Self Adaptive Communication based on Soil Moisture for Wireless Underground Sensor Networks

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Abstract: In wireless underground sensor networks, channel estimation for communication success requires absolute information about deployment and properties of soil. These properties include soil composition (sand, silt, clay), soil density, soil temperature, inter-node distance, node depth, operating frequency and soil moisture. However, only soil moisture shows most temporal and spatial variation and affects the underground communication in long term. Therefore, we propose only soil moisture based self adaptive communication approach that overcomes the requirement of precise knowledge about the parameters of soil and underground deployment. This approach strives to find the maximum soil moisture threshold for successful communication for any given deployment. And, the sensor nodes conserve energy by avoiding the communication in times of increased soil moisture. Our proposed method is proved to be 5 times more energy efficient than terrestrial medium access control methods i.e. B-MAC for underground monitoring applications under extreme weather conditions.

Keywords: WUSN; Soil Moisture; Adaptive Communication; Path Loss; Castalia

1. Introduction

A typical wireless underground sensor network (WUSN) is comprised of several resource-constrained embedded devices that are buried underground. These devices communicate wirelessly with each other. The evolution of WUSNs has resulted in several monitoring applications i.e. agricultural monitoring [1], infrastructure monitoring [2], landslide monitoring [3], and underground mine monitoring [4]. One such application requires to analyse the efficiency of reforestation techniques to combat desertification of large fields in Cameroon. However, persistent rains for extended periods in the region affect the underground communication as continuous increase in soil moisture results in no communication between buried sensor nodes. In terrestrial WSNs and their medium access control (MAC) protocols, i.e. T-MAC, S-MAC, B-MAC, or Contiki-MAC, the sensor nodes would either attempt to increase the transmit power or make multiple retries to establish the communication link. However, these aforementioned protocols will not work in WUSNs as communication will not be possible for long periods during persistent rains and the retries for establishing communication without knowing the state of the channel will only deplete the energy source.

Energy conservation is one of the most important aspects in WUSN as no energy harvesting methods are available as for traditional WSNs. The development of energy efficient communication protocols for WUSN requires precise knowledge about the underground channel. However, path loss estimation for communication success in WUSNs is extremely difficult due to its dependence on the soil composition (sand, silt, clay), soil density, soil temperature, soil moisture, operating frequency, burial depth and distance between the nodes. These parameters also change over time with persistent rains and growth of vegetation. Therefore, accurate path loss estimation in WUSN is not possible in real time. However, improvement or degradation of underground channel is directly correlated to the amount of soil moisture. Therefore, continuous measurement of soil moisture gives insight to the status of underground channel and possibility of successful communication.

The current work proposes a soil moisture based self adaptive communication approach for WUSNs, where buried sensor nodes interact with their surroundings and strive to find their respective moisture thresholds for communication. These thresholds allow the sensor nodes to conserve energy by sensing only and not communicating when channel is not feasible for communication. To the best of our knowledge, sensing-based MAC protocols for WSNs or WUSNs do not exist. Therefore, the results of this work are compared with communication without considering the soil moisture and low power consuming carrier sense medium access protocol for WSNs called B-MAC [5] as representative of terrestrial WSNs MAC protocols.

This work is evaluated in Castalia 3.2 [6], which is an OMNet++ based open source model framework for WSNs. The free space path loss model in Castalia 3.2 is modified to a lateral waves based channel model [7] for WUSNs. The results show that sensing based self adaptive communication for WUSNs can significantly enhance the lifetime and reduce the total number of retries of the sensor nodes. The main contributions of this paper are as follows:

- To propose a self adaptive communication protocol for WUSN based on soil moisture.
- To show that self adaptive communication enhances the lifetime and reduces the number of retries, of the buried sensor nodes.

This paper proceeds with a short overview of the state of the art work done in WUSNs and WSNs in Section 2. Section 3 provides background on path loss and soil moisture and explains the self adaptive communication for WUSNs. Section 4.2 deals with several environmental scenarios for WUSNs and the performance comparison of our approach with existing communication protocols for terrestrial WSNs. Section 4.4 presents the simulation environment, our weather models and the experimental results of our proposed self adaptive communication. Finally, Section 5 concludes the paper and gives an insight to our future work.

2. Related Work

In traditional WSNs, the energy conservation objective at medium access control (MAC) layer is achieved by reducing idle listening, overhearing, collisions and control packet overhead [8], without considering the scenario if no-communication is possible. The no-communication scenario for extended periods of time is more likely to happen in WUSNs than WSNs. This can lead to ineffective idle listening and overhearing resulting in reduced lifetime of the whole network.

There are several empirical and analytical studies performed to understand the dynamics of underground communication. In [9], authors used commodity sensor nodes operating at 2.4GHz for analyzing underground to underground (UG2UG) and underground to aboveground (UG2AG) communication. No UG2UG communication was possible and a communication range of only 7m was achieved for UG2AG communication. In [10] [11] [12] [13], authors have investigated analytically and empirically the impact of inter-node distance, node depth, soil moisture, soil composition and operating frequency on underground communication. They showed that only low frequencies from 300MHz to 700MHz are most suitable for underground communication and also increase in node depth and soil moisture values severely deteriorate the underground communication. In [14], authors proposed a semi-empirical model for UG2UG and UG2AG communication. The proposed model is evaluated by bit error rate (BER), peak data rate (PDR) and signal to noise ratio (SNR). However, the impact of soil composition and soil moisture on BER, PDR and SNR is not investigated for the proposed semi-empirical model. In [15], authors analyzed the impact of soil moisture, soil type, burial depth, transmission power and receiver antenna for 433MHz based LoRa systems on underground communication. The authors reported the degradation of UG2AG communication from 200m to 30m for an increase in volumetric water content (VWC) from 10% to 30%. These works have allowed in better understanding of the underground channel for communication and provided direction for the development of efficient data link layer, network layer and transport layer protocols for WUSNs. In [16], authors proposed a soil moisture based adaptive error control for WUSNs, to enhance the reliability of underground communication links. However, the no-communication scenario is not considered which is inevitable in extreme weather conditions in WUSN. In [17], authors proposed a soil moisture based transmit power control and environment aware routing protocol for WUSNs. They assumed that connectivity can always be ensured at all moisture values by increasing the transmit power or using aboveground relay nodes. However, this assumption cannot be generalised as it depends highly on the properties of the soil and deployment scenario. Similarly in some other monitoring applications in challenged environments, i.e. glacier monitoring [18], agriculture monitoring [19] and volcano monitoring [20], reliability of communication links is ensured using hybrid deployment topologies and no-communication scenarios are not considered.

In our own research we have been dealing with harsh underground environments for soil revitalisation projects in Cameroon [21]. There, we have developed a dedicated WUSN node, called MoleNet and we have made the experience that heavy rains can prohibit communication altogether over extended periods of time. This effect can only be seen in countries with rain seasons, but can make a WUSN deployment unusable for months. Shortening the distances between nodes does not help and deploying over-ground nodes is not feasible due to vandalism issues. At the same time, all typical WUSN applications gather soil moisture as part of their application requirements. In this paper, we explore how to leverage this readily available knowledge to detect a no-communication scenario and to wisely "survive" it with minimal energy waste.

3. Self Adaptive Communication for WUSN

In this section, we first discuss the lateral waves based path loss model for WUSNs and influence of soil moisture on path loss in underground communications. In Section 3.3 we present the details of our proposed self adaptive communication based on soil moisture for underground communications.

3.1. Path Loss Model for WUSN

There can be two types of deployment strategies in WUSN, underground topology or hybrid topology. In underground topology, all the sensor nodes are buried underground, whereas in hybrid topology, some sensor nodes are buried underground while others are deployed aboveground. This results in three types of communication links in WUSNs, underground to underground (UG2UG) communication, underground to aboveground (UG2AG) communication and aboveground to undergorund (AG2UG) communication. The UG2UG communication links experience higher path loss as compared to UG2AG communication, as the electromagnetic waves propagate only through soil medium. The path loss of electromagnetic (EM) waves highly depend on the dielectric properties of the propagation medium. In WUSN, the dielectric properties of the soil depend on the composition of soil (sand, silt, clay) and the amount of moisture in the soil [22]. The dielectric constant ε of the soil can be calculated using the Peplinski principle [23]:

$$\varepsilon = \varepsilon' + \varepsilon'' \tag{1}$$

$$\varepsilon' = 1.15\left[1 + \frac{p_b}{p_s}\left(\varepsilon_s^{\alpha'}\right) + m_v^{\beta'}\,{\varepsilon'_{fw}}^{\alpha'} - m_v\right]^{1/\alpha'} - 0.68 \tag{2}$$

$$\varepsilon'' = \left[m_v^{\beta''}\,{\varepsilon''_{fw}}^{\alpha'}\right]^{1/\alpha'} \tag{3}$$

where p_b is the bulk density and p_s is the specific density of the soil particles, ε_s is the dielectric constant of the soil's solid, m_v is the volumetric water content (VWC) of the soil, ε'_{fw} and ε''_{fw} are the real and imaginary parts of the dielectric constants of free water. β' and β'' are calculated from the proportion of soil particles (sand, silt and clay). The propagation constants α and β can be calculated using soil dielectric constant ε . Eventually the received power can be calculated using lateral waves based path loss model for WUSNs[7]. The three components of the received power are direct path P_r^d, reflected path P_r^r and lateral waves P_r^L.

$$P_r^d = P_t + 20\ log_{10}\lambda - 20\ log_{10}r_1 - 8.69\alpha r_1 - 45 \tag{4}$$

$$\begin{aligned} P_r^r =\ & P_t{+}20\ log_{10}\lambda - 20\ log_{10}r_2 - 8.69\alpha r_2 - 45 \\ & +20\ Log_{10}\Gamma \end{aligned} \tag{5}$$

$$\begin{aligned} P_r^L =\ & P_t{+}20\ log_{10}\lambda - 40\ log_{10}d - 8.69\alpha(h_t + h_r) \\ & +20\ Log_{10}T - 30 \end{aligned} \tag{6}$$

where parameters r_1, r_2, d, h_t, h_r are calculated from the depth of the nodes and the distance between the nodes. Although, depth and distance between the nodes can be known but parameters like β', β'', m_v can have different values even within a small monitoring field resulting in different propagation characteristics. Therefore, channel estimation in large fields can be very difficult. However, after deployment path loss in WUSN depends highly on the amount of moisture in soil.

3.2. Impact of Soil Moisture on Path Loss

In [22], authors investigated that after deployment of a WUSN, soil moisture is the most critical factor affecting the underground communication. In Figure 1, we show the same phenomenon based on the above described lateral waves channel model [7], where path loss of UG2UG communication links is directly proportional to the amount of soil moisture. If we assume a real-world deployment of our own MoleNet sensor nodes with their parameters as summarised in Table 1, we see that even small changes in the VWC increase the path loss so much that communication is not possible any more.

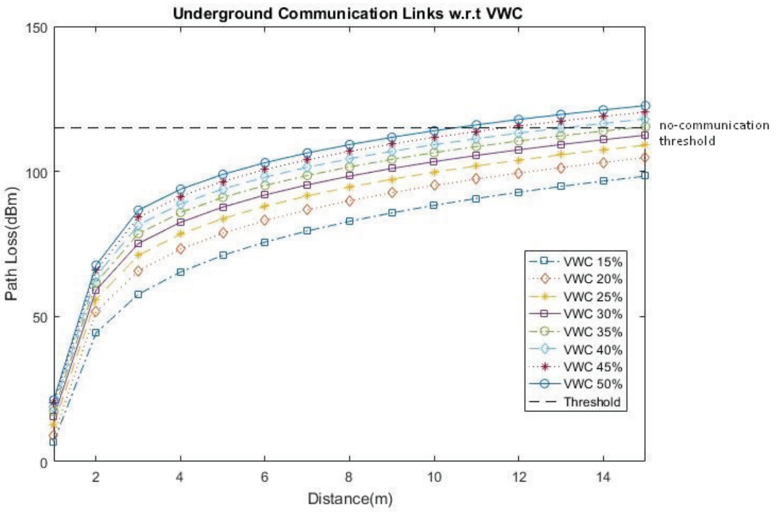

Figure 1. Path loss for UG2UG communication link for increase in volumetric water content (VWC) (sand=80%, clay=20%, bulk density=1.5g/cm^3, specific density=2.66g/cm ^{3}, depth=20cm, frequency=433MHz)

We also performed a field experiment to validate the impact of soil moisture on underground communication. For that purpose, two MoleNet[21] sensor nodes(Node 1, Node 2) operating at 433MHz are buried at a depth of 20cm. Another MoleNet sensor node is used as the sink node and is deployed aboveground (Figure 2). Node 2 is equipped with volumetric water content sensor.

The inter-nodal distance between the buried nodes is 12m as shown in Figure 2. Table 1 shows the configuration parameters for the performed experiment.

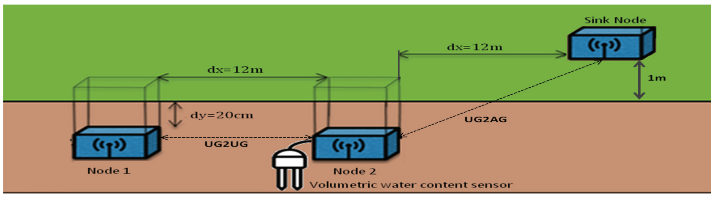

Figure 2. Deployment scenario for field experiment

Table 1. Configuration parameters of the experiment based on our MoleNet nodes [21]

Parameter	Value
Inter node distance (dx)	12m
Node depth (dy)	20cm
Frequency	433MHz
Transmit Power	10dBm
Modulation	FSK
Receiver Sensitivity	-105dBm
VWC Sensor	Decagon 5TM [24]

The impact of soil moisture is analyzed on UG2AG and UG2UG communication links. The soil moisture of the test field is increased gradually by pouring water over the experimental field. The results in Figure 3[1] show the impact of increase in soil moisture over UG2AG and UG2UG communication links. As soil moisture increases by 5.5%, the UG2AG link degrades significantly by 11dBm, while the UG2UG communication link breaks down completely.

An underground sensor node will deplete its battery if it constantly attempts to establish the communication with its neighbours before the soil moisture falls below the communication threshold. Therefore, it is required to take soil moisture into consideration to increase the communication success probability as well as conserving energy resources in WUSN. In the subsequent section, we present our soil moisture based adaptive communication approach for WUSNs.

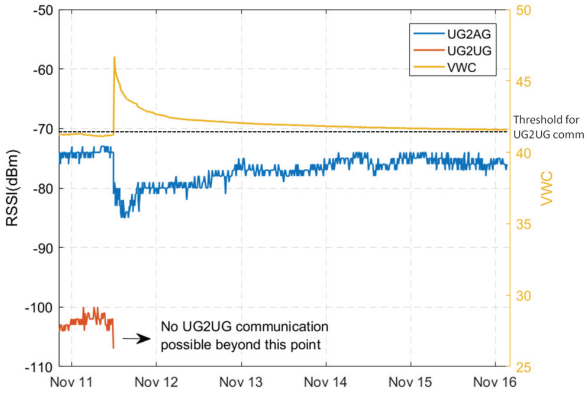

Figure 3. UG2AG and UG2UG communication links degradation in response to increase in volumetric water content (VWC)

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[1] The raw data of this experiment is available under http://github.com/ComNets-Bremen/WUSN

3.3. Soil Moisture based Self Adaptive Communication

We observe that once two nodes are buried in the soil, all parameters but the soil moisture are fixed. Their values are not known to us, but we can safely assume that they change very slowly over the lifetime of our sensors. Thus, we propose a self-adaptive protocol, which assumes there is a VWC threshold which dictates the success of communication. At the beginning, the exact value for any pair of nodes is unknown to us, but a "best guess" value can be used to start with. During the lifetime of the node, this value can be learned by observing when the communication was successful and when not. Each node keeps the currently learnt VWC threshold for each of its neighbours, thus adapting to the individual properties of each and any communication pair in the network.

Our approach is different from usual link layer and neighbourhood management protocols [25]. Those protocols assume that nodes are joining and leaving the network and attempt to discover them and to delete them from the neighbour table as soon as possible. In WUSNs, however, we can assume that neighbours are still there, but not reachable. Our approach also does not require additional communication to update neighbours' information, but uses the VWC, which is available in most of the WUSN applications anyway.

Figure 4 presents the flowchart of our algorithm in the case of one-hop communication with a single neighbour. It can be easily extended to several neighbours, considering that one threshold value (TH in the Figure) is maintained per neighbour. The multi-hop scenario can be deduced similarly. In our proposed algorithm, every transmit cycle is initiated by sensing the VWC. A transmission is attempted if the sensed VWC is below the default threshold for communication. In case of multiple failed attempts of transmission, the threshold of communication is updated to the current sensed VWC. If the sensed VWC is constantly on the rise then no transmissions are attempted till the VWC starts decreasing from its maximum reached value. If the sensed VWC remains above the communication threshold for more than specified communication time, then transmissions are attempted randomly with a certain probability to determine if communication threshold needs to be updated due to the change in other parameters (soil composition, vegetation) in underground environment. This allows in tracking and adaptation to diverse states of underground channel. In the next section, we will demonstrate how efficient our self-adaptive communication is in terms of energy efficiency.

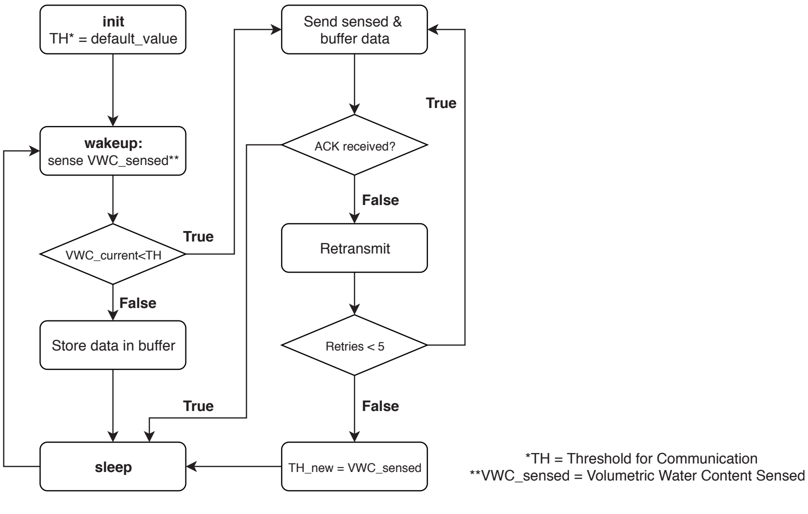


Figure 4. Self-adaptive communication based on VWC sensor data

4. Evaluation

In this section we demonstrate how efficient our approach is in saving energy in challenged scenarios with persistent rain. In order to realistically evaluate this in a simulation environment, we have modelled some real-world weather conditions, described first. The simulation environment itself and the obtained results follow later.

4.1. Scenarios for Adaptive Communication

We have modelled three different weather scenarios:

1. Persistent rain in Ngaoundere, Cameroon. The extreme conditions of the region pose severe challenges for the deployed WUSN. During the rainy season, it rains persistently for six months, making the underground communication near to impossible. Figure 5 shows exemplary the total amount of rain for different months of year 2016 [26]. Our own measurements of VWC for four days in Ngaoundere [21] during the rainy period showed an increase in VWC of up to 24% and no UG2UG communication was possible for the observed VWC.

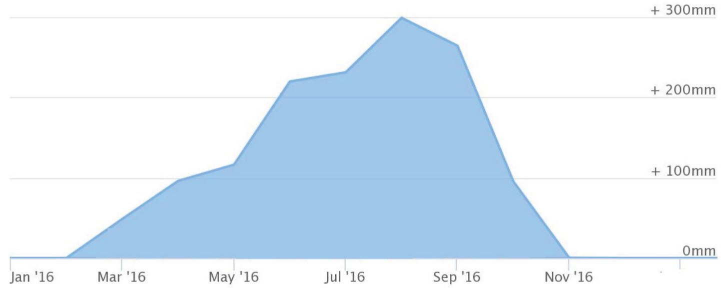


Figure 5. Total amount of rain (mm) in Ngaoundere, Cameroon for year 2016.

2. In order to evaluate the potential of our approach, we simulated another scenario where VWC is continuously increasing and decreasing around the communication threshold.
3. No rain scenario, with fixed soil moisture. We use this scenario to validate our approach that it does not have any negative impact on the performance of the network in case the challenging conditions never occur.

   Figure 6 shows all the aforementioned scenarios for different VWCs (Ngaoundere VWC, Varying VWC, No Rain VWC).

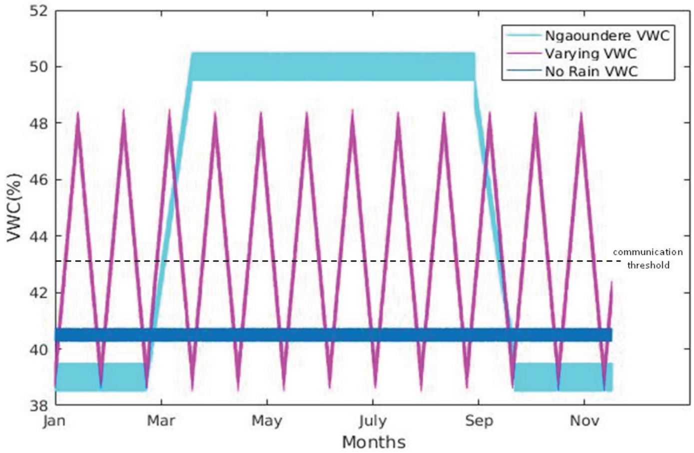


Figure 6. Three different scenarios of VWC for UG2UG communication

4.2. Simulation environment

For the evaluation of our approach we used Castalia 3.2 [6] simulator, which is an open source simulator for WSNs based on OMNeT++. By default, Castalia only supports the path loss model for free space and body area networks (BANs). Therefore, we implemented the path loss model [7] for

UG2UG communication in Castalia. The radio module in Castalia is also configured to RFM69 [27] transceiver that operates at 433MHz. The power consumption model for serial EEPROM memory (25LC512) is also implemented in Castalia to incorporate the power consumption due to buffering of data in our self adaptive communication. Table 2 shows the power consumption of the RFM69 transceiver and 25LC512 EEPROM in different modes of operation.

The power consumption of the VWC sensing itself is ignored, since we assume the application layer itself is interested in this data and it will be gathered irrespectively of the protocols used.

Table 2. Power Consumption of transceiver and buffer in different modes

Operation	Power Consumption (mW)
Radio (Tx)	109
Radio(Rx)	52.8
Radio (Sleep)	.0033
Buffer (Write)	27.5
Buffer (Read)	55
Buffer (Sleep)	.005

We have also modified the existing customizable physical process module in Castalia to include the VWC sensing. Traces of the Ngaoundere VWC, Varying VWC and No-Rain VWC scenarios are then fed to the sensor nodes using the VWC physical process module. Same scenario as the one shown in Figure 2 for the field experiment is used for evaluating the efficiency of the self adaptive communication in simulation. However, only UG2UG communication link is considered for the simulation scenario. Table 3 shows different parameters used for the path loss in the underground channel. Table 4 shows different parameters for the simulation environment.

Table 3. Parameters for underground path loss model in simulation

Soil Composition	C (20%), S(80%)
Bulk Density	$1.5g/cm^3$
Specific Density	$2.66g/cm^3$
Depth	$20cm$
Inter-node distance	$12m$
Operating Frequency	$433Mhz$

Table 4. Parameters for Simulation

Simulation Period	1 Year
Simulation Runs	10
VWC Variation	0.5%
Packet Loss Probability	1%
Sampling Time	5min

4.3. *Comparative study*

The main idea of our work is to leverage readily available sensor information on underground nodes, namely VWC. To the best of our knowledge, there are no other works based on VWC and thus comparison becomes hard. Still, we have considered several options, which one would follow in an underground scenario, if our protocol is not available. We discuss these options here and select some to evaluate in simulation against our protocol.

Non-adaptive one-hop communication. In this solution, the node is trying to send its data at the scheduled time to its parent. It does not use the VWC value at all and it is programmed to re-try five times until receiving an ACK from the parent. If the sending fails, the node will store the data in its buffer and re-try at the next sending interval.

Fixed-threshold VWC one-hop communication. Related works [28] [10] have explored this option widely. They try to estimate the VWC threshold in the particular environment, given the soil composition. This approach works theoretically well, but it is only as good as the knowledge about the soil on site. Moreover, the soil composition changes dramatically in short distances (stones and rocks hidden in the soil, underground water caprioles, etc.) and thus using one threshold for all nodes in a network is not very useful. In contrast, our approach will adapt the threshold to the particular communication pair without knowledge of the soil composition.

We do not compare against this solution, as our comparison is performed in a simulation environment, where knowledge is of course available, but unfair to use.

B-MAC. Another logical solution would be to used a duty-cycled MAC protocol, especially designed for sensor networks, e.g. B-MAC[5]. This protocol as the first to introduce duty cycling and considers only broadcast environments. Even if there are also more sophisticated versions of duty cycling, such as Contiki-MAC [29], neither of them use the VWC or any other environmental adaptiveness. We compare against this protocol because of its simplicity.

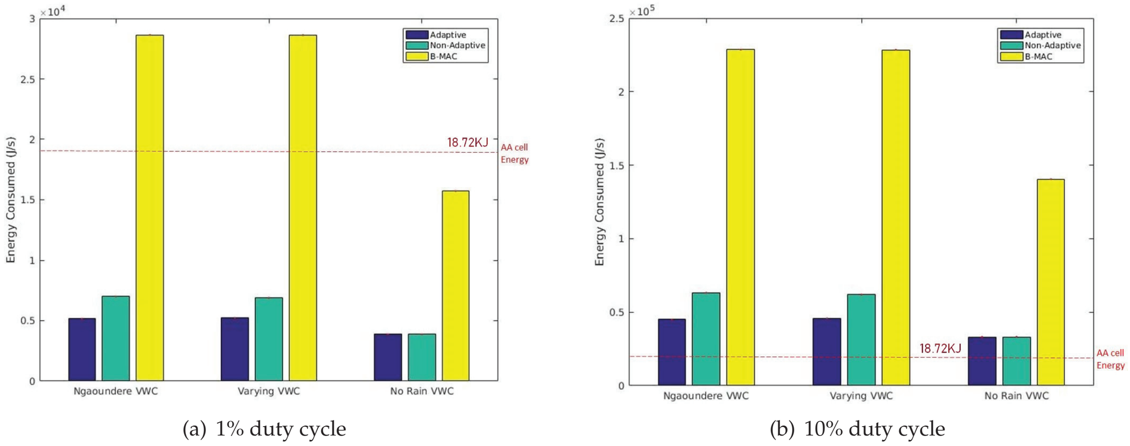
LoRaWAN. Probably the most intriguing option is to use LoRaWAN [30], especially because we assume one-hop communication only. However, maximum duty cycle of end devices in LoRaWAN cannot exceed 1% for any specific channel in EU-868 [31]. This restriction only allows sampling and transmission of data in real time and prevents continuous transmission of buffered data. However, in case of increased soil moisture underground channel becomes unsuitable for communication and the data cannot be always forwarded in real time. Thus, we do not compare against this option.

In summary, it is hard to find state-of-the art protocols to compare against our idea. Still, in order to demonstrate the work of our protocols and its advantages in underground environments with heavy rainfalls, we compare its performance against non-adaptive one-hop communication and against B-MAC.

4.4. Simulation results

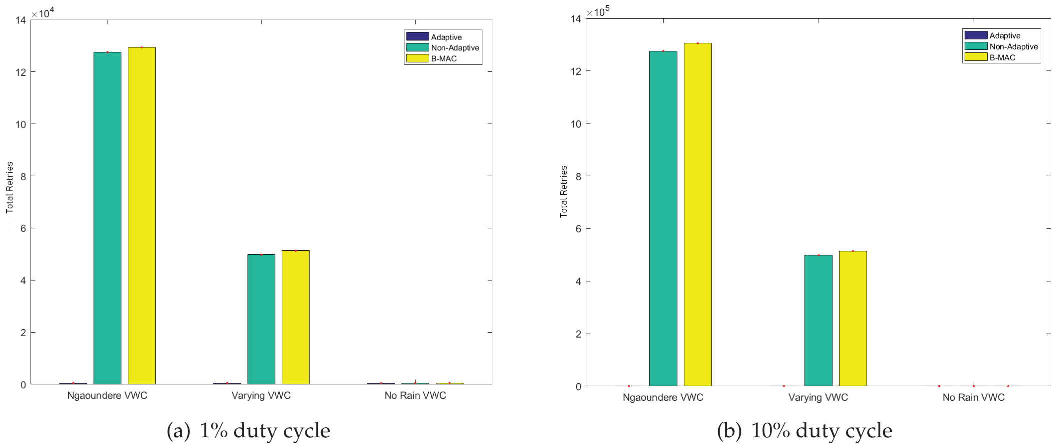
The energy efficiency of our approach is compared with non-adaptive communication and B-MAC for different duty cycles. Figure 7 shows the average energy consumption comparison of self adaptive communication with non-adaptive communication and B-MAC with 95% confidence interval for two different duty cycles i.e. 1% and 10%. For both the duty cycles, B-MAC consumes the most power as it continues to transmit the sensed data and also continues idle listening although the underground channel remains unsuitable for communication for extended period of time. The non-adaptive communication also consumes more power than adaptive communication as it strives to communicate with sink even when the underground channel is not suitable for communication. For the **No Rain** scenario, the overall power consumption for all the techniques is reduced, as the node manages to communicate throughout the year with the sink node and does not require to store the data on the buffer. However, the B-MAC still consumes significantly more power than adaptive and non-adaptive communication as the node only reduces the data buffering and retries but continues idle listening and overhearing.

Figure 8 shows that self adaptive communication has least number of retries as compared to non-adaptive and B-MAC for the first two scenarios. The number of retries for non-adaptive and B-MAC in the **Varying VWC** scenario reduces as there are more opportunities of communication than the first scenario, where communication is not possible for six months. For the **No Rain** scenario, the number of retries are almost identical for all three methods.



(a) 1% duty cycle (b) 10% duty cycle

Figure 7. Energy consumed (average) for three different scenarios with 95% confidence interval



(a) 1% duty cycle (b) 10% duty cycle

Figure 8. Total retries (averaged) for three different scenarios with 95% confidence interval

Our proposed soil moisture based communication also adapts the VWC threshold to other factors in WUSN i.e. depth of the sensor nodes, inter-node distance, soil composition, soil density, etc. To demonstrate this behaviour, the depth of the sensor nodes is varied and its impact is analysed on their respective VWC threshold, total retries and energy consumed by the sensor nodes. Ngaoundere VWC scenario is used as the soil moisture input. All the other parameters i.e. soil composition, bulk density, specific density, inter-node distance and operating frequency are same as in Section 4.2. Figure 9 shows the communication thresholds for burial depths of 15cm, 20cm and 25cm.

The underground communication deteriorates with increase in depth resulting in decrease in VWC threshold as well. A node buried at low depth (15cm) can manage to communicate at higher levels of VWC, but as the depth increases (25cm) the node will not be able to communicate at the same VWC. The impact of increase in depth is also shown on total number of retries and energy consumed in Figure 10. With increase in depth from 15cm to 25cm, the VWC threshold reduces from 46.9% to 39.7% resulting in decrease in possible communication time over the whole year. This leads to an increase in total number of retries for non-adaptive and B-MAC. The increased number of retries results also in higher energy consumed, as can be seen in Figure 10 on the right.

In summary, we have shown that our adaptive VWC based communication successfully leverages the readily available VWC information to optimise the performance of an WUSN in case of heavy rains and subsequent broken communication. At the same time, in case these harsh conditions do not occur, the protocol does not exhibit any extra overhead.

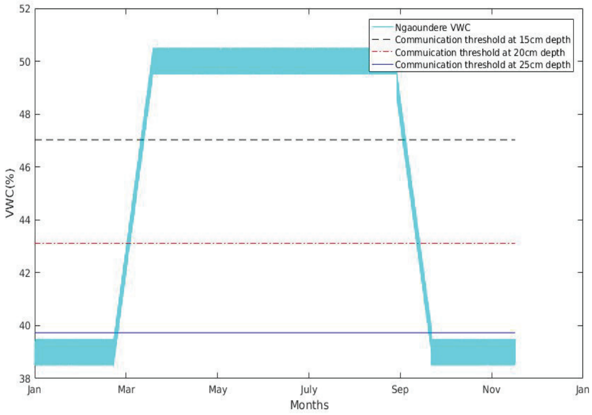
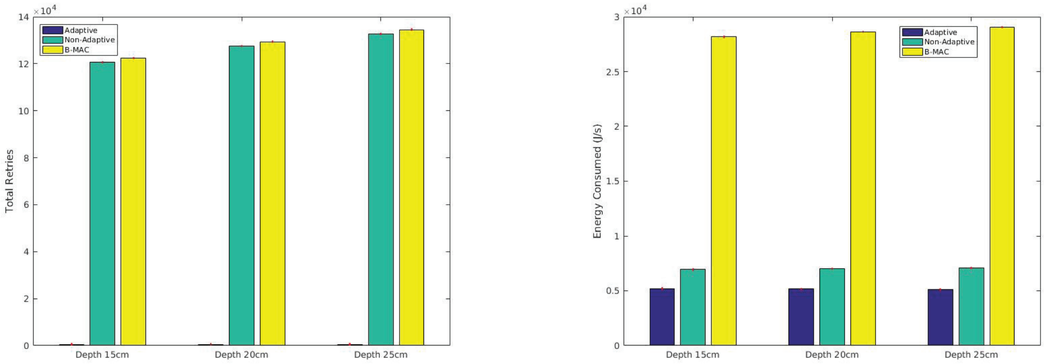


Figure 9. VWC thresholds for different depth of sensor nodes for the Ngaoundere scenario.



(a) Total retries (averaged) for different depths

(b) Energy consumed (averaged) for different depths

Figure 10. Total retries and energy consumed for 1% duty cycle with 95% confidence interval for different burial depths and the Ngaoundere scenario.

5. Conclusion

In this paper, we presented a self adaptive communication based on soil moisture for underground communication. Underground channel presents several challenges for UG2UG communication. Soil moisture based communication allows the buried sensor nodes to conserve their energy and also reduce total number of retries significantly. The results have shown that the communication protocols for terrestrial WSNs suffer due to increased number of packet retries and also waste energy when there is no communication possible.

The current work will be extended in the realization of reliable data link layer and network layer protocols for WUSNs based on sensed soil moisture.

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