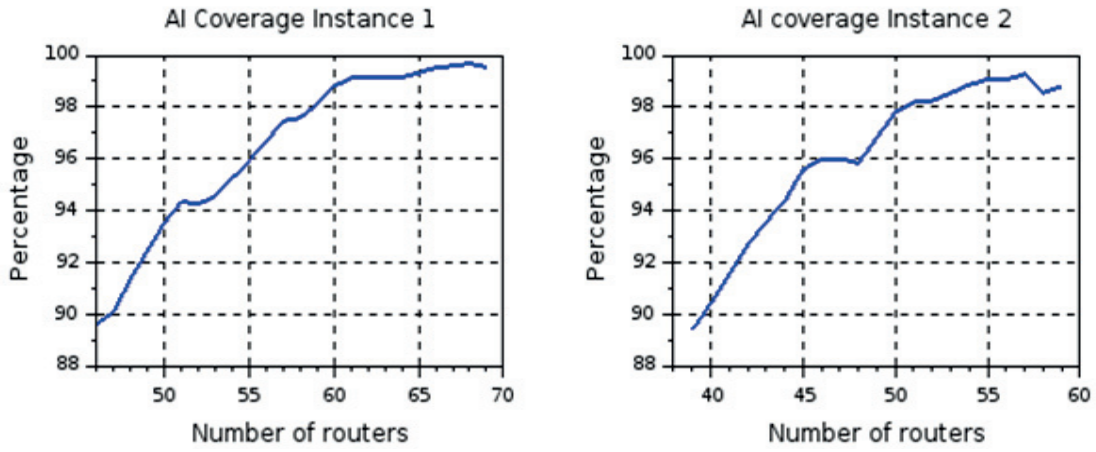


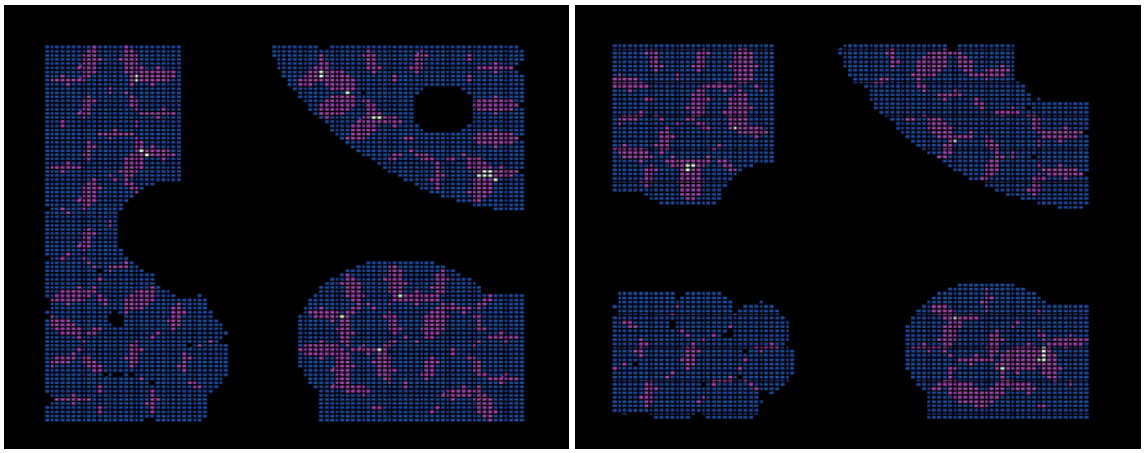
Figure 7.4 – Percentage coverage of the areas of interest from instances 1 and 2.

7.2.2 Results and discussion

Figure 7.4 shows the variation of the coverage percentage of the areas of interest depending on the number of routers in instance 1 and 2. Results from this figure show that the coverage percentage of the areas of interest is close to 100% with nr=1.5nr_{min}; this coverage percentage is close to 90% with nr= nr_{min}. We additionally obtain a coverage percentage of the areas of interest greater than 98% with nr ≈1.3*nr_{min} in both instances. These results are similar to the ones found with previous instances in chapter 6.

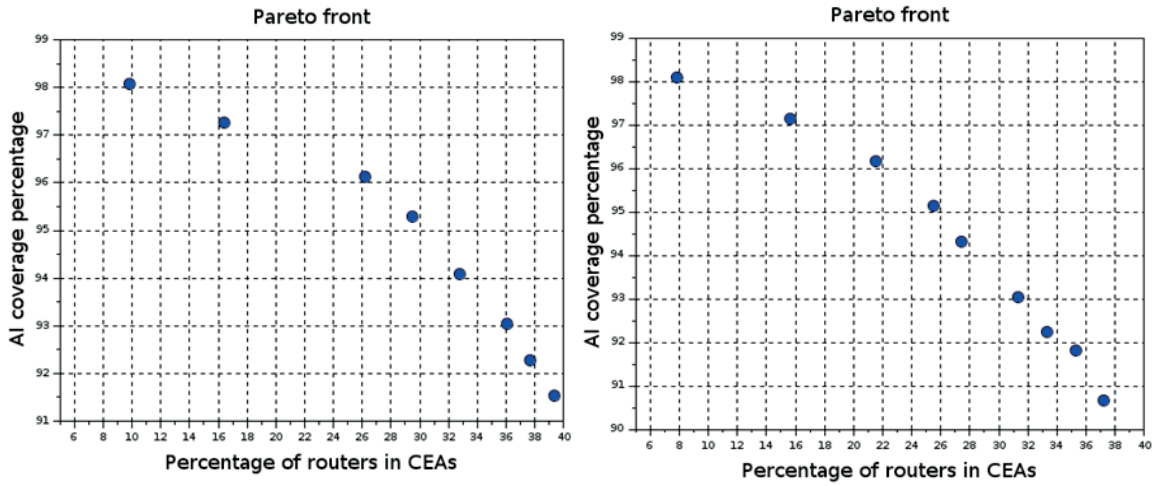
Router locations with nr ≈1.3*nr_{min} are shown in Figures 7.5 for instance 1 and 2. We can appreciate a quasi-absence of dead spots and a good router location that minimises the overlapping area between routers. In fact, the area covered by three routers (white space) is insignificant; most areas of interest are covered by one router (blue space).

We select a configuration of instance 1 and instance 2 to run the PARSA algorithm. The selected configuration of instance 1 has 61 routers with a coverage percentage of 98.74%; the one of instance 2 has 51 routers with a coverage percentage of 98.19%. After running the PARSA algorithm, we obtain the Pareto front plotted in Figure 7.6a and 7.6b, respectively for instance 1 and 2.



(a) (b)

Figure 7.5 – Router locations in disjoint areas of interest: (a) instance 1; (b) instance 2.

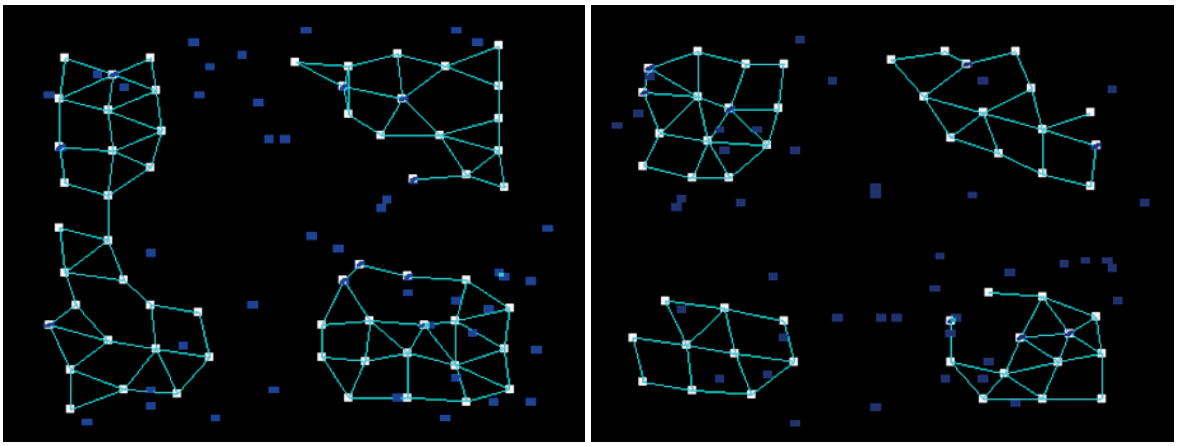


(a) (b)

Figure 7.6 – Pareto front between the coverage percentage of the areas of interest and the percentage of routers in CEAs: (a) instance 1 with 50 CEAs; (b) instance 2 with 50 CEAs.

After optimising the coverage and the cost, the network could result in a set of non-connected sub-networks, as it is the case in Figure 7.7. We have different sub-networks in these figures: three in instance 1 and four in instance 2. White squares represent routers and blue squares represent CEAs. White squares with a blue line represent routers located in CEAs. It is necessary to detect sub-networks and to link them optimally in order to obtain a connected network at this stage.

To easily address the following parts of the placement approach described in 7.1.2, we will assimilate our network instances to graphs. Therefore, it is necessary to recall some



(a) (b)

Figure 7.7 – Router locations after optimising the cost of the architecture: (a) instance 1 with nr=61 and 16% in CEAs; (b) instance 1 with nr=51 and 15% in CEAs.

definitions from graph theory.

7.3 Recalls in graph theory

Networks can conveniently be described as many other real-life situations by means of graphs. Graphs are used to figure out the relationships between a set of items.

Definition 7.1 (Graph): A graph $G = (V, E)$ is an ordered pair consisting of nonempty and finite sets V of vertices (also called nodes), and $E \subseteq \binom{V}{2}$ of edges, with each edge being an unordered pair.

Definition 7.2 (Path): A path in a graph is a sequence of vertices $v_0, \ldots, v_n$ for some $n \geq 0$ with $\{v_i, v_{i+1}\} \in E$ for $i = 0, \ldots, n-1$.

Definition 7.3 (Cycle): A cycle is a path $v_0 \ldots v_n$ with $n > 0$, $v_0 = v_n$, $v_1 \neq v_{n-1}$, and $v_i \neq v_{i+2}$ for $i = 0 \ldots n-2$.

Definition 7.4 (Acyclic graph): An acyclic graph is a graph containing no cycles.

Definition 7.5 (Connected graph): A connected graph is a graph in which there is a path from each vertex to any other vertex.

Definition 7.6 (Tree): A tree is a graph that is acyclic and connected.

Definition 7.7 (Connected component): A connected component usually shortened as

"component" is a subset of vertices in which every vertex has a path to each other, and the subset is not a part of some larger set with the property that each vertex can reach any other ([Easley/Kleinberg 2010], p. 29).

Definition 7.8 (Bridge): A bridge is an edge whose deletion increases the number of connected components.

A similitude can be made between each instance in Figure 7.7 and an undirected graph:

- Each router is assimilated to a vertex; a link between two routers is assimilated to an edge;
- Each edge is composed of two vertices; it is said to be incident to its two vertices or it joins its two vertices. Each link is composed of two routers and it joins these two routers as well;
- Two vertices joined by an edge are said to be adjacent. Two routers joined by a link are said to be connected as well.

7.4 Detecting sub-networks

The problem of detecting sub-networks is similar to the problem of detecting connected components in graph theory. This problem can be solved by using the Breadth-first search algorithm (BFS) or the Depth-first search algorithm (DFS). These algorithms are usually used to determine whether there exists a path between two vertices or to detect all vertices connected to a given one. They can be adapted for the detection of connected components in a given graph. The implementation of BFS proposed by Kleinberg and Tardos ([Kleinberg/Tardos 2006], p. 90 f.) is given in Algorithm 7.1 $Discovered$ indicates whether a vertex is discovered. L_i is the set of nodes at distance i from the given vertex s. T is a tree whose root is s.

The BFS algorithm is easily adapted to detect sub-networks as follows: replace $Discovered$ by $Subnet$. $Subnet(i)$ will indicate the number of the sub-network to which belongs router i. Go through the list of routers; for each router: if the router does not belong to a sub-network, generate a sub-network number and affect it to the router. Affect this number to all connected routers found by invoking newBFS with this router number. At line 10 of Algorithm 7.1, determining whether a vertex v is incident to a vertex u amounts to determine if the corresponding routers v and u are connected. The connectivity between two routers is checked by functions distance($Ctr(i)$,$Ctr(j)$) and LOS($Ctr(i)$,$Ctr(j)$) as defined in the previous chapter. $Ctr(i)$ is the location of router i. The algorithm for sub-network detection is given in Algorithm 7.2.

Algorithm 7.1 Breadth-first search

Input: G: a graph
s: a vertex of
Output: All vertices reachable from

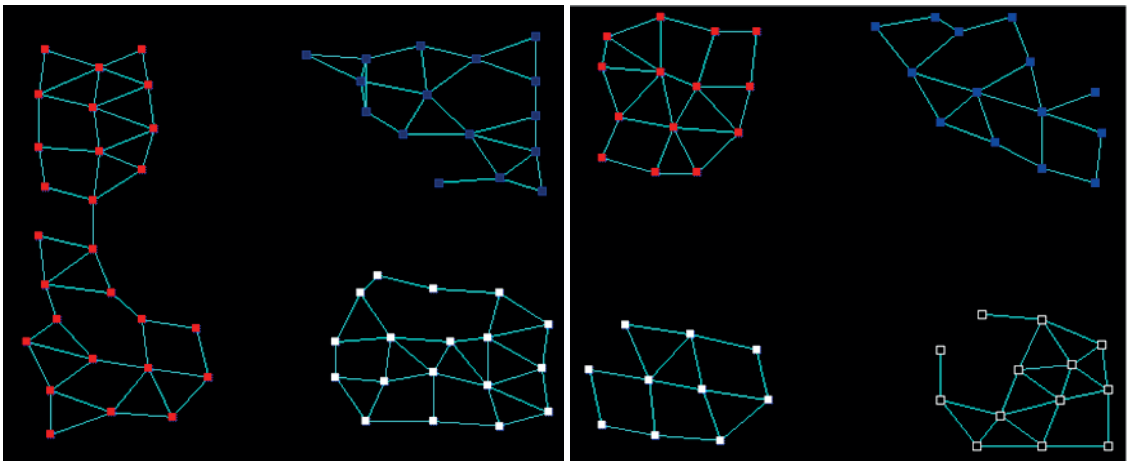
```
1  Begin
2  | Discovered(s):= true
3  | Discovered(v):=false // For all other edges that means v ≠ s
4  | L(0):=s // Initialise L(0) to consist only of s
5  | i:=0 // Set the layer counter
6  | T:=∅ // Set the current BFS tree
7  | while L(i) is not empty do
8  |   | L(i+1):=∅ // Initialise an empty list L(i+1)
9  |   | for each node u ∈ L(i) do
10 |   |   | Consider each edge (u,v) incident to u
11 |   |   | if Discovered(v):=false then
12 |   |   |   | Discovered(v):=true
13 |   |   |   | Add (u,v) to T
14 |   |   |   | Add v to L(i+1)
15 |   | i:=i+1 // Move to the next layer
16 End
```

The sub-network detection algorithm is applied for both instances 1 and 2; Figure 7.8 is showing the detected sub-networks. Different colours represent vertices of different connected components in each instance.

Algorithm 7.2 Sub-networks Detection

Input: : Location of all routers
Output: : Set of sub-networks

```
1  Begin
2  | SubNet:= zeros(1, nr) // No router is assigned to a sub-network
3  | Num:=0 // To label each sub-network before inserting
4  | for i:= 1 to do // For each router i in Ctr
5  |   | if SubNet(i):=0 then // Router i is not yet in a sub-network
6  |   |   | Num:=Num+1 // Create a sub-network
7  |   |   | SubNet(i):=Num // Assign i to this sub-network
8  |   |   | newBFS(i, Ctr, Num, SubNet)
9  End
```



(a) (b)

Figure 7.8 – Detected sub-networks: (a) instance 1 with three sub-networks; (b) instance 2 with four sub-networks.

7.5 Joining sub-networks

Sub-networks are detected with the aim of joining them later. Joining sub-networks should involve as low cost as possible by minimising the number of additional routers. To achieve this, the basic idea should be to look for the closest pairs of router nodes (vertices) between each pair of sub-networks. Comparing all router nodes during the determination of the closest pair of routers between two sub-networks can be very time-consuming, especially when the number of sub-networks and the number of nodes per sub-network is important. An efficient approach is to ignore inner nodes of the convex hull of each sub-network.

7.5.1 Convex hull

Let us consider a set of points in a two dimensional plane. The convex hull of this set of points is the smallest convex polygon that contains all the points of the set. An example of convex hull is the set of points linked in red in Figure 7.9.

An efficient algorithm to determine the convex hull H of a set of points P is the Graham scan algorithm [Graham 1972]. It consists of three steps as described in ([Goodrich/Tamassia 2002], p. 580):

1. Find a point a of the convex hull H. Usually the first point is the point with the minimum y-coordinate (and the minimum x-coordinate if there are different points with this minimum y-coordinate). Point a is called the anchor.

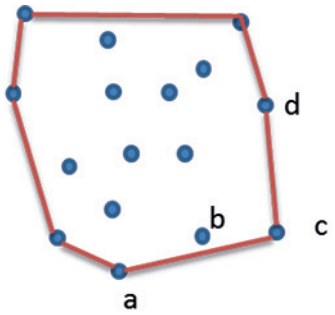


Figure 7.9 – Example of convex hull.

2. Sort the rest of points P- $\{a\}$ counterclockwise by angle with respect to the anchor point a. In the case of equality between several points, put the nearest point first. S is a list containing the set of sorted points.

3. Add the anchor point a at first and last position of S. Scan points then in S in radial order, and set the list H with the first two points of S. H will contain progressively the points of the convex hull. For each new point p: If p forms a left turn with the last two points in H, or if H contains fewer than two points, then add p to the end of H. Otherwise remove the last point in H and repeat the test for p.

The scan stops when we reach anchor a stored at the end of S. Computing angles to order the points is time consuming at step 2, since trigonometric functions are not easy to evaluate. We just consider the orientation of an ordered triplet of points to be efficient. For instance, the orientation of the ordered triplet of points (a, b, c) in Figure 7.9 is clockwise (make a right turn). That means, (a, b) have a greater polar angle than (a, c). Therefore, b is greater than c. At the third step, orientation is also used to determine if the first three points in H form a left turn; the orientation in this case should be counterclockwise as shown by the ordered triplet (a, c, d). The orientation of an ordered triplet (a, b, c) is determined by (7.1).

$$orientation(a,b,c) = (b.y - a.y) * (c.x - b.x) - (b.x - a.x) * (c.y - b.y) \tag{7.1}$$

If $orientation$=1, then the three points are on the same line (co-linear). The three points form a clockwise if $orientation$ >0, otherwise a counterclockwise. The Graham scan algorithm to determine the convex hull proposed in ([Goodrich/Tamassia 2002], p. 581) is given in Algorithm 7.3.

We get the different convex hulls shown in red in Figure 7.10a and 7.10b, respectively

Algorithm 7.3 Graham scan (Convex hull)

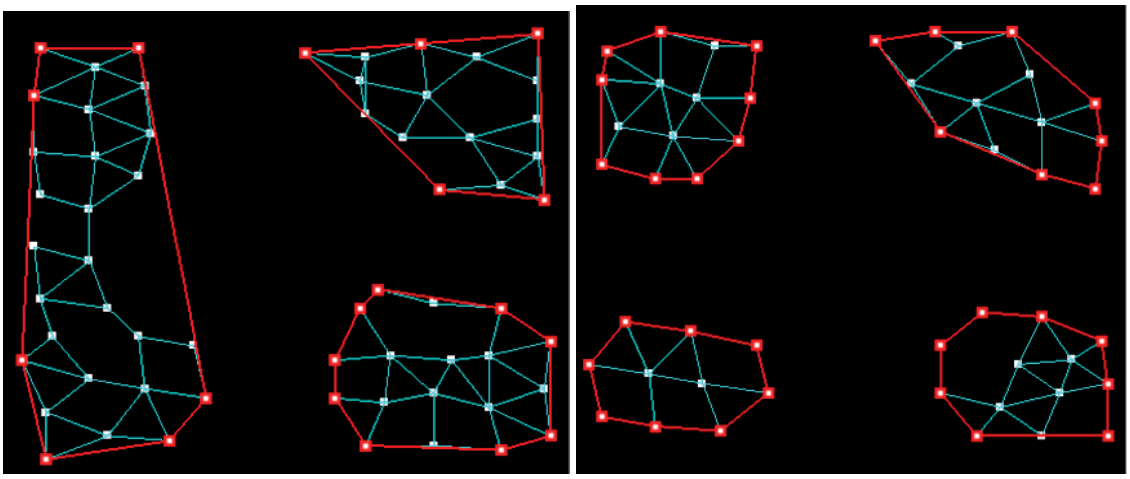
Input: list S starting with point a and the rest of points sorting by angle depending on a
Output: list S with only convex hull vertices

```
1   Begin
2   | S.insertLast(a) // Copy a at the end of S
3   | prev:=S.first() // a is the initial value of prev
4   | curr:=S.after(prev) // Consider next point as part of the current convex hull
5   | repeat
6   |   | next:=S.after(curr) // Move forward in S
7   |   | if orientation(prev, curr, next)<0 then //Make a left turn
8   |   |   | prev:=curr
9   |   | else// curr is not in the convex hull and should be removed
10  |   |   | S.remove(curr)
11  |   |   | prev:=S.before(prev)
12  |   |   | curr:=S.after(prev)
13  | until curr:=S.last()
14  | S.remove(S.last()) // Remove the copy of a
15  | return S
16  End
```

for instance 1 and 2 after experimentation. Only a third of nodes are involved in the determination of the closest pair in instance 1. Two thirds are involved in instance 2. The determination of the convex hull before joining the sub-networks is a moot point. In fact, the use of the convex hull is efficient for sub-networks with a great number of inner nodes like in instance 1.

7.5.2 Joining strategy

Joining each sub-network to its closest one provides no guarantee of having a connected network at the end. It is also not economical to create a complete mesh between all sub-networks. An efficient idea should be to join the sub-networks progressively as proposed in Algorithm 7.4. This algorithm works as follows: We remove a sub-network from the list of sub-networks and we consider it as the giant component. Then we remove the closest one to the giant component from the list of sub-networks, and we merge this sub-network to the giant component. We continue until all sub-networks are removed from the list and merged to the giant component. Two functions are crucial in Algorithm 7.4: closestPairOnConvexHull(GC, LS) and MergeOn(x, y, z). The first determines the closest sub-network in the list of sub-network LS to the giant component GC, and the closest pair (a,b) of routers from which the sub-network will be merged to the giant component.



(a) (b)

Figure 7.10 – Convex hulls of sub-networks: (a) instance 1; (b) instance 2.

Algorithm 7.4 Merging sub-networks

Input *LS*: list of sub-networks
Output *GC*: Giant Component (All sub-networks connected)

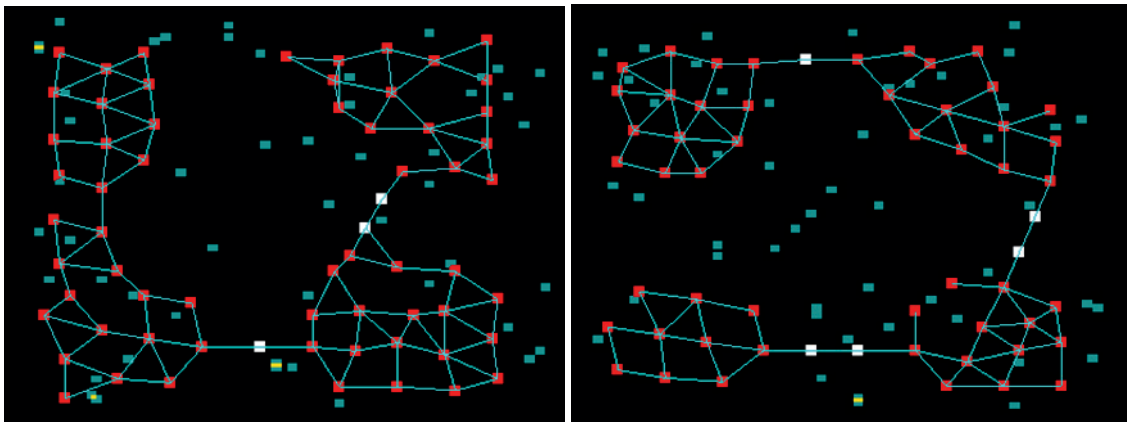
```
1  Begin
2  | GC:=LS(1) // Initialise GC with the first sub-network in LS
3  | LS.remove(1) // Remove this sub-network from LS
4  | while LS do// Finding and merging the closest sub-network to GC
5  |    | [nextToMerge, (a,b)]:=closestPairOnConvexHull(GC, LS)
6  |    | MergeOn(GC, LS(nextToMerge), (a,b))
7  |    | LS.remove(nextToMerge)
8  | return GC
9  End
```

closestPairOnConvexHull looks for the closest pair on the convex hull of each sub-network in *LS* and *GC* only. The convex hull of each sub-network in *LS* is determined at the beginning. When merging a sub-network in *LS* to *GC*, the set of convex hull vertices of this sub-network is added to the one of *GC*. The convex hull of *GC* is not recomputed by this way.

The second function MergeOn connects the giant component to the closest sub-network via the closest pair of routers (a,b) found by closestPairOnConvexHull. The distance between the closest routers is computed and the number of additional routers is determined as well as their locations.

After running the joining strategy on instances 1 and 2, we obtain three additional routers

for instance 1 and five additional ones for instance 2. Figure 7.11a and 7.11b show the connected network respectively for instances 1 and 2. Red squares represent router emplacements, determined after the initial phase. White squares represent additional router emplacements, determined after applying the joining strategy.



(a) (b)

Figure 7.11 – Connected network after joining strategy: (a) instance 1; (b) instance 2.

The next and last step is to assign communication channels between routers once the location of routers is determined.

7.6 Channel assignment

WMNs are prone to interference, due to the number of nodes and their proximity. Router nodes are usually equipped with multiple radios that should be tuned to non-overlapping channels, to reduce interference in WMNs and therefore to optimise their capacity. IEEE 802.11 radio specifications provide three non-overlapping channels in the 2.4 GHz band (802.11b/g/n) and at least 12 non-overlapping channels in the 5 GHz band (12 for 802.11a and more for 802.11n/ac).

One radio is usually used for local access network and the rest for the backhaul. Since user devices are operating at 2.4 GHz, the local access network uses this band while the backhaul is operating at 5 GHz.

A potential link exists between two routers if they are located at a line of sight within their transmission range. We called the set of potential links the physical topology of the network. Figure 7.11a and 7.11b represent the physical topology of the network respectively for instance 1 and 2.

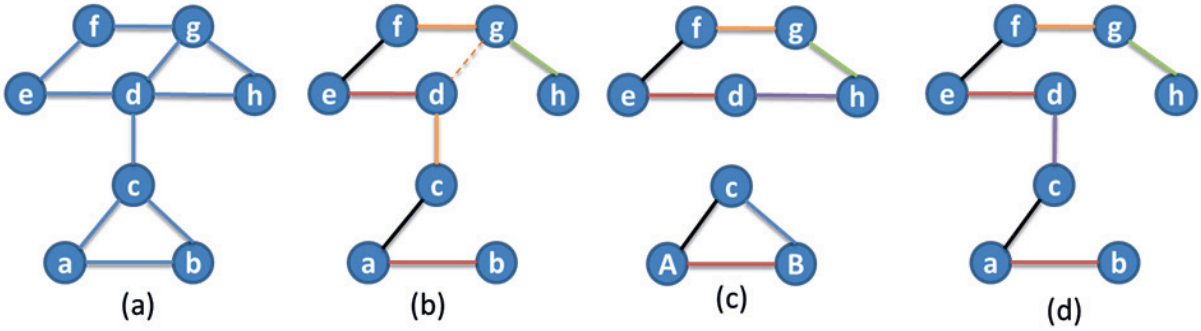


Figure 7.12 – Network topology and channel assignment: (a) Physical topology; (b) logical topology with interfering links (c,d) and (d,g); (c) logical topology without interference but partitioning of the network; (d) logical topology without interference and without partitioning.

An effective link exists between two routers if they are located at a line of sight within their transmission range and if they each have a radio tuned on the same channel. We called the set of effective links the logical topology of the network. This set of links is determined during the channel assignment.

The physical topology of the network can be different from the logical topology after channel assignment, because of the limited number of radios per mesh router. In fact, the effective number of non-overlapping channels per mesh router is limited to the number of radio interfaces at this mesh router, although the number of non-overlapping channels in the 5 GHz band is quite considerable. For instance, let us consider the graph in Figure 7.12a. This graph represents a network with eight routers (from router *a* to router *h*). All edges are representing potential links between routers. This corresponds to the physical topology of the network. Let us suppose that each router is equipped with two radio interfaces and they are operating in the 5 GHz band, meaning that up to 12 non-overlapping channels can be used. The final network could look like Figure 7.12b, 7.12c, or 7.12d after channel assignment. We stated in the prior chapter that we are using omni-directional antennas. Therefore the links (*c*,*d*) and (*f*,*g*) in Figure 7.12b are interfering, since they are using the same channel, while sharing a potential link (*d*,*g*). There exists no interference in Figure 7.12c; but the channel assignment results in a logical topology that partitions the network. Finally, Figure 7.12d represents a network with no interference and without partitioning.

The problem of channel assignment can be therefore stated as follows: Given a set of mesh routers each having a set of radios (one or more) and a set of potential links, determine the set of effective links that minimises the number of interfering links and the number of hops to the sole gateway, while avoiding partitioning the network.

7.6.1 Bridge problem

As defined earlier in section 7.3, a bridge in graph theory is an edge whose deletion increases the number of connected components. For instance, the link (*c*,*d*) in Figure 7.12a is a bridge. Similarly, some links between a pair of routers are considered as bridges: the failure of a router, part of these links, results in the partitioning the network. They can be additional routers used to link different sub-networks during the joining strategy phase or they can be among the routers of a sub-network as it is the case in the red sub-network of instance 1 in Figure 7.8a; this sub-network contains one such pair of routers. Henceforth, we refer each router in such a pair of routers as router-bridge; not to confuse with a network bridge used to connect different network segments or bridge routers (also called brouter) acting both as network bridge and router.

Router-bridges represent bottlenecks in the network. Interference at these routers should be alleviated and the path from these routers to the gateway should be minimised in order to efficiently use the limited capacity of the sole gateway in the network, since the throughput decreases with the number of hops.

Approach for bridge determination

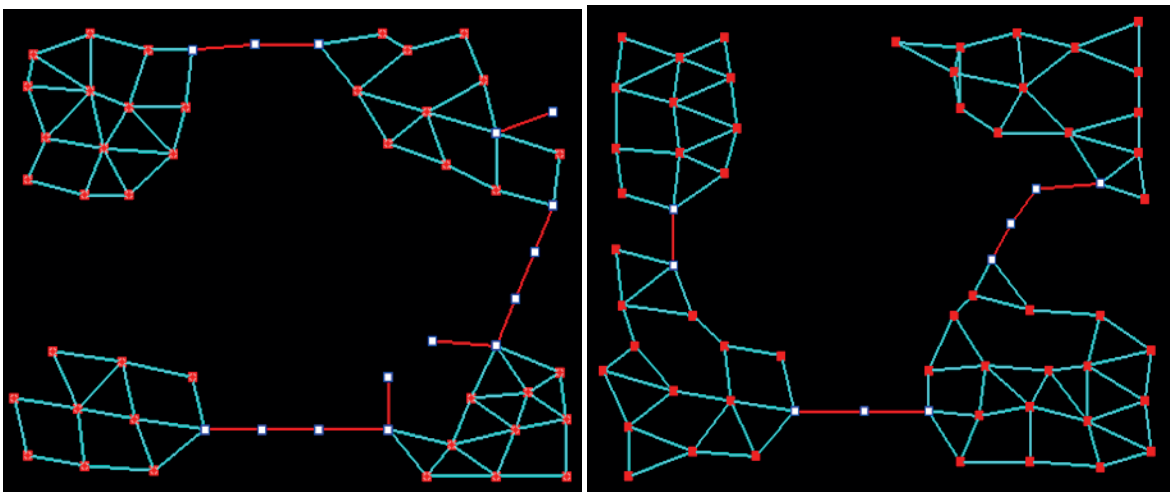
Tarjan's bridge-finding algorithm [Tarjan 1974] is the first linear time algorithm for finding bridges in a graph. Schmidt [2013] proposed recently a simpler algorithm based on chain decompositions. Let us consider a graph *G*. A chain in *G* can be a path or a cycle. After decomposing *G* into chains, an edge *e* is a bridge if and only if it is not contained in any cycle.

Algorithm 7.5 DFSE-BD (DFS Extended-Bridge Determination)

Input: *G*: A Graph
Output: List of edges in cycle

```
1   Begin
2   | Discovered(v):=1
3   | listPath.append(v)
4   | for each w ∈ v.AdjacentVertices do
5   |   | if Discovered(w):=0 then
6   |   |   | listEdgesInCycle:=DFSE(G, w, listPath, listEdgesInCycle)
7   |   | elseif inList(w, listPath) then
8   |   | listEdgesInCycle:=updateVisitedEdges(listEdgesInCycle, listPath, w, v);
9   | listPath.delete(last)
10  | return listEdgesInCycle
11  End
```

Algorithm 7.5 aims to find bridges in a graph *G* by determining cycles using the Depth-First



(a) (b)

Figure 7.13 – Bridge determination: (a) instance 1 with 11 bridges detected; (b) instance 2 with five bridges detected.

Search algorithm (DFS). The DFS algorithm considers the depth first, meaning for each current vertex v, it will look for all adjacent vertices of a vertex w adjacent to v before moving to another vertex x also adjacent to v. A stack is usually used in the DFS algorithm to allow moving back to a lesser depth. The main idea of Algorithm 7.5 is to use a list rather than a stack and to check whether the current vertex is already in the list while going deeper. A vertex v is selected at the beginning, then marked as discovered and added to the list of vertices called *listPath*. All consecutive pairs of vertices from the first to the last one in *listPath* are representing the current path. As long as a vertex w adjacent to v is not discovered, we call the algorithm on this vertex recursively. But if w is already discovered, we check if it is present in the list of vertices of the current path (we compare w with the n-1 first item of the list, since the last item is supposed to be v. If w is present in the list, let us suppose at position i, then edges composed of consecutive pairs of vertices in *listPath* from i to n are added to the list of edges in cycle. When all vertices adjacent to v are discovered, then we remove v from *listPath*, and the algorithm returns the list of visited edges *listEdgesInCycle*. Edges that are not in *listEdgesInCycle* are considered as bridges.

Algorithm 7.5 has been run on instance 1 and 2; the result is presented in Figure 7.13. White squares represent router-bridges; the bridges are drawn in red. Eleven bridges and 15 router-bridges have been determined in instance 1 and four bridges with seven router-bridges in instance 2.

7.6.2 Approach for channel assignment

The channel assignment problem can be assimilated to the problem of the list edge colouring one, since routers in the network comprise multiple radios. Every edge has a list of admissible colours in the list edge colouring problem; the aim is therefore to find a proper edge colouring in which each vertex receives a colour from its list, and no two adjacent edges have the same colour.

Assimilating the channel assignment problem to the list edge colouring one is suitable when routers in the network are using directional antennas. In that way, we just have to ensure that every pair of adjacent edges is using two different colours (representing two different channels). In the case of omni-directional antennas, a channel can be reused at a distance of two hops (corresponding to two edges) as shown in Figure 7.12d with links (*a,b*) and (*e,d*). In fact, since antennas are supposed to be omni-directional, the signal from router *a* to router *b* can be detected at the location of router *c*. Reusing the same channel for the link (*c,d*) could generate an interference between the two links.

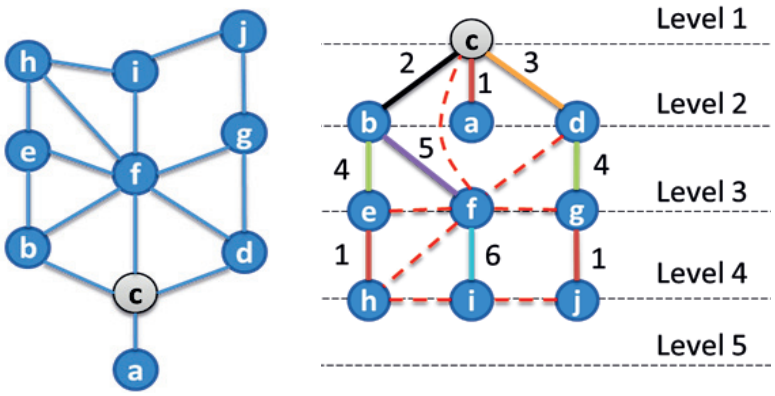
The list edge colouring problem is known as to be NP-complete ([Marx 2004], p. 10). However, this problem can be solvable for trees in polynomial time. The approach used to solve the present problem of channel assignment is based on the construction of a spanning tree satisfying our constraint of observing a minimal distance of two hops (edges) in the reuse of a channel. The spanning tree is constructed using a BFS algorithm, starting from the Internet gateway. Each node constructs two blacklists of channels at each level, based on the channels already used by its relatives. The first, *myBlacklist,* will be used by the node during the determination of its channels and the second, *myBlacklistToBeSaved,* will be saved and used in further iterations. We define some terms to distinguish relatives of each node in this approach:

- **Parent**: The parent of a current node *c* at level *i* of the BFS algorithm is the node *f* at level *i*-1 such that *(f,c)* represents an edge in the spanning tree.
- **False parent**: A false parent of a current node *c* at level *i* of the BFS algorithm is any node *f'* at level *i*-1 such that *(f',c)* represents a link in the network topology but not an edge in the spanning tree.
- **Grandparent**: The grandparent of a current node *c* at level *i* of the BFS algorithm is the node *g* at level *i*-2 such that *g* is the parent of the parent *f* of *c* in the spanning tree.
- **Child**: A child of a current node *c* at level *i* of the BFS algorithm is any node *s* at level *i*+1 such that *c* is the parent of *s* in the spanning tree.

- **False child**: A false child of a current node *c* at level *i* of the BFS algorithm is any node *s'* at level *i*+1 such that *(c,s')* represents a link in the network topology but not an edge in the spanning tree.
- **Sibling**: A sibling of a current node *c* at level *i* of the BFS algorithm is any node *b* at the same level *i* such that *(c,b)* represents a link in the network topology with *c* and *b* having the same parent in the spanning tree.
- **False sibling**: A false sibling of a current node *c* at level *i* of the BFS algorithm is any node *b* at the same level *i* such that *(c,b)* represents a link in the network topology with *c* and *b* having different parents in the spanning tree.

myBlacklistToBeSaved of a node will contain the channels assigned by this node to its relatives in addition to the channel assigned to this node by its parents. *myBlacklist* of each node will contain the channels from *myBlacklistToBeSaved* of each of its relatives, in addition to channels used between its false children and their parents.

The network topology example in Figure 7.14a is considered in order to explain the channel assignment approach. We suppose the number of radios per node to be at most three. We use seven lists: *LGP*: list of grandparents; *LGPC*: list of grandparent channels; *LP*: list of fathers; *LPC*: list of father channels; *LC*: list of current nodes; *LCC*: list of current node channels; *LS*: list of sons. Figure 7.15 provides a step-by-step progression of the approach and Figure 7.14b shows the final network after channel assignment.



(a) (b)

Figure 7.14 – Channel assignment approach: (a) network topology; (b) Result of the approach.

We start from the gateway supposed to be *c*, we add it to *LC* and we mark it as *discovered*. Since *c* is the root, it has neither a parent nor a grandparent. Consequently its *myBlacklist*

Level 1		LGP=Ø	LGPC=Ø	LP=Ø	LPC=Ø	LC={{c}}
	Node c	mB_c=Ø		mBS_c={1,2,3}		LS_c={a,b,d}
				LCC={{1,2,3}}		LS={{a,b,d}}
Level 2		LGP=Ø	LGPC=Ø	LP={{c}}	LPC={{1,2,3}}	LC={{a,b,d}}
	Node a	mB_a={1,2,3}		mBS_a={1}		LS_a=Ø
	Node b	mB_b={1,2,3}		mBS_b={2,4,5}		LS_b={e,f}
	Node d	mB_d={1,2,3,5}		mBS_d={3,4}		LS_d={g}
				LCC={{1},{2,4,5},{3,4}}		LS={{e,f},{g}}
Level 3		LGP={{c}}	LGPC={{1,2,3}}	LP={{a,b,d}}	LPC={{1},{2,4,5},{3,4}}	LC={{e,f},{g}}
	Node e	mB_e={2,4,5}		mBS_e={1,4}		LS_e={h}
	Node f	mB_f={1,2,3,4,5}		mBS_f={5,6}		LS_f={i}
	Node g	mB_g={3,4,5,6}		mBS_g={1,4}		LS_g={j}
				LCC={{1,4},{5,6},{1,4}}		LS={{h},{i},{j}}
Level 4		LGP={{a,b,d}}	LGPC={{1},{2,4,5},{3,4}}	LP={{e,f},{g}}	LPC={{1,4},{5,6},{1,4}}	LC={{h},{i},{j}}
	Node h	mB_h={1,4,5,6}		mBS_h={1}		LS_h= Ø
	Node i	mB_i={1,5,6}		mBS_i={6}		LS_i= Ø
	Node j	mB_j={1,4,6}		mBS_j={1}		LS_j= Ø
				LCC={{1},{6},{1}}		LS= Ø
Level 5		LGP={{e,f},{g}}	LGPC={{1,4},{5,6},{1,4}}	LP={{h},{i},{j}}	LPC={{1},{6},{1}}	LC=Ø END
mB=myBlacklist mBS=myBlacklistToBeSaved						

Figure 7.15 – Step by step application of the channel assignment approach.

is empty. For each node in *LC*, we look for all adjacent nodes representing its relatives. Bridges are put first in the list of relatives. The list of children of node *c*, LS_c, contains {*a*,*b*,*d*}. The first channel is assigned to *a* since it is a bridge. Two edges are then selected among the three remaining ones; let us suppose *b* and *d*. We select the smallest available two channel numbers for *b* and *d*. *myBlacklistTobeSaved* of *c* contains therefore {1,2,3}. The list of current node channels *LCC* at level *i* is a list containing *myBlacklistTobeSaved* of nodes at level *i*. *LCC* contains therefore {{1,2,3}}. *LS* at level *i* is an ordered list containing the list of children of each node at level *i*. *LS* contains therefore {{*a*,*b*,*d*}}. We move then to the next level. The content of *LC* is saved in *LP*, the one of *LS* in *LC*, and the one of *LCC* in *LPC*. That means, the list of children at level *i* becomes the list of current nodes at level *i+1*, the list of current nodes becomes the list of parents and the list of parents becomes the list of grandparents.

We consider the next level (level 2). The first element of *LC* is *a*. We mark it as *discovered*. *myBlacklist* of *a* contains only *myBlacklistTobeSaved* of its parent *c* since *a* has no other relative. *myBlacklistTobeSaved* of *a* contains therefore only 1 and is LS_a empty. We leave *a* and consider the next node *b*. We mark it as *discovered*. *b* has two children: *e* and *f*. *myBlacklist* of *b* contains {1,2,3}. We look for the smallest number not contained in this list; we assign it to the first child of *b* and the following smallest number to the following child. Number 4 and 5 are therefore used. *myBlacklistTobeSaved* of *b* contains{2,4,5} and LS_b contains {*e*,*f*}. We move then to node *d*. We mark *d* as *discovered*. It has a child *g*. We observe also that *d* has a false child *f*, since *f* has already a parent *b*. We consider only the channel shared by *f* and its parent. We do not consider all the channels used by the parent of *f* because there is no potential link between *d* and the parent of *f* that is *b*. *myBlacklist* of *d* contains therefore {1,2,3,5}. The smallest available number, which is 4, is assigned to *g*. *myBlacklistTobeSaved* of *d* contains therefore {3,4} and LS_d contains {*g*}. At the end of this iteration, *LCC* contains{{1},{2,4,5},{3,4}} and *LS* contains {{e,f},{g}}.

We move to the next iteration (Level 3). We start with the first node *e*. We mark *e* as *discovered*. It has a child *h*. *e* considers *myBlacklistToBeSaved* of its parent *b*. *e* has also a sibling *f*. But *e* cannot consider *f* because *f* is not yet marked as *discovered*, that means *f* has not yet assigned channels to its relatives. *myBlacklist* of *e* contains therefore {2,4,5}. The smallest number, 1, is assigned to *h*. *myBlacklistTobeSaved* of *e* contains therefore {1,4} and LS_e contains {*h*}. We move to node *f* and we mark it as *discovered*. *f* has a child *i*. *f* considers *myBlacklistToBeSaved* of its parent *b*. It considers also *myBlacklistToBeSaved* of its grandparent *c*, since it has a link to him. It continues by considering its sibling *e* since it has also a link to *e* and *e* is already marked as *discovered*. Node *f* has also a false parent *d* and a false sibling *g*. It should therefore consider *myBlacklistToBeSaved* of *d*, and the channel shared by its false sibling *g* and its parent (of *g*). *myBlacklist* of *f* contains therefore {1, 2, 3, 4, 5}. Node *f* assigns channel 6 to its child *i*. *myBlacklistTobeSaved* of *f* contains therefore {5,6} and LS_f contains {*i*}. We move to node *g* and we mark it as *discovered*. *g* has a child *j*. *g* considers *myBlacklistToBeSaved* of its parent *d*. It considers also *myBlacklistToBeSaved* of its false sibling *f*, since *f* is already marked as discovered. Node *j*, the child of *g*, has a link to another node *i* in the next level. The channel shared by *i* with its parent is also considered by *g*. *myBlacklist* of *g* contains therefore {3,4,5,6}. The smallest available number, 1, is assigned to *j*. *myBlacklistTobeSaved* of *g* contains therefore {1,4} and LS_g contains {*j*}. *LCC* contains{{1,4},{5,6},{1,4}} and *LS* contains {{h},{i},{j}} at the end of this iteration.

We move to the next iteration (Level 4). We start with the first node *h* and we mark it as *discovered*. *h* has a false parent *f*. *myBlacklist* of *h* contains {1,4,5,6}. Since it has no children, its *myBlacklistTobeSaved* contains therefore {1} and LS_h is empty. We move to node *i* and we mark it as *discovered*. *i* has a *discovered* false sibling *h*. *i* considers

Algorithm 7.6 BFSE-STCA (BFS Extended-Spanning Tree Channel Assignment)

Input G: A Graph
Output listAssignedChannel: A spanning tree representing channel assignment

```
1  Begin
2  | Set LGP, LP, LC, LS, LGPC, LPC, LCC, as empty list
3  | Set listAssignedChannel as empty list
4  | LC := v   // v is the root
5  | Discovered(v):=true
6  | while LC not empty do
7  |   | for each node w not marked as discovered in LC do
8  |   |   | Discovered(w) := true
9  |   |   | LR := ListRelative(w, G)
10 |   |   | (parent,channelP) := fParent(w)
11 |   |   | (listChannelParents, listParents):=fListChannelParents(LP, LPC, LR)
12 |   |   | listChannelGParents:=fListChannelGParents(LGP, LGPC, parent, w)
13 |   |   | (listChannelBro, listSib)=fListChannelSib(LP, LC, LCC, w)
14 |   |   | myBlacklist:= listChannelParents+ listChannelGParents+ listChannelSib
15 |   |   | myBlacklistToBeSaved := channelP
16 |   |   | RemoveDiscoveredNodeAndSibling(LR)
17 |   |   | sortNode(LR)
18 |   |   | while numberRadio(w)>0 and LR not empty do
19 |   |   |   | if numberRadio(LR(1)) := initialNumberRadio then
20 |   |   |   |   | childChannel:=fChildChannel(LGP, LGPC, parent, LR(1))
21 |   |   |   |   | myBlacklist := myBlacklist+ sonChannel
22 |   |   |   |   | ch:=findChannel(listOfChannel- myBlacklist)
23 |   |   |   |   | listAssignedChannel.append(w, LR(1), ch)
24 |   |   |   |   | myBlacklist:= myBlacklist+ch
25 |   |   |   |   | myBlacklistToBeSaved:= myBlacklistToBeSaved +ch
26 |   |   |   |   | Decrease nbAvailableRadio(w) and nbAvailableRadio(LR(1))
27 |   |   |   |   | LStmp.apend(LR(1))
28 |   |   |   |   | LR.removeFirst
29 |   |   | LS.append(LStmp); LCC.append(myBlacklistToSave)
30 |   | LGP:=LP; LGPC:=LPC; LP:=LC; LPC:=LCC; LC:=LS;
31 |   | Reset LCC and LS as empty list
32 | return listAssignedChannel
33 End
```

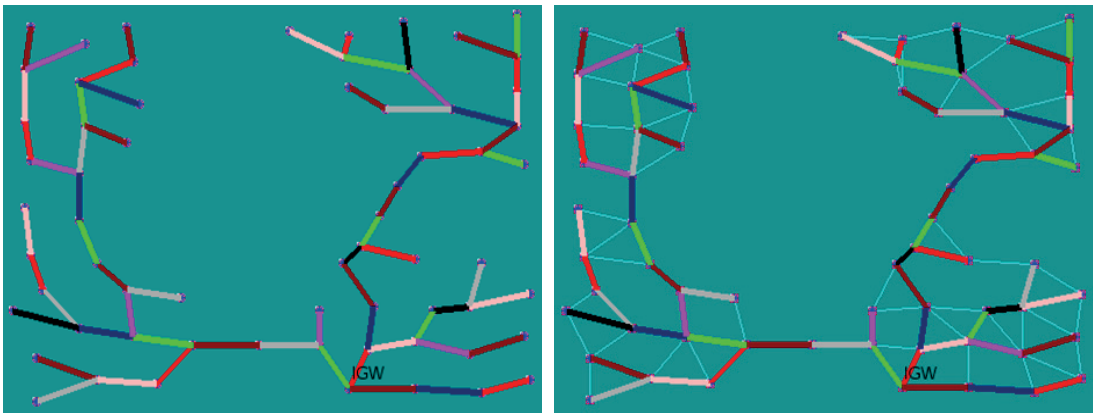
myBlacklistToBeSaved of its parent f and the one of h. *myBlacklist* of i contains therefore {1,5,6}. Since i has no children, its *myBlacklistTobeSaved* contains therefore {6} and LS_i is empty. We move to node j and we mark it as *discovered*. j has a *discovered* false sibling i. j considers *myBlacklistToBeSaved* of its parent g and the one of i. *myBlacklist* of j contains {1,4,6}. Since j has no children, its *myBlacklistTobeSaved* contains therefore {1} and LS_j is

empty. LCC contains{{1},{6},{1}} and *LS* is empty at the end of this iteration. We move to the next iteration (Level 5). The process stops since *LC* is empty.

The approach resulted in Algorithm 7.6. Let us consider *w*, a node at level *i* of the algorithm. The list of relatives *LR* of *w* at line 9 of the algorithm is determined using the adjacency matrix of *G*. The function fParent determines the parent (*parent*) of *w* and the channel shared between *w* and its parent (*channelP*), which is the node already discovered among the relatives of *w*. This is error free since each node has only one parent. fListChannelParents checks in case of false parents, fListChannelGParents in case of a potential link to the grandparent, and fListChannelSib in case of a potential link to siblings or false siblings.

RemoveDiscoveredNodeAndSibling reduces the list of relatives *LR* to the potential children of node *w*, and sortNode puts router-bridges first in the new list *LR*. $initialNumberRadio$ of node *v* indicates the initial number of radios at node *v*, and $numberRadio$ of node *v* indicates the current number of available radios at this node. *w* assigns a channel to its children whose number of radios is equal to the initial number of radios. This is to avoid a child to have more than one parent. $listAssignedChannel$ contains progressively the effective links and their channels.

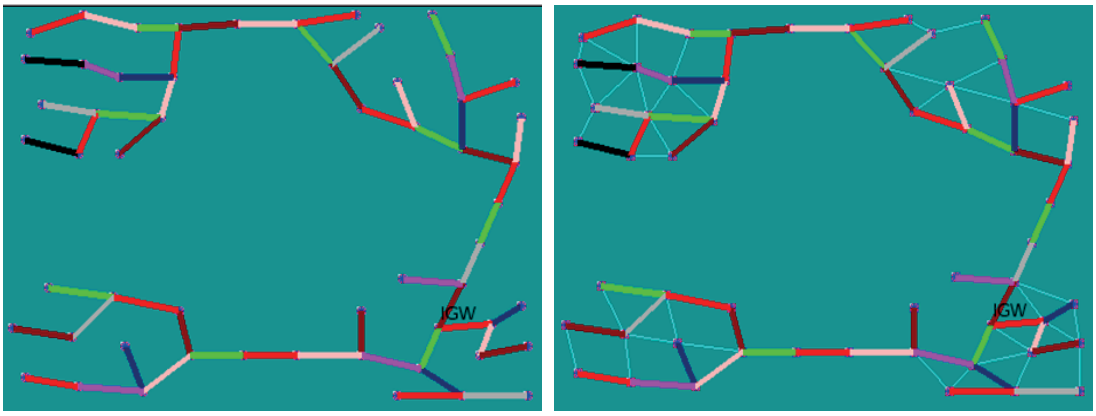
Experimentation and results



(a) (b)

Figure 7.16 – Result of channel assignment for instance 1: (a) spanning tree with effective links; (b) potential and effective links.

Algorithm 7.6 has been run on instances 1 and 2 with the assumption that each router has a number of radios between one and three. The algorithm used eight channels in both instances at the end of the experimentation. Figures 7.16 and 7.17 present the result of the channel assignment algorithm respectively on instance 1 and 2. Each colour is representing a channel. We can observe that interference is minimised in both instances;



(a) (b)

Figure 7.17 – Result of channel assignment for instance 2: (a) spanning tree with effective links; (b) potential and effective links.

most of the colours are reused at exactly two hops. This means, the approach provides a result close to the optimum. The algorithm also minimises the path to the gateway, mainly for bridges. The spanning tree provides the minimal number of radios necessary in order to keep all nodes in the giant component for each node.

Although minimising the number of radios per node is economically efficient, it is however afflicted with some consequences. The first one is the fact that the network will suffer from the lack of robustness, since failure of a node will partition the network. The second consequence is the fact that most of the nodes to communicate with other nodes different from the gateway will use an effective path (set of effective links) longer than their potential path (set of potential links). However, this architecture is efficient when all services and data used at each node in the network are located at the gateway or accessed through it. This is usually the case in rural regions.

8 Conclusion and Future work

The planning problem of wireless mesh networks in rural regions has been considered in the framework of this thesis. Rural regions are usually disregarded by telecommunication operators because of the low income of the population and the difficulty to connect these areas. We tackled especially the spreading of the signal in the case of a rural community. The aim of this work was to provide an efficient approach to determine a cost-effective wireless mesh network architecture, given an area to cover.

Since the planning problem is not only a technical matter, we started by analysing two rural communities: Mbé in the north region and Garoua-Boulaï in east region of Cameroon. This was done in order to assess the feasibility of such a project and the readiness of the local population to welcome it. Then we selected a wireless technology depending on the rural constraints we previously mentioned. Afterwards we studied the signal attenuation in a looking-like rural region, after defining three scenarios: Free space, wooded area, and built-up area. Finally, a placement approach for maximising the coverage and minimising the cost is proposed. Since these objectives are in conflict, the proposed approach finds out a set of trade-off between the two objectives.

8.1 Summary of results

The analysis of the two rural localities revealed a fair good penetration of ICT with 92% of the sample owning a telephone, and 50% having access to a computer. However, around 40% of the sample has never used the Internet despite the presence of the multipurpose telecentres. The assessment of these telecentres revealed their low impact on the local population. In fact, 70% of the population declared having never been in a telecentre despite the fact that two thirds of the sample are located at not more than three km from it. Moreover, the low percentage using the telecentre declared not to spend more than one hour, because of the cost of a working session. The results also show a low affordability as

expected: Two thirds of the sample declared to be able to pay between 1000XAF (1,52 EUR) and 2500 XAF (3,80EUR) per month. Finally, the most desired e-services are e-education, e-health, e-government, and e-commerce. This last result is similar to the one from the ITU report [Kawasumi 2004].

We proposed an empirical path loss model for 802.11n routers in chapter 4, after comparing predictions of different models on the data gathered from the field. The choice of the technology depends on many factors and has been justified in chapter 3. The proposed model is based on the Liechty model [Liechty 2007] and considers the distance to the breakpoint that is ignored in the Liechty model. We also determined attenuation factors and path loss exponents in different scenarios.

We defined a network model for rural regions and we formulated the planning problem considering the coverage and the environmental constraints in chapter 6. We provided an algorithm based on simulated annealing to solve the problem of mesh router placement. The algorithm considers first a continuous area to cover and minimises the number of routers while maximising the coverage. The algorithm has been run several times on different dissimilar instances. We obtain a mean variation of less than 4% of the coverage percentage of the area of interest between the best and the worst values for different runs. This shows some convergence despite the probabilistic nature of the approach. We also observe that an optimal number is around 1.3 times the minimal number of routers, which is the ratio between the area of interest and the area covered by a router. This optimal number of routers provides a coverage percentage of the areas of interest of at least 98%. We also proposed a new multi-optimisation algorithm to consider the cost after the coverage. The PARSA algorithm optimises the cost with respect of a minimal coverage percentage of the area of interest and it outputs a set of trade-offs between these two objectives. The slight variation of around 3% of the cost between the different runs for a given configuration shows also some convergence of the algorithm, despite its probabilistic nature.

We proposed a four steps approach that tackles realistic scenarios where the area of interest is a set of disjoint areas in the last chapter. The first step combines the SA and the PARSA algorithms used in the previous chapter and provides similar results in terms of coverage and cost. We proposed a sub network detection algorithm based on the Breath First Search (BFS) algorithm in the second step, and an algorithm for joining the sub networks in the third step. This latter algorithm is based on an incrementally approach using the closest-pair on the convex-hull of sub networks. Finally, we proposed an algorithm for channel assignment, considering that routers are using omni-directional antennas. BFSE-SPCA assigns channels by constructing a spanning tree based on the BFS algorithm starting from the Internet gateway. This algorithm minimises the interference while providing a minimal

number of radios per node. We also exposed the problem of a router-bridge in this last section and proposed an efficient algorithm for determining bridges in a graph based on Depth First Search (DFS): DFSE-BD (DFS-Bridge Determination). This algorithm is inspired by the approach based on the chain decomposition proposed in [Schmidt 2013].

All algorithms in chapters 6 and 7 have been implemented in Scilab [Ramchandran/Nair 2011]. Scilab is an open-source software for numerical computation.

8.2 Future work

This work arises some perspectives that can be summarised as follows:

Integrating the path loss model and path loss coefficient

We proposed a new path loss model to determine the signal attenuation as well as the path loss coefficient for diverse types of obstacles in chapter 4. But neither this path loss model nor the path loss coefficients are used in chapters 6 and 7. This has been done to alleviate the complexity of the problem. We just supposed that the attenuation factor of an obstacle is high enough to completely fade the signal. A suitable approach for integrating the path loss model and the path loss coefficient should be defined with more precision during planning.

Adding the robustness after channel assignment

The aim of constructing a spanning tree for the channel assignment was to minimise the path of nodes, especially router-bridges, to the gateway. The algorithm uses the minimal number of radios per node in order to get a spanning tree during the channel assignment process. But when nodes have more radios than required by the algorithm such that more links can be established, the remaining radios would be unused. These radios can however be used to provide some robustness to the network. A simple solution is to turn each remaining potential link on a random available channel. But this solution could degrade the quality of the solution provided by the BFSE-SPCA algorithm. However, a possible approach to deal with this case could be to consider the colouring of the spanning tree generated by the BFSE-SPCA algorithm, and to extend this colouring to other edges while satisfying the constraints. This new problem could therefore be assimilated to the one of the list edge colouring of a pre-colouring graph.

Considering the heterogeneousness in planning

We suppose all routers having the same characteristics especially the transmission range and the type of antenna during the planning phase. But this is not always the case in

reality. Disjoint areas of interest are in fact usually connected by long links of directional antennas. Considering the heterogeneousness is therefore important for two reasons: To reflect reality and to enable the coverage of a larger space while limiting the number of hops in the network. Though planning is coverage-driven in rural regions, Johnson has experimentally shown that the mesh network becomes the bottleneck rather than the sole Internet gateway after seven hops in a single radio network ([Johnson 2007], p. 2). How to merge long and short links during the topology design would be an interesting future work.

Comparing other optimisation techniques

The approach used in this work to tackle the placement problem of mesh routers in rural regions relies on simulated annealing. It would be interesting to adapt other optimisation techniques, especially genetic algorithms and particle swarm optimisation, which are also used for this type of problem, and to compare their results to those presented in this work.

Design of a tool for the planning of wireless mesh networks in rural regions

The last and more interesting future work is to design a tool for the planning of wireless mesh networks in rural regions, based on the approach proposed in this work. Proposing such a tool could foster the deployment of these networks.

Terms and acronyms

ATA: Analog Telephony Adapter.

BFS: Breadth First Search.

BFSE-SPCA: Breadth First Search Extended – Spanning Tree Channel Assignment.

BTS: Base Transceiver Station. Sometimes shorten BS for Base Station

CAMTEL: Cameroon Telecommunication.

CAPEX: Capital Expenditures.

CEA: Cost-effective Elementary Area.

DFS: Deep First Search.

DFSE-BD: Depth First Search Extended – Bridge Detection.

EA: Elementary Area.

EAI: Elementary Area of Interest.

GDP: Gross Domestic Product.

HTTP: Hypertext Transfer Protocol.

ICT: Information and Telecommunication Technology.

IEEE: The Institute of Electrical and Electronics Engineers

IGW: Internet Gateway.

ISM band: The Industrial, Scientific and Medical band

ITU: International Telecommunication Union.

LEO, **MEO**, **GEO**: Low, Medium, Geostationary Earth Orbit

LOS: Line Of Sight.

MCT: Multipurpose Community Telecentre.

MINPOSTEL: Ministry of Post and Telecommunication.

MOO: Multi-Objective Optimisation.

MOOP: Multi-Objective Optimisation Problem.

NEA: Non-line of sight Elementary Area.

NLOS: Non- Line Of Sight.

OPEX: Operational Expenditures.

PARSA: Pareto Reverse Simulated Annealing.

PEA: Prohibitive Elementary Area.

QoS: Quality of Service.

SA: Simulated Annealing.

SMS: Short Message Service.

TVWS: TV White Spectrum, a term referring to the available frequency in TV spectrum.

VSAT: Very Small Aperture.

WiLD: Wi-Fi Long Distance.

WLAN: Wireless Local Network.

WMAN: Wireless Metropolitan Network.

WMN: Wireless Mesh Network.

WPAN: Wireless Personal Network.

WRAN: Wireless Regional Network.

Literature

Print resources

[A4AI 2014]
Owono, J. and F. Blanc: *Internet and Broadband in Cameroon: Barriers to affordable access – Case Study*. Alliance for Affordable Internet, Washington, DC 2014.

[Akyildiz 2005a]
Akyildiz, I.F. and X. Wang: *A Survey on Wireless Mesh Networks*. IEEE Communications Magazine 43 (2005) No. 9, pp. 23-30.

[Akyildiz 2005b]
Akyildiz, I.F., X. Wang, and W. Wang: *Wireless mesh networks: a survey*. Computer Networks 47 (2005) No. 4, pp. 445-487.

[Akyildiz/Wang 2008]
Akyildiz, I.F. and X. Wang: *Cross-layer design in wireless mesh networks*. IEEE Transactions on Vehicular Technology 57 (2008) No. 2, pp. 1061-1076.

[Amaldi et al. 2007]
Amaldi, E., A. Capone, M. Cesana, I. Filippini, and F. Malucelli: *Optimization models and methods for planning wireless mesh networks*. Computer Networks 52 (2008) No. 11, pp. 2159-2171.

[Andrade/Hoefel 2010]
Andrade, C.B. and R.P.F. Hoefel: *IEEE 802.11 WLANS: A comparison on indoor coverage models*. 23rd IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), Calgary, AB 2010, pp. 1-6.

[Aoun et al. 2006]
Aoun, B., R. Boutaba, Y. Iraqi, and G. Kenward: *Gateway placement optimization in wireless mesh networks with QoS constraints*. IEEE Journal on selected Areas in Communications 24 (2006) No. 11, pp. 2127-2136.

[Arindam et al. 2005]
Arindam, K.D., M.K. Hamed, V. Rajiv, and R. Sumit: *Optimization Models for Fixed Channel Assignment in Wireless Mesh Networks with Multiple Radios.* IEEE Conference on Sensing, Communication, and Networking (SECON), Santa Clara, CA 2005, pp. 463-474.

[Beljadid/Hafid/Gendreau 2007]
Beljadid, A., A.S. Hafid, and M. Gendreau: *Optimal design of broadband wireless mesh networks.* IEEE Global Telecommunications Conference (GLOBECOM), Washington, DC 2007, pp. 4840-4845.

[Benyamina et al. 2007]
Benyamina, D, A. Hafid, M. Gendreau, and N. Hallam: *Managing Wireless Mesh Networks - Analysis and Proposals.* 3rd IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMOB), White Plains, NY 2007, p. 47.

[Benyamina/Hafid/Gendreau 2008a]
Benyamina, D., A. Hafid, and M. Gendreau: *A multi-objective optimization model for planning robust and least interfered wireless mesh networks.* IEEE Global Telecommunications Conference (GLOBECOM), New Orleans, LO 2008, pp. 1-6.

[Benyamina/Hafid/Gendreau 2008b]
Benyamina, D., A. Hafid, and M. Gendreau: *Wireless mesh network planning: a multi-objective optimization approach.* 5th IEEE International Conference on Broadband Communications, Networks and Systems (BROADNETS), London 2008, pp. 602-609.

[Benyamina/Hafid/Gendreau 2009a]
Benyamina, D., A. Hafid, and M. Gendreau: *On the design of bi-connected wireless mesh network infrastructure with QoS constraints.* IEEE Global Telecommunications Conference (GLOBECOM), Honolulu, HI 2009, pp. 1-8.

[Benyamina/Hafid/Gendreau 2009b]
Benyamina, D., A. Hafid, and M. Gendreau: *Optimal placement of gateways in multi-hop Wireless Mesh Networks: A clustering-based approach.* 34th IEEE Conference on Local Computer Networks (LCN), Zurich 2009, pp. 625-632.

[Benyamina/Hafid/Gendreau 2012]
Benyamina, D., A. Hafid, and M. Gendreau: *Wireless mesh networks design—a survey.* IEEE Communications Surveys and Tutorials 14 (2012) No. 2, pp. 299-310.

[Benyamina/Hallam 2009c]
Benyamina, D. and N. Hallam: *Multi-criteria optimization approach for the deployment planning problem of multi-hop wireless networks.* International conference on Compu-

tational and information science (CIS) World Scientific and Engineering Academy and Society (WSEAS) 2009, pp. 454-460.

[Benyamina/Hallam/Hafid 2008a]
Benyamina, D., N. Hallam, and A. Hafid: *On optimizing the planning of multi-hop wireless networks using a multi objective evolutionary approach.* International Journal of Communications 4 (2008) No. 4, pp. 213-221.

[Bernardi et al. 2011]
Bernardi, G., M.K. Marina, F. Talamona, and D. Rykovanov: *IncrEase: A tool for incremental planning of rural fixed Broadband Wireless Access networks.* IEEE Global Telecommunications Conference (GLOBECOM), Houston, TX 2011, pp. 1013-1018.

[Bondy/Murty 1976]
Bondy, J.A. and U.S.R. Murty: *Graph theory with application.* Elsevier, Amsterdam 1976.

[Brown/Gregory 1997]
Brown, D. and M. S. Gregory: *A report on technology independent methodology for the modelling, simulation, and empirical verification of wireless communication system performance in noise and interference limited systems operation on frequencies between 30 and 1500 mhz.* Technical report, Telecommunication Industry Association (TIA) TR8 Working Group 8.8, May 1997.

[Butler et al. 2013]
Butler, J., E. Pietrosemoli, M. Zennaro, C. Fonda, S. Okay, C. Aichele, S. Buettrich, J. Forster, K. Weirenga, E. Vyncke, B. Baikie, L. Hosman, M. Ginguld, and E. Togo: *Wireless networking in the developing world.* 3rd ed., Limehouse Book, Copenhagen 2013.

[CDP GB 2014]
Communal Development Plan of Garoua-Boulaï, 2014.

[CDP Mbé 2014]
Communal Development Plan of Mbé, 2014.

[Cerny 1985]
Cerny V.: *A thermodynamical approach to the traveling salesman problem: An efficient simulation algorithm.* Journal of Optimization Theory and Applications 45 (1985) No. 1, pp. 41–51.

[Chaudhry et al. 2010]
Chaudhry, A.U., R.H. Hafez, O. Aboul-Magd, and S.A. Mahmoud: *Throughput improvement in multi-radio multi-channel 802.11 a-based wireless mesh networks.* IEEE Global

Telecommunications Conference (GLOBECOM), Miami, FL 2010, pp. 1-5.

[Chen/ Chekuri 2007]
Chen, C.C. and Chekuri, C: *Urban wireless mesh network planning: The case of directional antennas*. Technical Report UIUCDCS-R-2007-2874, Dept. of Computer Science, College of Engineering, Urbana, IL 2007.

[Cichon/Kürner 1993]
Cichon, D.J. and T. Kürner: *Digital mobile radio towards future generation systems: Cost 231 final report*. Technical report, COST European Cooperation in the Field of Scientific and Technical Research, Action 231, 1993.

[Darties/Theoleyre/Duda 2009]
Darties, B., F. Theoleyre, and A. Duda: *A divide-and-conquer scheme for assigning roles in multi-channel wireless mesh networks*. 34th IEEE Conference on Local Computer Networks (LCN), Zurich 2009, pp. 277-280.

[De Marco 2009]
De Marco, G.: *MOGAMESH: A multi-objective algorithm for node placement in wireless mesh networks based on genetic algorithms*. 6th IEEE International Symposium on Wireless Communication Systems (ISWCS), Tuscany 2009, pp. 388-392.

[Decree1638 2012]
Decree No. 2012/1638 / PM of 14 June 2012 laying down the rules for establishment and / or operation of networks and provision of electronic communications services subject to the system of authorization. Yaoundé, Cameroon 2012.

[Ding/Xu/Zheng 2009]
Ding, J., J. Xu, and Z. Zheng: *Gateway deployment optimization in wireless mesh network: A case study in china*. IEEE/INFORMS International Conference on Service Operations, Logistics and Informatics (SOLI), Chicago, IL 2009, pp. 300-305.

[Easley/Kleinberg 2010]
Easley, D. and J. Kleinberg: *Networks, crowds, and markets: Reasoning about a highly connected world*. Cambridge University Press, New York, NY 2010.

[ECC 2003]
European Radio Communications Committee: *The analysis of the coexistence of FWS cells in the 3.4 - 3.8 GHz bands*. ERC Report, European Conference of Postal and Telecommunications Administrations (CEPT), May 2003.

[Egli 1957]

Egli, J.: *Radio propagation above 40 mc over irregular terrain.* IRE - IEEE 45 (1957), pp. 1383-1391.

[Erceg 2001]
Erceg, V. et al.: *Channel models for fixed wireless applications.* Technical Report, IEEE 802.16 Broadband Wireless Access Working Group, January 2001.

[Erceg et al. 1998]
Erceg, V., L.J. Greenstein, S. Tjandra, S.R. Parkoff, A. Gupta, B. Kulic, A. Julius, and R. Jastrzab: *An empirically based path loss model for wireless channels in suburban environments.* IEEE International Global Telecommunications Conference (GLOBECOM), Sydney, NSW 1998, pp. 922-927.

[Franklin/Murthy 2007]
Franklin, A.A. and C.S.R. Murthy: *Node placement algorithm for deployment of two-tier wireless mesh networks.* IEEE Global Telecommunications Conference (GLOBECOM), Washington, DC 2007, pp. 4823-4827.

[Friis 1946]
Friis, T.H.: *A note on a simple transmission formula.* Proceedings of the I.R.E. and Waves and Electrons, May 1946, pp. 254-256.

[Fu et al. 2014]
Fu, B., Y. Xiao, H. Deng, and H. Zeng: *A survey of cross-layer designs in wireless networks.* IEEE Communications Surveys & Tutorials 16 (2014) No.1, pp. 110-126.

[Garces 2000]
Garces, R. and J.J. Garcia-Luna-Aceves : *Collision avoidance and resolution multiple access for multichannel wireless networks.* 9th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM) 2 (2000), pp. 595-602.

[Geier 2010]
Geier, J.: *Designing and deploying 802.11 n wireless networks.* Pearson Education, Indianapolis, IN 2010.

[Goodrich/Tamassia 2002]
Goodrich, M.T. and R. Tamassia: *Algorithm design.* Wiley, Hoboken, NJ 2002.

[Graham 1972]
Graham, R.L.: *An efficient algorithm for determining the convex hull of a finite planar set.* Information Processing Letters 1 (1972) No. 4, p. 132 f.

[Green/Obaidat 2002]

Green, D.B. and A.S. Obaidat: *An accurate line of sight propagation performance model for Ad-hoc 802.11 wireless LAN (WLAN) devices*. IEEE International Conference on Communications (ICC), New York, NY 2002, pp. 3424-3428.

[Gupta/Kumar 2000]
Gupta, P. and P.R. Kumar: *The capacity of wireless networks*. IEEE Transactions on Information Theory 46 (2000) No. 2, pp. 388-404.

[Hata 1980]
Hata, M.: *Empirical formula for propagation loss in land mobile radio services*. IEEE Transaction on Vehicular Technology 29 (1980) No. 1, pp. 317-325.

[ITU 1997]
International Telecommunication Union: *Propagation data and prediction models for the planning of indoor Radio communication systems and radio local area networks in the frequency range 900 MHz to 100 GHz*. Recommendations, P series No. 1238, Geneva 1997.

[ITU 2001]
International Telecommunication Union: *Telecommunication sector reform: Cameroon's Experience*. Africa Regional Preparatory Meeting for the World Telecommunication Development Conference (WTDC-02), Yaoundé 2001, pp. 1-12.

[ITU 2012]
ITU:*Measuring the Information Society 2013*. International Telecommunication Union, Geneva 2013.

[Johnson 2013]
Johnson, D.: *Re-architecting Internet Access and Wireless Networks for Rural Developing Regions*. PhD thesis, University of California Santa Barbara, CA 2013.

[Kawasumi 2004]
Kawasumi, Y.: *Global Survey on Rural Communications*. International Telecommunication Union, ITU News (2004) No. 5.

[Kirkpatrick et al. 1983]
Kirkpatrick, S., C.D. Gelatt, and M.P. Vecchi: *Optimization by simulated annealing*. Science 220 (1983) No. 4598, pp. 671–680.

[Kleinberg/Tardos 2006]
Kleinberg, J. and E. Tardos: *Algorithm design*. Pearson Education, New York, NY 2006.

[Li et al. 2008]
Li, F., Y. Wang, X.Y. Li, A. Nusairat, and Y. Wu : *Gateway placement for throughput optimiza-*

tion in wireless mesh networks. Mobile Networks and Applications 13 (2008) No.1-2, pp. 198-211.

[Liang et al. 2008]
Liang, X.U., K. Yamamoto, H. Murata, and S. Yoshida: *Performance Improvement of Wireless Mesh Networks by Using a Combination of Channel-Bonding and Multi-Channel Techniques.* The Institute of Electronics, Information and Communication Engineers (IEICE) transactions on communications 91 (2008) No. 10, pp. 3103-3112.

[Liechty 2007]
Liechty, L.C.: *Path loss measurements and model analysis of 2.4 GHz wireless network in an outdoor environment.* Master thesis, Georgia Institute of Technology, Atlanta, GA 2007.

[Louenkam/Gaspard/Ndie 2013]
Louenkam N., G. Gaspard, and T.D. Ndié: *An Approach of Making Telephony in a Local Wireless Environment: Application to Bluetooth Technology.* E-Infrastructure and e-Services for Developing Countries. Springer, Berlin 2013, pp. 323-330.

[Mardeni/Solahuddin 2012]
Mardeni, R. and Y. Solahuddin: *Path Loss Model development for Indoor Signal loss prediction at 2.4 GHz 802.11n Network.* IEEE International Conference on Microwave and Millimeter Wave Technology (ICMMT), Shenzhen 2012, pp.1-4.

[Marina et al. 2010]
Marina, M.K., S.R. Das, and A.P. Subramanian : *A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks.* Computer networks 54 (2010) No. 2, pp. 241-256.

[McKinsey 2014]
Cabral, A., L. Moodley, and S. Yeboah-Amankwah: *Digital divide: The impact of closing Africa's Internet gap.* Telecommunications, Media, and Technology Practice, McKinsey Global Institute (2014) No. 24.

[Medeisis/Kajackas 2000]
Medeisis, A. and A. Kajackas: *On the use of the universal Okumura-Hata propagation prediction model in rural areas.* IEEE Vehicular Technology Conference, Boston, MA 2000, pp. 450-453.

[Metropolis et al. 1953]
Metropolis, N., A. Rosenbluth, M. Rosenbluth, A. Teller, and E. Teller: *Equation of state calculations by fast computing machines.* Journal of Chemical Physics 21 (1953) No. 6, pp. 1087–1092.

[MINPOSTEL 2012]
Ministry of Posts and Telecommunications: *Firmly on the road to emergence.* Yaoundé, Cameroon 2012.

[NAICT 2007]
National Agency for Information and Communication Technologies: *National policy for the development of information and communication technologies.* Yaoundé, Cameroon 2007.

[Neto/Best/Gillet 2005]
Neto, I., M.L. Best, and S.E. Gillett: *License-exempt wireless policy: Results of an African survey.* Information Technologies and International Development 2 (2005) No. 3, pp. 73-91.

[Nirmala/Pujeri 2012]
Nirmala, M. and R.V. Pujeri: *Performance of TCP Vegas, Bic and Reno Congestion Control Algorithms on Iridium Satellite Constellations.* International Journal of Computer Network and Information Security 4 (2012) No. 12, pp. 40-49.

[Noutat/Ndie/Tangha 2013]
Noutat, S.J.N., T.D. Ndié, and C. Tangha: *Wireless Community Network Services: Opportunities and Challenges for DCs: Case of Rural Cameroon.* E-Infrastructure and e-Services for Developing Countries. Springer, Berlin 2013, pp. 308-317.

[Nungu 2011]
Nungu, A.: *Analysis of the Serengeti broadband network.* Technical report, Kungliga Tekniska Högskolan (KTH), Stockholm 2011.

[Nungu/Bjorn/Nsubis 2008]
Nungu, A., P. Bjorn, and G. Nsubis: *Serengeti broadband.* 2nd ACM SIGCOMM Workshop on Networked Systems for Developing Regions (NSDR), ACM, New York, NY 2008, pp. 37-42.

[Okumura et al. 1968]
Okumura, Y., E. Ohmori, T. Kawano, and K. Fukuda: *Field strength and its variability in VHF and UHF land mobile radio service.* Review of the Electrical Communication Laboratory 16 (1968) No. 9-10, pp. 825–873.

[Pahlavan/Krishnamurthy 2002]
Pahlavan, K. and P. Krishnamurthy: *Principles of Wireless Networks: A Unified Approach.* Prentice Hall, Upper Saddle River, NJ 2002.

[Pathak/Dutta 2011]
Pathak, P. H. and R. Dutta: *A survey of network design problems and joint design approaches*

in wireless mesh networks. IEEE Communications Surveys and Tutorials 13 (2011) No.3, pp. 396-428.

[Pejovic 2012]
Pejovic, V.: *Adaptive and Resource-Efficient Rural Area Wireless Networks.* PhD thesis, University of California Santa Barbara, CA 2012.

[Ramachandran et al. 2006]
Ramachandran, K.N., E.M. Belding-Royer, K.C. Almeroth, and M.M. Buddhikot: *Interference-Aware Channel Assignment in Multi-Radio Wireless Mesh Networks.* 25th IEEE International Conference on Computer Communications, Barcelona 2006, pp. 1-12.

[Ramchandran/Nair 2011]
Ramchandran, H. and A.S. Nair: *Scilab (a Free Software to Matlab).* S Chand and Co. Ltd., New Delhi 2011.

[Rana/Mohan 2012]
Rana, M. and A. Mohan: *Segmented-locally-one-dimensional-FDTD method for EM propagation inside large complex tunnel environments.* IEEE Transactions on Magnetics 48 (2012) No. 2, pp. 223-226.

[Roh/Lee 2010]
Roh, H.T. and J.W. Lee: *Optimal placement of a relay node with controllable mobility in wireless networks considering fairness.* 7th IEEE Consumer Communications and Networking Conference (CCNC), Las Vegas, NV 2010, pp. 1-5.

[Schiller 2003]
Schiller, J.H.: *Mobile communications.* 2nd ed., Pearson Education, Indianapolis, IN 2003.

[Schmidt 2013]
Schmidt, J.M.: *A simple test on 2-vertex-and 2-edge-connectivity.* Information Processing Letters 113 (2013) No. 7, pp. 241-244.

[Seidel/Rappaport 1992]
Seidel, S.Y. and T.S. Rappaport: *914 MHz Path Loss prediction models for indoor wireless communications in Multifloored Buildings.* IEEE Transactions on Antennas and Propagation 2 (1992) No. 2, pp. 207-217.

[Sen/Raman 2007]
Sen, S. and B. Raman: *Long distance wireless mesh network planning: problem formulation and solution.* 16th ACM International Conference on World Wide Web, Alberta 2007, pp. 893-902.

[Shibata et al. 2009]
Shibata, Y., Y. Sato, N. Ogasawara, G. Chiba, and K. Takahata: *A New Ballooned Wireless Mesh Network System for Disaster Use.* IEEE International Conference on Advanced Information Networking and Applications (AINA), Bradford, UK 2009, pp. 816-821.

[Sichitiu 2005]
Sichitiu, M.L.: *Wireless mesh networks: opportunities and challenges.* 6th World Wireless Congress (WWC), San Francisco, CA 2005, pp. 1-6.

[Stüber 2002]
Stüber, G. L.: *Principles of mobile communication.* 2nd ed., Kluwer, Alphen 2001.

[Sun/Tan/The 2005]
Sun, Q., S.Y. Tan, and K.C. Teh: *Analytical formulae for path loss prediction in urban street grid microcellular environments.* IEEE Transactions on Vehicular Technology 54 (2005) No. 4, pp. 1251-1258.

[Taflove/Hagness 2005]
Taflove, A. and S.C. Hagness: *Computational electrodynamics: the finite-difference time-domain method.* 3rd ed., Artech House, Norwood, MA 2005.

[Talbi 2009]
Talbi, El-G.: *Metaheuristics: From Design to Implementation.* Wiley, Hoboken, NJ 2009.

[Tan/Tan 1995]
Tan, S.Y. and H.S. Tan: *Propagation model for microcellular communications applied to path loss measurements in Ottawa city streets.* IEEE Transactions on Vehicular Technology 44 (1995) No. 2, pp. 313-317.

[Tang 2009]
Tang, M.: *Gateways Placement in Backbone Wireless Mesh Networks.* International Journal of Communications, Network and System Sciences 2 (2009) No. 1, pp. 44-50.

[Tang/Xue/Zhang 2005]
Tang, J., G. Xue, and W. Zhang: *Interference-aware topology control and QoS routing in multi-channel wireless mesh networks.* 6th ACM International Symposium on Mobile ad hoc networking and computing (MobiHoc), Urbana-Champaign, IL 2005, pp. 68-77.

[Tarjan 1974]
Tarjan, R.E.: *A note on finding the bridges of a graph.* Information Processing Letters 2 (1974) No. 6, pp. 160 f.

[Tummala 2005]

Tummala, D.: *Indoor propagation modelling at 2.4GHz for IEEE 802.11 Networks.* Master thesis, University of North Texas, Denton, TX 2005.

[Waharte/Boutaba/Anelli 2009]
Waharte, S., R. Boutaba, and P. Anelli: *Impact of Gateways Placement on Clustering Algorithms in Wireless Mesh Networks.* IEEE International Conference on Communications (ICC), Dresden 2009, pp. 1-5.

[Wang et al. 2007]
Wang, J., B. Xie, K. Cai, and D.P. Agrawal: *Efficient mesh router placement in wireless mesh networks.* IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS), Pisa 2007, pp. 1-9.

[Wang/Thai/Du 2009]
Wang, F., M.T. Thai, and D.Z. Du: *On the construction of 2-connected virtual backbone in wireless networks.* IEEE Transactions on Wireless Communications 8 (2009) No. 3, pp. 1230-1237.

[Wu/Luo/Yang 2009]
Wu, W., J. Luo, and M. Yang: *Gateway placement optimization for load balancing in wireless mesh networks.* 13th International Conference on Computer Supported Cooperative Work in Design (CSCWD), Santiago 2009, pp. 408-413.

[Wu/Luo/Yang 2010]
Wu, W., J. Luo, and M. Yang: *Cost-effective placement of mesh nodes in wireless mesh networks.* 5th International Conference on Pervasive Computing and Applications (ICPCA), Maribor 2010, pp. 261-266.

[Xhafa et al. 2011]
Xhafa, F., A. Barolli, C. Sánchez, and L. Barolli: *A simulated annealing algorithm for router nodes placement problem in Wireless Mesh Networks.* Simulation Modelling Practice and Theory 19 (2011) No. 10, pp. 2276-2284.

[Xhafa/Sánchez/Barolli 2009]
Xhafa, F., C. Sánchez, and L. Barolli: *Ad hoc and neighborhood search methods for placement of mesh routers in wireless mesh networks.* 29th IEEE International Conference on Distributed Computing Systems Workshops (ICDCS), Montreal 2009, pp. 400-405.

[Xhafa/Sánchez/Barolli 2010]
Xhafa, F., C. Sánchez, and L. Barolli: *Genetic algorithms for efficient placement of router nodes in wireless mesh networks.* 24th IEEE International Conference on Advanced Information Networking and Applications (AINA), Perth, WA 2010, pp. 465-472.

[Xin/Wang 2009]
Xin, Q., and Y. J. Wang: *Gateway selection scheme for throughput optimization in multi-radio multi-channel wireless mesh networks.* 5th International Conference on Mobile Ad-hoc and Sensor Networks (MSN), Wu Yi Mountain 2009, pp. 187-195.

[Zhao et al. 2012]
Zhao, B., X. Qi, D. Yu-Kai, R. Wang, and H. Song: *Accurate fourth-order doppler parameter estimation approach for geosynchronous SAR.* 9th IEEE European Conference on Synthetic Aperture Radar (EUSAR), Nuremberg 2012, pp. 615-618.

[Zheng et al. 2011]
Zheng, Z., L.X. Cai, M. Dong, X. Shen, and H.V. Poor: *Constrained energy-aware AP placement with rate adaptation in WLAN mesh networks.* IEEE Global Telecommunications Conference (GLOBECOM), Houston, TX 2011, pp. 1-5.

[Zhou et al. 2010]
Zhou, P., X. Wang, B.S. Manoj, and R. Rao: *On optimizing gateway placement for throughput in wireless mesh networks.* EURASIP Journal on Wireless Communications and Networking (2010) No. 1, pp. 1-12.

Online resources

[Africatopsuccess.com 2014]
Africatopsuccess: *Cameroun : le quatrième opérateur mobile est connu.*
http://www.africatopsuccess.com/2014/09/29/cameroun-le-quatrieme-operateur-mobile-est-connu/, visited: December 2014.

[Ayvazian/Schwartz 2012]
Ayvazian, B., R. Schwartz: *WiMAX Technology Roadmap: the Path to Harmonization of 4 G Technology Standards.* WiMAX Forum, 2012.
http://www.wimaxforum.org/LiteratureRetrieve.aspx?ID=177981, visited: February 2015.

[Bhatnagar 2015]
Bhatnagar, A.: *Google to launch Project Loon powered internet in India by 2016.*
http://www.digitbrunch.com/internet/google-launch-project-loon-powered-internet-india-2016, visited: January 2015.

[Businessincameroon.com 2014]
Businessincameroon: *Orange Cameroon reveals communications costs.*
http://www.business incameroon.com/telecom/2611-5149-orange-cameroon-reveals-communications-costs, visited: December 2014.

[Cameroon-tribune.cm 2014]
Cameroon-tribune: *Government Urges P&T Minister To Extend ICT Coverage*.
https://www.cameroon-tribune.cm/index2.php/index.php?option=com_content&view=article&id=83323:government-urges-pat-minister-to-extend-ict-coverage&catid=1:politique&Itemid=3, visited: December 2014.

[CIA 2014]
CIA: *GDP - composition, by sector of origin*.
https://www.cia.gov/library/publications/the-world-factbook/fields/2012.html, visited: December 2014.

[Codr 2008]
Codr, J.: *Wireless Options for Providing Internet Services to Rural America*. April 2008.
http://www.cse.wustl.edu/~{}jain/cse574-08/ftp/rural/, visited: January 2015.

[Davies 2010]
Davies, C. and M. Tutton: *The fight to stem Africa's rural exodus*.
http://www.nepad.org/fr/foodsecurity/news/1902/fight-stem-africas-rural-exodus, visited: December 2012.

[Ecofin 2014]
Ecofin: *Cameroun : Nexttel déçoit avec des tarifs plus chers que ceux d'Orange et de MTN*.
http://www.agenceecofin.com/operateur/1709-22855-cameroun-nexttel-decoit-avec-des-tarifs-plus-chers-que-ceux-d-orange-et-de-mtn, visited: December 2014.

[GSMA 2009]
GSM Association: *GSM coverage, population (%)*. 2009.
https://mobiledevelopmentintelligence.com/statistics/67-gsm-coverage-population, visited: February 2015.

[GSMA 2014]
GSM Association: *Digital Inclusion* 2014.
http://www.gsma.com/mobilefordevelopment/wp-content/uploads/2014/11/GSMA_Digital-Inclusion-Report_Web_Singles_2.pdf, visited: January 2015.

[Itnewsafrica.com 2013]
Itnewsafrica: *Google launches balloon-powered Internet access*. June 2013.
http://www.itnewsafrica.com/2013/06/google-launches-balloon-powered-internet-access/, visited: January 2015.

[ITU 2015]
ITU: *ICT Facts & Figures: The world in 2015*.

http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2015.pdf, visited: April 2015.

[Loon 2015]
Google: *Project Loon*.
http://www.google.com/loon/, visited: January 2015.

[Manohar 2001]
Manohar, K.: *Will Technology Trickle Down to Rural America?* 2001.
http://www.netaction.org/alt-tech/alt-tech.pdf, visited: January 2015.

[Marx 2004]
Marx, D.: *NP-completeness of list colouring and precolouring extension on the edges of planar graphs*. Technical report, 2004.
http://www.cs.bme.hu/~{}dmarx/papers/planar-edge-prext.pdf, visited: April 2015

[McKinsey 2013]
McKinsey: *Lions go digital: The Internet's transformative potential in Africa*, McKinsey Global Institute.
http://www.mckinsey.com/insights/high_tech_telecoms_internet/lions_go_digital_the _internets_transformative_potential_in_africa , visited: December 2014.

[MINPOSTEL 2014]
MINPOSTEL: *Présentation du projet des télécentres*.
http://www.minpostel.gov.cm/index.php?option=com_content&view=article&id=47&Itemid=37&lang=en, visited: October 2014.

[Newplans.net 2015]
Newplans.net: *Determining the Fresnel Zone*.
http://newplans.net/WiFi/Long%20Distance/fresnel.htm, visited: January 2015.

[NICT 2013]
The National Institute of Information and Communications Technology: *World's First TV White Space Prototype Based on IEEE 802.22 for Wireless Regional Area Network*. 2013.
http://www.nict.go.jp/en/press/2013/01/30-1.html, visited: February 2015.

[NIST 2006]
National Institute of Standards and Technology:*Hata and CCIR Formulas IST*.
http://w3.antd.nist.gov/wctg/manet/calcmodels_r1.pdf, visited: January 2015.

[Orange.com 2014]
Orange Cameroon: *Group's activities in Cameroon*.

http://www.orange.com/en/about/Group/global-footprint/Orange/countries/Group-s-activities-in-Cameroon, visited: December 2014.

[Radio-electronics.com 2015]
Poole, I.: *Radio Signal Path Loss.*
http://www.radio-electronics.com/info/propagation/path-loss/rf-signal-loss-tutorial.php, visited: January 2015.

[Radio-electronics.com 2015a]
Poole, I: *WiMAX IEEE 802.16 technology tutorial.*
http://www.radio-electronics.com/info/wireless/wimax/wimax.php, visited: February 2015.

[Radio-electronics.com 2015b]
Poole, I: *IEEE 802.16 WiMAX standards.*
http://www.radio-electronics.com/info/wireless/wimax/ieee-802-16-standards.php, visited: February 2015.

[Radio-electronics.com 2015c]
Poole, I: *WiMAX Network Architecture.*
http://www.radio-electronics.com/info/wireless/wimax/network-architecture.php, visited: February 2015.

[Rakesh/Dalal 2007]
Rakesh, J. and U. Dalal: *A survey of mobile WiMax IEEE 802.16 m standard.* arXiv preprint arXiv:1005.0976, 2010.
http://arxiv.org/abs/1005.0976, visited: December 2014.

[Sharma 2008]
Sharma, A.: *Floating a New Idea For Going Wireless, Parachute Included.* February 2008.
http://www.wsj.com/articles/SB120347353988378955, visited: January 2015.

[Tjensvold 2007]
Tjensvold, J.M.: *Comparison of the IEEE 802.11, 802.15.1, 802.15.4 and 802.15.6 wireless standards.* September 2007.
https://janmagnet.files.wordpress.com/2008/07/comparison-ieee-802-standards.pdf , visited: January 2015.

[Trading Economics 2012]
Trading Economics: *Rural population (% of total population) in Cameroon.*
http://www.tradingeconomics.com/cameroon/rural-population-percent-of-total-population-wb-data.html, visited: June 2013.

[UN DESA 2012]
UN DESA (United Nation, Department of Economics and Social Affairs).
http://esa.un.org/unup/CD-ROM/WUP2011-F01-Total_Urban_Rural.xls, visited: December 2012.

[Vsat-systems.com 2015]
Vsat-systems: *How broadband satellite Internet works.*
http://www.vsat-systems.com/satellite-internet/how-it-works.html, visited: January 2015.

[Weise 2009]
Weise, T.: *Global Optimization Algorithms - Theory and Application.*
http://www.it-weise.de, visited: February 2015

[World Bank 2011]
World Bank: *Access to electricity (% of population)* .
http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS/countries, visited: October 2014.

[World Bank 2014]
World Bank: *Cameroon-Data.*
http://data.worldbank.org/country/cameroon, visited : October 2014.

[World Statistics 2014]
World Statistics: *République du Cameroun - Statistics.*
http://www.statistiques-mondiales.com/cameroun.htm, visited: October 2014.

[Wright 2012]
Wright, S. J.: *Continuous Optimization (Nonlinear and Linear Programming).*
http://pages.cs.wisc.edu/~{}swright/papers/wright_continuous.pdf, visited: January 2015.

Appendix A. ICT Questionnaire used in rural regions

1) Sex: **2) Age**: ____

☐ Male ☐ Female

3) Occupation:

☐ Farmer ☐ Fisherman ☐ Buyer/Seller

☐ Civil Servant ☐ Lecturer/Teacher ☐ Student

☐ Retired ☐ Unemployed

4) Highest level of education

☐ Doctorate ☐ Master ☐ Bachelor

☐ Certificate for University entrance ☐ Secondary School ☐ Primary School

☐ None

5) Languages

French: ☐ Bad ☐ Good ☐ Very Good

English: ☐ Bad ☐ Good ☐ Very Good

Fo foulbé: ☐ Bad ☐ Good ☐ Very Good

Other language: _____

6) Monthly family income (less than)

☐ 10.000 ☐ 25.000 ☐ 50.000

☐ 100.000 ☐ 200.000 More_____

7) Computing device

☐ Computer ☐ Telephone ☐ Tablet

☐ None

8) Operating System

Computer: **Telephone:**

☐ Windows ☐ Android

☐ Linux ☐ iOS

☐ Apple OS ☐ Java Virtual Machine

Other: _____ Other: _____

9) Internet connexion via

☐ Computer ☐ Telephone ☐ None

10) Use of **Computer:** **Internet:**

☐ Once per day ☐ Once per day

☐ Once per week ☐ Once per week

☐ Once per month ☐ Once per month

☐ Never ☐ Never

11) Distance to Telecentre

☐ <= 1 Km ☐ <=3 km ☐ <=5km

☐ > 5km

12) Duration of a visit

☐ <=1hour ☐ <=2 hours ☐ <= 4 hours

☐ > 4 hours

13) Goal of using telecentre (ordering by priority 1, 2, …)

☐ Work ☐ Education ☐ Keep in touch

☐ Seeking job Other: _____

14) Equipment and Service of the telecentre

☐ Computer ☐ Telephone ☐ Fax

☐ Photocopier ☐ Printer ☐ Scanner

☐ E-mail ☐ Chat ☐ Web search

☐ News ☐ Text processing Other: _____

15) Visited Websites **Social networks**

☐ Google ☐ Facebook

☐ Yahoo ☐ Youtube

Other: _____ Other: _____

16) Which online services can be useful for you?

☐ E-Education ☐ E-Health ☐ E-Payment

☐ E-Commerce ☐ E-Government Other: _____

17) Are you interested in access to the Internet from home?

☐ Yes ☐ No ☐ It depends on the costs

18) How much would you pay for Internet per month? (Up to)

☐ 1.000 ☐ 2.500 ☐ 5.000

☐ 10.000 ☐ 20.000 More: _____

Appendix B. Structured interview for MCT managers

1) ICT adoption in this locality

_____
_____
_____

2) Use of telecentre services

_____
_____
_____

3) Use of online services (Education, health, commerce, payment, governmental…)

_____
_____
_____

4) Obstacles to Internet penetration

_____
_____
_____

5) Success and remaining problems of the telecentre

_____
_____
_____

6) Impact of the culture

_____
_____
_____

7) Propositions for next ICT projects

_____
_____
_____

Appendix C. Structured interview for business people

1) Facing problems in your business (transaction, payment, provisioning…)

2) Services to improve the business

3) Most important service

4) Services from the Internet

5) Useful E-services (Commerce, education, health, payment, governmental…)

6) Ready to pay for the Internet (How much?)

Appendix D. Datasheet

Scenario: **Wooded Area** Transmitter: **Alpha Network N2** Receiver: **Dodocool 300Mbps**

Coordinates		Measurement									
Latitude	Longitude	1	2	3	4	5	6	7	8	9	10
7.417123°	13.543603°	-51	-57	-52	-49	-56	-55	-51	-52	-53	-54
7.416740°	13.543590°	-51	-58	-50	-53	-53	-52	-52	-55	-52	-54
7.416840°	13.543810°	-57	-51	-59	-47	-51	-51	-53	-52	-54	-55
7.417680°	13.543700°	-59	-58	-47	-49	-47	-54	-52	-53	-51	-50
7.417480°	13.543940°	-57	-60	-51	-57	-51	-54	-53	-57	-56	-56
7.418011°	13.543780°	-59	-60	-51	-51	-51	-52	-53	-56	-55	-56
7.418095°	13.543795°	-57	-60	-57	-51	-51	-53	-54	-56	-56	-57
7.417100°	13.544280°	-51	-51	-57	-58	-60	-53	-54	-56	-57	-57
7.418025°	13.544050°	-59	-64	-51	-57	-59	-56	-57	-58	-60	-59
7.418595°	13.543895°	-59	-60	-66	-51	-60	-57	-58	-60	-60	-61
7.417550°	13.544625°	-64	-66	-60	-60	-60	-60	-61	-62	-63	-64
7.417790°	13.544620°	-66	-67	-66	-60	-60	-62	-63	-65	-64	-65
7.418300°	13.544485°	-65	-66	-60	-60	-60	-61	-63	-62	-64	-61
7.418550°	13.544350°	-66	-67	-64	-65	-66	-63	-65	-66	-67	-67
7.418400°	13.544500°	-65	-66	-66	-59	-60	-61	-62	-64	-65	-64
7.418665°	13.544278°	-66	-67	-60	-64	-60	-61	-62	-65	-64	-65
7.418810°	13.544150°	-64	-66	-71	-60	-57	-61	-62	-65	-65	-65
7.418040°	13.544820°	-60	-65	-69	-65	-60	-62	-63	-64	-64	-66
7.418960°	13.544160°	-65	-72	-66	-66	-65	-64	-67	-68	-68	-67
7.416570°	13.545045°	-65	-66	-65	-64	-65	-63	-64	-65	-66	-67