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A Data Collection Mechanism for Wi-Fi Based Underground Sensor Networks

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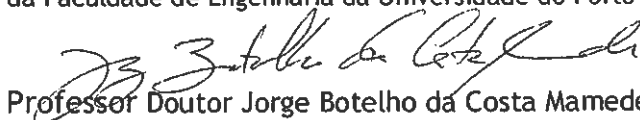
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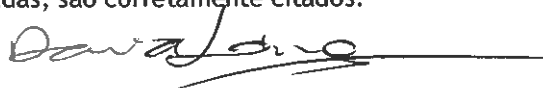


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Abstract

Wireless Underground Networks (WUN) is an emerging research topic in the Wireless Networks field. It will enable a wide variety of applications in fields such as agriculture, border patrol, assisted navigation, sports field maintenance, intruder detection, and infrastructure monitoring. For instance, considering an agricultural scenario, deploying underground wired networks can be a complex, time-consuming task and expensive maintenance is expected. In this context the need of a WUN - a network formed by a set of buried nodes communicating through a wireless link in an underground environment - arises. Obtaining data efficiently from these buried nodes may pose a problem due to the asymmetry between underground-to-aboveground and aboveground-to-underground communications, and the specific characteristics of the soil medium. Recent work in this field has been oriented to dedicated sensor-network protocols as IEEE 802.15.4, and not on IEEE 802.11, which is much more widespread and cost-effective.

In this dissertation we propose a novel mechanism aimed at collecting data from buried nodes to an aboveground node, using the IEEE 802.11 standard at 2.4 GHz. Simulation results performed using ns-3 show an improvement of the delay and throughput vs. the standard data collection mechanism.

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David Lino

*“Art without engineering is dreaming;
engineering without art is calculating.”*

Steven K. Roberts

Contents

1	Introduction	1
1.1	Context	1
1.2	Motivation	2
1.3	Objectives	2
1.4	Document Structure	2
2	State of the Art	3
2.1	Wireless Underground Networks	3
2.2	WUN Radio Propagation Models	4
2.2.1	U2A Radio Propagation Model	4
2.2.2	A2U Radio Propagation Model	5
2.2.3	U2U Radio Propagation Models	6
2.3	IEEE 802.11	7
2.4	Research on WUNs	9
2.5	Data Collection Mechanisms for WUNs	10
2.6	Discussion	10
3	Proposed solution	11
3.1	Target Scenario	11
3.2	Data Collection Mechanism	11
3.2.1	Control and Data Messages	12
3.2.2	Detailed Description	13
4	Simulation Evaluation	17
4.1	Software Architecture	17
4.1.1	ns-3 Introduction	17
4.1.2	Wi-Fi Module	17
4.1.3	Propagation Module	18
4.1.4	Node Functions	18
4.2	Simulation Scenarios and Setup	18
4.2.1	Simulation Setup	19
4.3	Simulation Results	22
4.3.1	Simulation Description	22
4.3.2	Delay	22
4.3.3	Data Collection Loss Ratio	25
4.3.4	Aggregate Throughput	27
4.4	Discussion	28

5 Conclusions	31
References	33

List of Figures

2.1	<i>Generic WUN [1].</i>	3
2.2	<i>Illustration of the U2A channel model.</i>	5
2.3	<i>Illustration of the A2U channel model.</i>	6
2.4	<i>Illustration of the two-ray U2U channel model.</i>	7
2.5	<i>IEEE 802.11 MAC access mechanisms [2].</i>	7
2.6	<i>IEEE 802.11 MAC Architecture [2].</i>	8
2.7	<i>Mac Frame format.</i>	8
3.1	<i>Proposed Network Topology.</i>	12
3.2	<i>Underground header fields.</i>	13
3.3	<i>Packet flow when USNs are reached by the UMN.</i>	14
3.4	<i>Packet flow when no USNs are reached by the UMN.</i>	15
4.1	<i>Positions for 4 and 8 nodes.</i>	20
4.2	<i>Positions for 12 and 16 nodes.</i>	20
4.3	<i>Positions for 20 nodes.</i>	21
4.4	<i>Delay results for 4 and 8 nodes in sand soil.</i>	23
4.5	<i>Delay results for 12 and 16 nodes in sand soil.</i>	23
4.6	<i>Delay results for 20 nodes in sand soil.</i>	24
4.7	<i>Delay results for 4 and 8 nodes in sand soil.</i>	24
4.8	<i>Delay results for 12 and 16 nodes in sand soil.</i>	25
4.9	<i>Delay results for 20 nodes in loam soil.</i>	25
4.10	<i>Data Collection Loss Ratio results for sand.</i>	26
4.11	<i>Data Collection Loss Ratio results for loam.</i>	27
4.12	<i>Throughput results for sand.</i>	28
4.13	<i>Throughput results for loam.</i>	29

List of Tables

3.1	<i>Underground header Node field values and their semantics.</i>	13
3.2	<i>Underground header Control field vaues and their semantics.</i>	13
4.1	<i>Node functions.</i>	18
4.2	<i>Settings for the nodes used in the simulations.</i>	19
4.3	<i>Dielectric constant for loam and sand soil.</i>	19
4.4	<i>Mean distance between the buried nodes and the aboveground node.</i>	19

Acronyms

A2U	Aboveground-to-underground
AMN	Aboveground Master Node
AP	Access Point
CRC	Cyclic Redundancy Check
DCM	Data Collection Mechanism
DCF	Distributed Coordination Function
DCLR	Data Collection Loss Ratio
EDCA	Enhanced Distributed Coordination Function
EM	Electro Magnetic
FCS	Frame Check Sequence
HCF	Hybrid Coordination Function
HT	High-Throughput
MAC	Medium Access Protocol
MCF	Mesh Coordination Function
MI	Magnetic Induction
MMPDU	MAC management protocol Data Unit
MSDU	MAC Service Data Unit
NAV	Network Allocation Vector
OTA	Over-the-air
PCF	Point Coordination Function
PHY	Physical layer of the OSI Model
U2A	Underground-to-aboveground
U2U	Underground-to-underground
UMN	Underground Master Node
USN	Slave Node
VWC	Volumetric Water Content
WUN	Wireless Underground Networks
WUSN	Wireless Underground Sensor Networks

Chapter 1

Introduction

1.1 Context

Communications networks in underground environments find application in agricultural and sports fields, border patrol, and mining facilities. In all these cases, the buried nodes typically need to transfer data to a sink node. Thus, an appropriate data collection mechanism is needed. The development of cheap and easy to deploy wireless underground nodes can significantly reduce installation costs when compared to wired underground networks. Although in the case of wireless communications, the signal can be carried in Electromagnetic Waves (EM) or through Magnetic Induction (MI), MI technologies are not disseminated enough to be considered a cost-effective solution. Being Wi-Fi so disseminated and with the constant upgrade in low-power Wi-Fi solutions, using off the shelf IEEE 802.11 devices seems to be a suitable approach.

The concept of underground communications was proposed a few years ago [3]. It consists of a sender and a receiver both buried underground establishing a communication link through the soil. This concept was further extended to also include aboveground nodes [4]. In this case there are three different communication links: Underground-to-Underground (U2U), Aboveground-to-Underground (A2U), and Underground-to-Aboveground (U2A). In [5], the achieved results show that U2A channel as a higher range and better throughput than the A2U channel; both of these have better range than the U2U channel, with the burial depth playing a major role regarding the U2U link performance: the more deep in the soil, the more Volumetric Water Content (VWC) is present, and thus the channel suffers from more attenuation.

One of the major research challenges is managing channel access and ensuring communications through the soil, which has significantly greater attenuation and random channel variations due to various parameters, including VWC and soil texture [1], parameters that do not apply to wired channels or over-the-air (OTA) channels.

In terms of Wireless Underground Networks (WUN) based on EM communications, most recent researches focus on sensor networks, operating at 433 MHz, instead of 2.4 GHz, that have a higher deployment cost than a commodity router.

1.2 Motivation

Previous studies on WUNs are mostly focused on sensor networks and their performance. Consequently, there is a lack of studies regarding IEEE 802.11-based WUN; there is only a previous MSc [5] where the performance of an IEEE 802.11-based WUN has been evaluated. With the results achieved in such work and knowing the different variables that affect the propagation in the underground medium, such as VWC, communication direction (U2A or A2U), soil texture and rock density, a dedicated data collection mechanism is in order. Considering the costs of deploying and maintaining dedicated sensor modules and the lack of a suitable data collection mechanism for WUNs, this thesis proposes a multi-hop data collection mechanism targeting in particular agricultural scenarios and considering the asymmetry between A2U and U2A channels.

1.3 Objectives

The goal of this dissertation is to develop a multi-hop data collection mechanism that suits the underground communications scenario, facilitating communications from underground nodes to an aboveground sink node. To achieve this goal, the following specific objectives have been defined:

- Review technologies and fundamentals of signal propagation through soil and through the soil-air interface;
- Study experiments, proposed propagation models and IEEE 802.11 related research results of interest to our work;
- Study the available data collection mechanisms for WUNs;
- Evaluate if it is necessary to modify the IEEE 802.11 MAC in order to adapt it to the underground to aboveground communications scenario;
- Define how to maximize the data gathered by the protocol;
- Test and analyse the proposed solution versus a single-hop data collection mechanism through simulations in ns-3.

1.4 Document Structure

This document is organized in the following way. Chapter 2 presents the related work, the underground propagation models, and experiments that have been carried out so far for WUNs, as well as an overview of IEEE 802.11 MAC layer. Chapter 3 describes the proposed multi-hop data collection mechanism. Chapter 4 presents the results obtained using ns-3 simulations performed, considering our multi-hop data collection mechanism and the single-hop data collection mechanism. Finally, Chapter 5 draws the conclusions and points out the future work.

Chapter 2

State of the Art

In this chapter a definition of a Wireless Underground Network (WUN) is presented, followed by its applications and the related concepts, latest research in the area, underground propagation models, and the set of experiments done so far regarding WUNs based on standard wireless technologies. Also, IEEE 802.11 core MAC mechanisms are explained.

2.1 Wireless Underground Networks

Wireless Underground Networks (WUN) can be defined as a set of devices buried underground, which use a wireless technology to communicate. Contrary to the common wireless technologies we use everyday, where the propagation medium is the air, WUN nodes communicate mainly through the soil. A generic WUN is shown in Fig. 2.1.

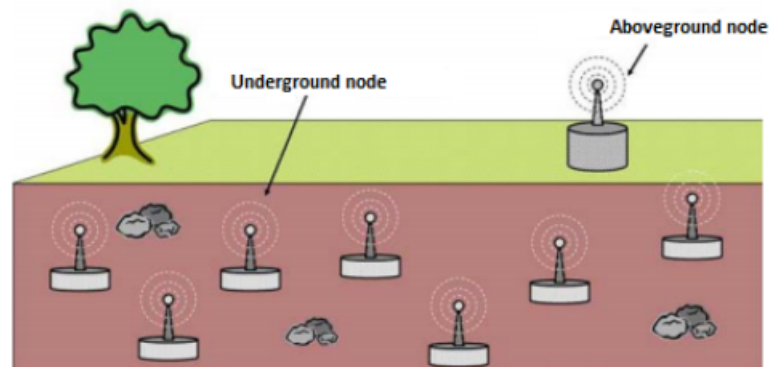


Figure 2.1: *Generic WUN [1].*

Communications through the soil can be severely limited by the soil and rocks lossy dielectric materials. Soil characteristics like volumetric water content, soil density, texture and mineral content directly affect its permittivity, permeability, and electrical conductivity. Signal frequency

also directly affects the radio wave path loss. Wet clay soil produces the most attenuation while dry sandy soil produces the least attenuation [3].

As described in [5] there are three different transmission cases when considering WUNs:

- **Underground-to-Underground (U2U)**. Communications between two buried nodes. In this case the propagation medium is the soil.
- **Underground-to-Aboveground (U2A)**. Communications from a buried node to an aboveground one. In this case the propagation medium is hybrid, soil and air.
- **Aboveground-to-Underground (A2U)**. Communications from an aboveground node to a buried node. In this case the propagation medium is hybrid, air and soil.

In the two last cases the propagation medium is both the soil and the air and the ground surface interface, can have a big impact on the communications link. As the signal has to cross this interface, high levels of reflection and attenuation exist, resulting in poor communications between nodes. Note that these effects are different depending on the communications direction the A2U channel suffers from more path loss than the U2A channel.

2.2 WUN Radio Propagation Models

In this section the propagation models for the U2A, A2U and U2U are presented along with the characteristic associated to each model.

2.2.1 U2A Radio Propagation Model

The U2A received signal path is composed by two parts [6], the underground path d_1 and the aboveground path d_2 , as shown in Fig 2.2. Note that due to the soils relative dielectric constant being much higher than the air, the signal is refracted at the soil to air interface. Also, all signals with an incident angle θ_1 higher than the critical angle θ_c will be completely reflected. The U2A path loss as defined in [6] is given by

$$P_{u-a}dB = P_u dB + P_a dB + 10 \log_{10} \left| \frac{1}{\nu e^{-j2\pi(d_1/\lambda + d_2/\lambda_0)}} \right|^2 \quad (2.1)$$

$$P_u = 6 + \log_{10} d_1 + 20 \log_{10} \beta + 8.69 \alpha d_1 - 10 \log_{10} G_a \quad (2.2)$$

$$P_a = 20 \log_{10} f + 20 \log_{10} d_2 - 147.56 - 10 \log_{10} G_b \quad (2.3)$$

where P_a represents the path loss for the aboveground part, P_u is the path loss for the underground part, and P_{u-a} is the path loss for the U2A link. The distance between the soil-air border and the aboveground node is represented by d_2 , G_b is the aboveground node antenna gain, d_1 is the distance between the underground node and the soil-air border, G_a is the underground node antenna gain,

α attenuation constant of soil, β is the phase constant, λ is the wave length in soil, λ_0 is the wave length in free space, ν is the refraction coefficient from soil to air and f the operating frequency.

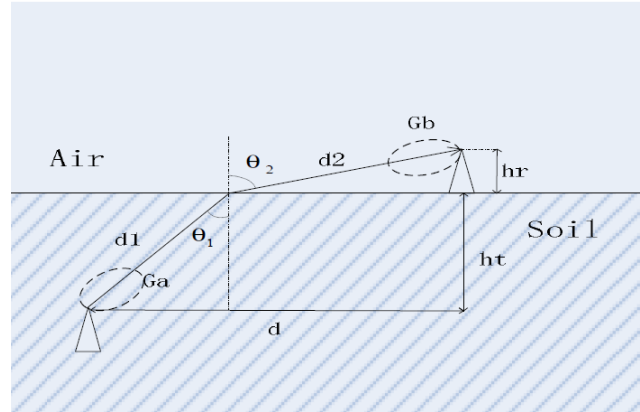


Figure 2.2: Illustration of the U2A channel model.

2.2.2 A2U Radio Propagation Model

Fig. 2.3 depicts the A2U communications scenario and the parameters considered by the model. Similar to the U2A channel model, the path loss of the aboveground to underground link is [6]:

$$P_{a-u}dB = P_a dB + P_u dB + 10 \log_{10} \left| \frac{1}{\nu e^{-j2\pi(d_1/\lambda_0 + d_2/\lambda)}} \right|^2 \quad (2.4)$$

$$P_a = 20 \log_{10} f + 20 \log_{10} d_1 - 147.56 - 10 \log_{10} G_a \quad (2.5)$$

$$P_u = 6 + \log_{10} d_2 + 20 \log_{10} \beta + 8.69 \alpha d_2 - 10 \log_{10} G_b \quad (2.6)$$

The parameters stated in this model have the same meaning as for the U2A propagation model.

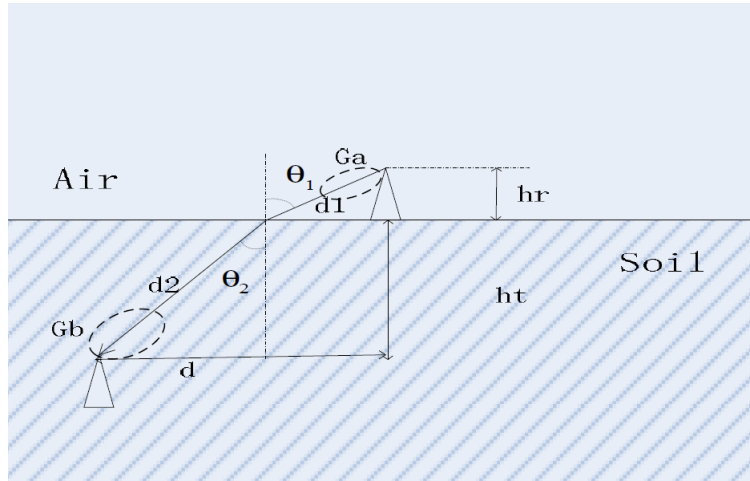


Figure 2.3: Illustration of the A2U channel model.

2.2.3 U2U Radio Propagation Models

Two U2U radio propagation models were considered for the U2U case. First, the Friis Propagation model, which considers only the direct path between nodes. The attenuation on the single path can be calculated using the following equation [7]:

$$P_{sl}dB = 6.4 + 20\log(d) + 20\log(\beta) + 8.69\alpha d - 10\log(G_a G_b) \quad (2.7)$$

where d is the distance between nodes, β is the phase shift constant, α is the attenuation constant. However, when considering the U2U communication scenario, one must also consider the wave reflected on the soil surface, as depicted in Figure 2.4. The authors of [8] propose a propagation model that takes into account this factor. The path loss depends on the reflection coefficient soil-air interface and on the burial depth, as nodes buried deeper will receive less of the reflected wave. The total path loss can be calculated using the following:

$$P_{fl}dB = P_{sl}dB - 10\log \left| 1 + \frac{\sqrt{G_c G_d} R d e^{-j\Delta\phi}}{\sqrt{G_a G_b} (r_1 + r_2)} e^{-j\Delta\phi} \right|^2 \quad (2.8)$$

where P_{sl} is the path loss calculated using the Friis model, $\Delta r = (r_1 + r_2 - d)$, $\Delta\phi = 2\pi(r_1 + r_2 - d)/\lambda$ and R is the reflection coefficient of the soil-air interface.

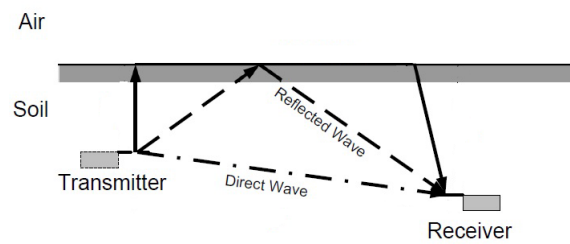


Figure 2.4: Illustration of the two-ray U2U channel model.

2.3 IEEE 802.11

The IEEE 802.11 protocol defines the MAC and PHY procedures for wireless connectivity for fixed, portable and moving stations. Its fundamental medium access method is a Distributed Coordination Function (DCF) known as *carrier sense multiple access with collision avoidance*. DCF is implemented in most common Wi-Fi networks, but a Point Coordination Function (PCF) can also be implemented; in PCF the Access Point (AP) handles when each station is free to access the medium, much like a regular polling function. Both these techniques are contention-based, as they differ from using the medium through back-off timers. Fig. 2.5 depicts IEEE 802.11 MAC access

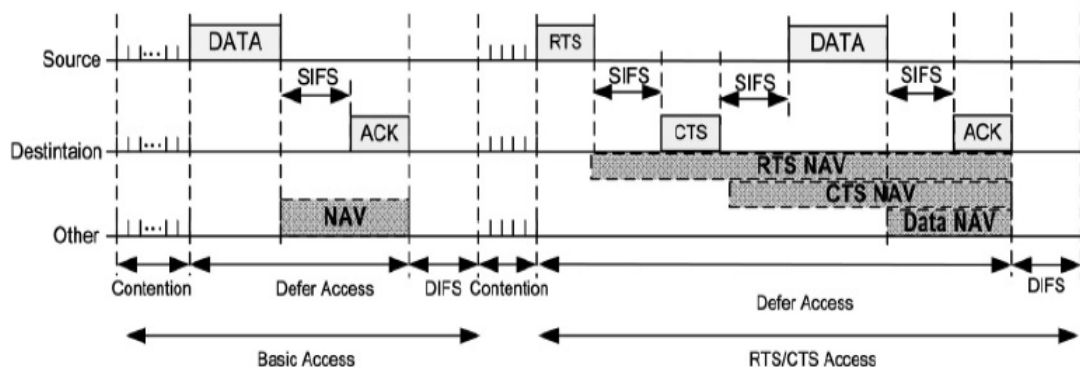


Figure 2.5: IEEE 802.11 MAC access mechanisms [2].

mechanisms. For QoS networks there is also the possibility of implementing an Hybrid Coordination Function where functions from DCF and PCF are used, with some enhancement. For mesh networks a Mesh Coordination Function (MCF) can be used. It can be used in contention-based mode with enhanced distributed channel access (EDCA) or contention-free using *MCF controlled channel access*. Figure 2.6 shows the MAC architecture in which PCF and HCF are functions of DCF. A station is said to be compliant with IEEE 802.11 when it is able to construct a subset of MAC frames and to decode a potentially different subset, upon validation of the frame in question. The subset of frames constructed or decoded by the station is determined by the functions it implements. There are three basic types of frames:

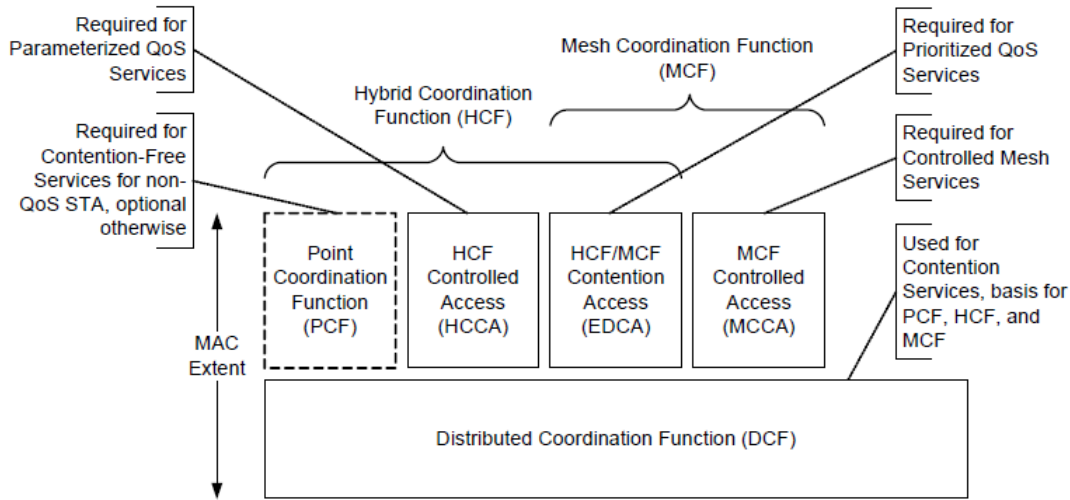


Figure 2.6: IEEE 802.11 MAC Architecture [2].

- *Data Frames*, carry higher-level protocol data;
- *Control Frames*, perform channel acquisition, carrier sensing and acknowledgement functions;
- A *Management Frames*, handle access point associations/handover and the access to wireless networks.

Each frame consists of three basic components:

- A *MAC header*, which includes frame control, duration, address, optional sequence control information, optional QoS control information and optional *High Transfer* control fields.
- A variable-length *frame body*, which contains information specific to the frame *type* and *subtype*;
- A *frame check sequence (FCS)*, which contains an IEEE 32-bit CRC. All stations must be able to validate frames using the FCS.

The MAC frame format comprises a set of fields that occur in a fixed order in all frames. Figure 2.7 depicts the general MAC frame format, which has a minimum length of 40 octets (excluding the frame body).

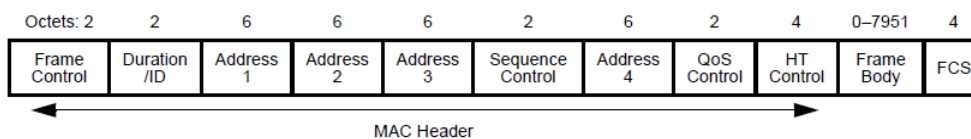


Figure 2.7: Mac Frame format.

The Frame Control holds information regarding the frames nature, its relation with the Distribution System, if there are other MAC service Data Units (MSDU) pending, if it is a retransmission, the power state of the transmitter and whether the frame was cryptographically encrypted. It is 16-bit in length. The Duration field is 16-bit length and mainly used for QoS purposes; the transmitting station calculates the amount of time required to transmit the frame and the receiving end uses this value as the basis for setting up his corresponding Network Allocation Vector. The four Address fields, each one containing a 48-bit address, are used to indicate the Basic Service Set Identifier, source address, destination address, transmitting station address and the receiving station address. A MAC sublayer address may be an *individual address*, an address associated with a particular station on the network, or a *group address* which can be either *broadcast* or *multi-cast*. The Sequence Number is a 12-bit field contains a fragment number and a sequence number. The sequence number is a 12-bit field indicating the sequence number of MSDU, aggregate MSDU or a MMPDU (MAC management protocol data unit). The fragment number indicates the number of each fragment associated with an MSDU. Each fragment contains a copy of the sequence number, which is unaltered throughout retransmissions. The QoS part is a 16-bit field, present when the subfield or subfield type is equal to 1, indicates to which traffic category or traffic stream the QoS frame belongs to as well various QoS-related information that varies with the frame type, subtype and type of transmitting station. The High-Throughput field is always present in a Control Wrapper frame and is present in QoS Data and management frames, determined by the Order bit of the Frame Control field. It is used to establish connections of 100 Mb/s and greater.

IEEE 802.11 already provides fragmentation and aggregation, Block ACK, No ACK, RTS/CTS and other techniques to further reduce collisions and improve bitrates.

2.4 Research on WUNs

Currently, there is research being done on WUNs, but mostly focusing on IEEE 802.15.4-based WUNs. In [3], experiments were carried out using MicaZ nodes from Crossbow, which operate at 2.4 GHz frequency with a transmitting power of 0 dB. They concluded that communication was impossible in the U2U case regardless of the buried depth, and obtained a maximum range of 2.5 meters at 0.13 meters of burial depth with almost complete path loss and a packet error ratio of 10% and 38%, in the A2U and U2A cases respectively, and 7 meters with a 0.06 meters burial depth. In of [9] the authors reinforced this statement and also performed test that showed a high temporal stability over a 24h period for the U2U channel when compared to the Over-the-Air (OTA) channel. Their experiments performed with the transmitter fixed at 40 cm underground, show that the receiver buried at 10 cm has worst RSSI than when buried at 0 cm, due to the reflections caused by the soil-air interface. This has also been concluded by means of simulation results presented in [7], where a two-path channel model is used to describe low depth deployments and a single-path model is assumed for high depth deployments. Further tests performed in [5] with a transmission power of 20 dB show a transmission range between two underground nodes in loamy soil to be 2.8, 2.2, 1.6 and 1.4 meters for a burial depth of 10, 20, 30 and 40 cm respectively.

Sandy soil shows ranges of 2.6 meters for a 20 cm burial depth and 2 meters for 40 cm burial depth. In [10] the authors tested three different carrier frequencies, 433 MHz, 868 MHz and 915 Mhz, at various depths and with different VWC. They concluded that the 433 MHz suffers the least path loss, 70dB when the node is buried at 0.6 meters. Their experiment also shows that for 15% VWC the path loss suffered by the 868 MHz band is nearly equal to that of the 915 MHz band.

2.5 Data Collection Mechanisms for WUNs

In [11] a system to monitor the underground water content of golf fields is presented. The authors propose a topology where an underground probe node communicates with an aboveground infrastructure node, with distances reaching from 6 to 62 meters. The authors ensured communication by transmitting in the 868 Mhz band and using a lightweight MAC to reduce the number of preamble transmissions, and thus, saving energy. Although the article is more focused in the soil water content results, the authors reinforce what is stated in [3] and [5] through measuring the number of packets received by the infrastructured nodes. They point out that starting in December, the number of packets received increases greatly, sometimes up to 4 times the expect number. This is due to the U2A channel having slightly better range and packet loss ratio than the A2U, the infrastructure aboveground node sending an acknowledgement to the underground probe node each time a packet is received and due to the rain in December increasing the soil's VWC.

Vuran and Tooker present in [12] a collection of protocols designed for wireless underground network sensors and in [13] a 48% energy reduction was achieved through *Dynamic Packet Length Control* schemes; even if not designed based on IEEE 802.11 this literature still holds valuable information for this research.

2.6 Discussion

In this chapter we defined WUNs, presented EM propagation models regarding the A2U, U2A and U2U scenarios and the research carried out in the WUN field. In addition, we analysed the IEEE 802.11 core mechanisms, and mentioned the data collection mechanisms for WUNs present in the literature. The literature states that the U2A channel has a better communication channel than the A2U channel, and both of them are better than the U2U channel. The experiments analysed also confirm that the 433, 868 and 915 MHz frequencies suffer from less path loss than the 2.4 GHz.

Although there is significant research in this field, there is almost no research considering IEEE 802.11 applied to wireless underground network, in particular regarding data collection mechanisms for this type of networks.

Chapter 3

Proposed solution

This chapter describes the new data collection mechanism proposed for Wi-Fi based Underground Sensor Networks. First, the target scenario is described. Afterwards, the control messages defined as part of the data collection mechanism are presented and finally a detailed description of the mechanism is given.

3.1 Target Scenario

As we referred in Chapter 1, although there are many cases where U2A/A2U and U2U are needed we decided to focus the application on scenarios with a varying topology, which are frequently found in agricultural fields, as opposed to scenarios with a static topology, namely infrastructure monitoring and border patrol.

The big difference between these topologies is how the information from the sensor nodes is obtained. Considering infrastructure monitoring, while planning the installation of sensor nodes on a buildings foundations one can previously determine the best position where the nodes will be placed and thus design it so maximum connectivity is ensured. While it is true that these positions can also be planned for an agricultural scenario the work carried out in these types of fields typically involve raking and ploughing, operations which normally rummage the soil. Because of this, even if the optimum positions are previously determined, it is likely that any underground nodes caught in the process will change their position. Thus the target topology for the proposed Data Collection Mechanism (DCM) is a moving aboveground sink node and a number of stationary underground node.

3.2 Data Collection Mechanism

The proposed mechanism is designed to maximize the data that a moving aboveground sink can obtain from buried nodes. Bearing in mind the scenario described in section 3.1 and that communications are more favourable in the U2A case, it can be concluded that typical single-hop mechanisms are not suitable for this kind of asymmetric communications when nodes are buried

deep, as RTS/CTS and ACK packets can easily be lost, increasing the number of unnecessary re-transmissions or even preclude any communications link between underground and aboveground nodes.

With these considerations in mind, we find it best to first assure that packets are delivered to an aboveground node. To ensure this, a double-hop, no ACK method is proposed. As shown in Fig. 3.1, we assume that there is only one Aboveground Master Node (AMN), an Underground Master Node (UMN) and a number of Underground Slave Nodes (USN) for each temporary network. The UMN must have the best channel to communicate with the AMN and be reachable at least by one USN. In order to cover a large area of underground nodes with only one mobile AMN, the UMN has to change periodically.

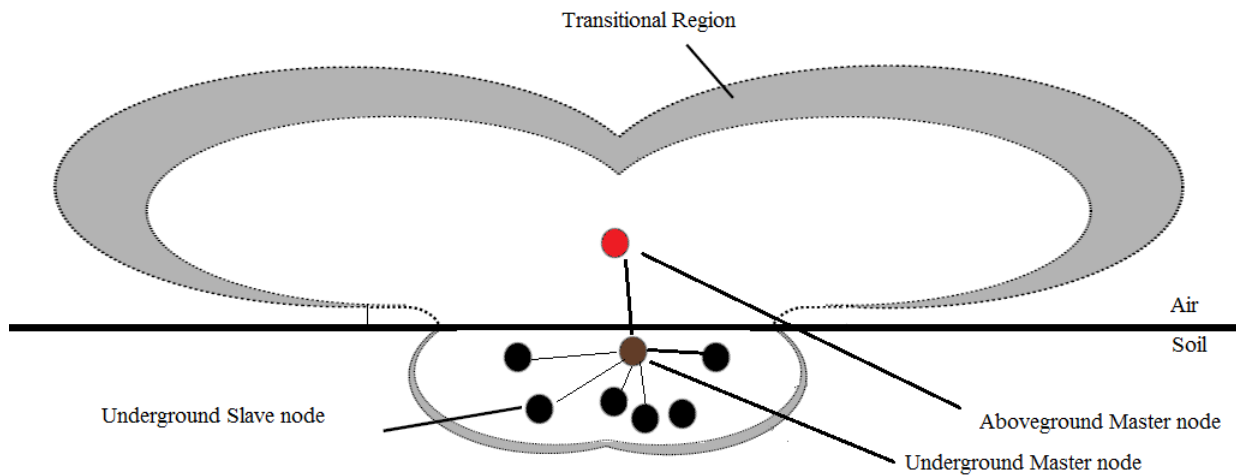


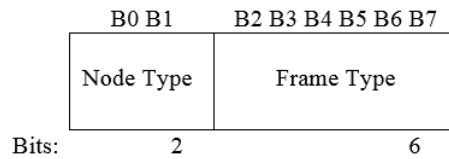
Figure 3.1: *Proposed Network Topology.*

When a USN needs to transmit, it first transmits to the UMN, which in turn transmits to the AMN the data frames from all the USNs that could reach him. If the user needs to identify the origin of the messages, a node tag must be added to the start of the USNs data messages. The control and data messages are sent in the Application layer, on top of UDP.

One of the most important features of the proposed solution is that it disables the Acknowledgements, and the retransmissions sent in lack of such, and the RTS/CTS mechanism used by the IEEE 802.11 MAC. This decision was made based on the fact that the A2U channel is worst than the U2A [1] and so the response messages of these mechanism are more prone to be lost than the messages that trigger them.

3.2.1 Control and Data Messages

In order to identify the source and the type of Control/Data message, the header shown in Figure 3.2 was defined. It is 1 byte in length and contains two fields:

Figure 3.2: *Underground header fields.*

- Node field: The type of node. Aboveground Master Node, Underground Slave Node or Underground Master Node;
- Control field: The type of message. Association Request, Association Response, No Neighbours and Data.

The following tables summarize the values both fields can assume.

Value (B0 B1)	Meaning	Description
0	AMN	Sending node is AMN
1	USN	Sending node is USN
2	UMN	Sending node is UMN
3	-	Unused

Table 3.1: *Underground header Node field values and their semantics.*

Value (B2 - B7)	Meaning	Description
0	ASSOC_REQ	Association Request
1	ASSOC_REP	Association Response
2	NO_NEIGHBOURS	Informs the AMN there are no neighbouring nodes
3	DATA	Frame contains application data
4 - 7	-	Unused

Table 3.2: *Underground header Control field values and their semantics.*

3.2.2 Detailed Description

This subsection details the data collection mechanism. All packets exchanged contain an Underground Header. The Figures 3.3 and 3.4 portray the packets exchanged when the mechanism successfully reaches the node and when it does not, respectively. The Node field (NF) is set according to the node that sends the packet. The Control field (CF) is set according to the last received packets CF and NF, as well as the receiver's NF, e.g. when a USN receives a message

with CF set to ASSOC_REQ and NF set to AMN it sets the CF of his response to ASSOC_REP while the NF is set to USN.

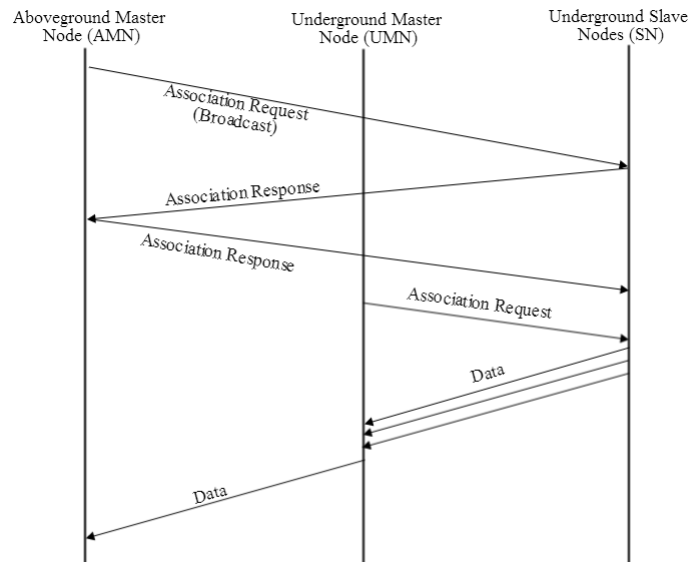


Figure 3.3: Packet flow when USNs are reached by the UMN.

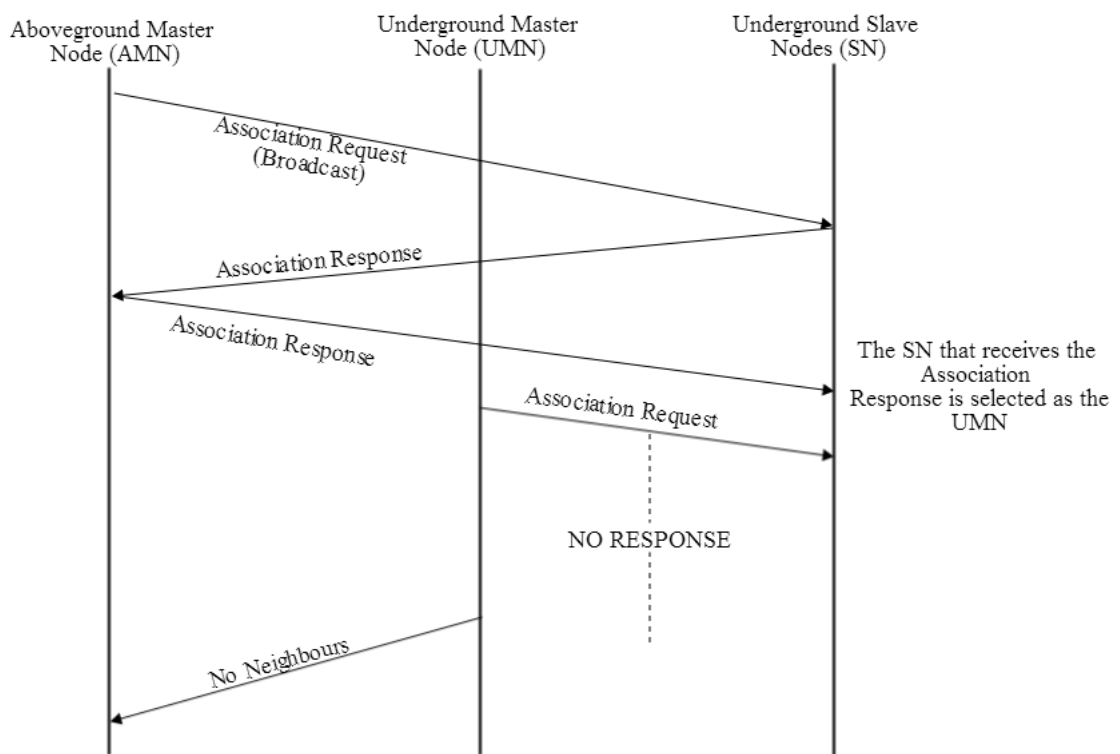


Figure 3.4: Packet flow when no USNs are reached by the UMN.

Chapter 4

Simulation Evaluation

In this chapter the work carried out to evaluate the solution proposed in Chapter 3 is presented. First, we present the software architecture, followed by the simulation scenarios and the simulation setup. Next, we present the results obtained by means of ns-3 simulation and finally, we compare the performance of the proposed data collection mechanism against the state of the art single-hop data collection mechanism.

4.1 Software Architecture

The data collection mechanism presented in Chapter 3 was implemented under ns-3. In this section, the software details regarding the implementation details are provided, starting by a description of the ns-3 Simulator operation and modules used, including the module added in [14], which is crucial to our simulation results, followed by the changes made to the stable distribution.

4.1.1 ns-3 Introduction

ns-3 is an opensource discrete-event network simulator. It is highly modular and customisable, making it one of the mostly used tools in network research and follows the OSI model. After creating a node, the user must sequentially install the various layers of the protocol stack. First, the interfaces (point-to-point, wireless, etc.), followed by the MAC layer, network layer, transport layer and finally, the application layer. The simulator contains modules for all of these layers and more, such as headers, trailers, and every other mechanism needed for the operation of a communications network. This modularity is suitable for adding features to an existing protocol, or simply for creating one from scratch. The alignment that ns-3 has with real-world interfaces due to the use of Unix libraries, allows our solution to easily be ported to an existing Wi-Fi device.

4.1.2 Wi-Fi Module

One of the main goals of this work was to remove ACKs from the Wi-Fi module, as they highly contribute to collisions and retransmissions [11]. In order to do so, the DCF and Transmission

operation files were changed, removing the lines issuing and waiting for ACKs. This change affects all ACKs issued by other protocols, such as ARP.

4.1.3 Propagation Module

In order to test our protocol in the underground medium, the propagation module must contain a model for soil propagation. The work developed in parallel [14] with this MSc was used to that purpose. To include these changes, the Delay and Path Loss files were changed. In them we can define the soils dielectric constant using its real and imaginary part.

4.1.4 Node Functions

The functions developed to implement the protocol are described in the following table.

Function	Description
void StartAMN()	Initiates the protocol by broadcasting an Association Request.
void StartUMN()	Initiates the UMN phase of the protocol by broadcasting an Association Request.
void ForwardUMN()	Forwards the data received by the UMN to the AMN in a DATA frame. If there are no neighbour nodes, NO_NEIGHBOUR frame is sent instead.
void CheckNeighbours()	Checks if there were responses to the UMN broadcast.
void ReceivePacketUMN()	Handles packet reception and defines the actions to take afterwards.
void ReceivePacketAMN()	Handles packets reception for the AMN and defines the actions to take afterwards.
void ReceivePacketUSN()	Handles packets reception for the USN and defines the actions to take afterwards.

Table 4.1: Node functions.

4.2 Simulation Scenarios and Setup

To fully evaluate the proposed data collection mechanism, it was tested both in sand and loam soils, with 5 different node topologies, starting with 4 nodes and progressing arithmetically to 20 nodes. The parameters used to configure the wireless nodes are presented below. They are based on the values used in [5].

4.2.1 Simulation Setup

The parameters set for every simulation were the following:

Node TX Power	Node RX Gain	Frame MTU	Rate adaptation algorithm	MAC
20 dB	0 dB	1500 bytes	AARF	IEEE 802.11g

Table 4.2: Settings for the nodes used in the simulations.

Soil type	Sand	Loam
Soils dielectric constant	7.0 + i0.6	4.5 + i1.7

Table 4.3: Dielectric constant for loam and sand soil.

4.2.1.1 Simulation Scenarios

The buried node positions for the simulations are determined by the first tested, where the topology is as presented in Figure 4.1a where the AMN is depicted as the red dot and the USNs are represented by the brown dots. The remaining topologies are presented in Figures 4.1b-4.3 are created by placing the nodes in the same place but shifting them by $\frac{d}{2}$ on the x -axis d is the horizontal distance between two nodes on the same axis. The AMN is always placed in the center. The slave nodes were buried at depths of 0.2 and 0.4 meters so that they do not completely overlap when repetitions of the topology occur. Figure 4.2a shows a case where there are 3 nodes on the same xx and yy coordinates, one of them being the AMN, where this difference of depth is crucial between two nodes on the same axis.

Table 4.4 presents the average absolute distance between each buried node and the above-ground node.

No. Buried nodes	4	8	12	16	20
Average distance (cm)	85.5	86.8	88.8	91.4	94.8

Table 4.4: Mean distance between the buried nodes and the aboveground node.

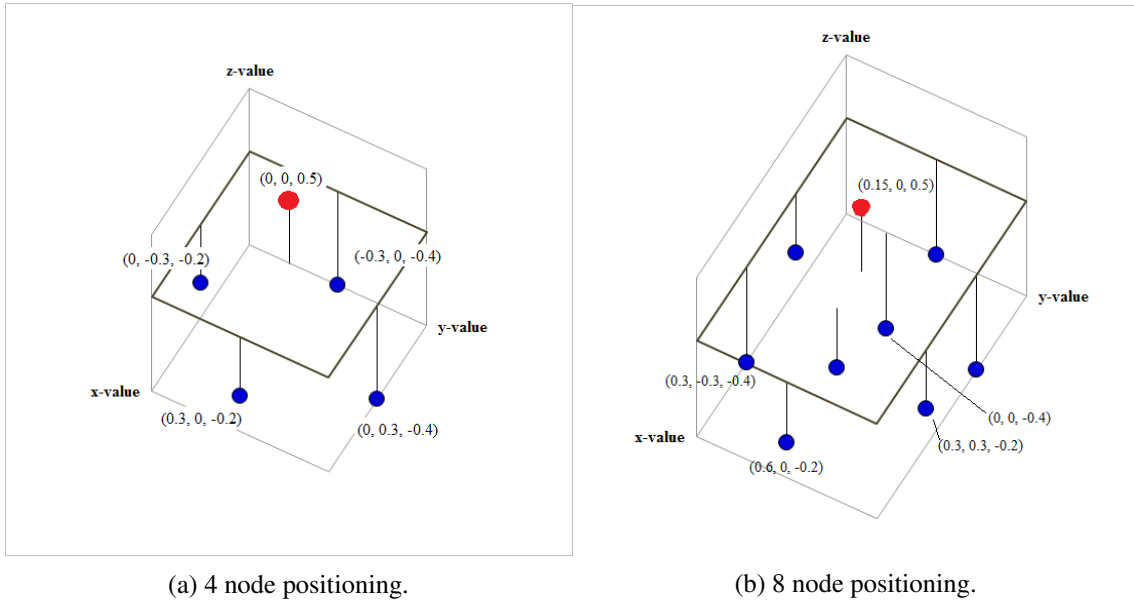


Figure 4.1: Positions for 4 and 8 nodes.

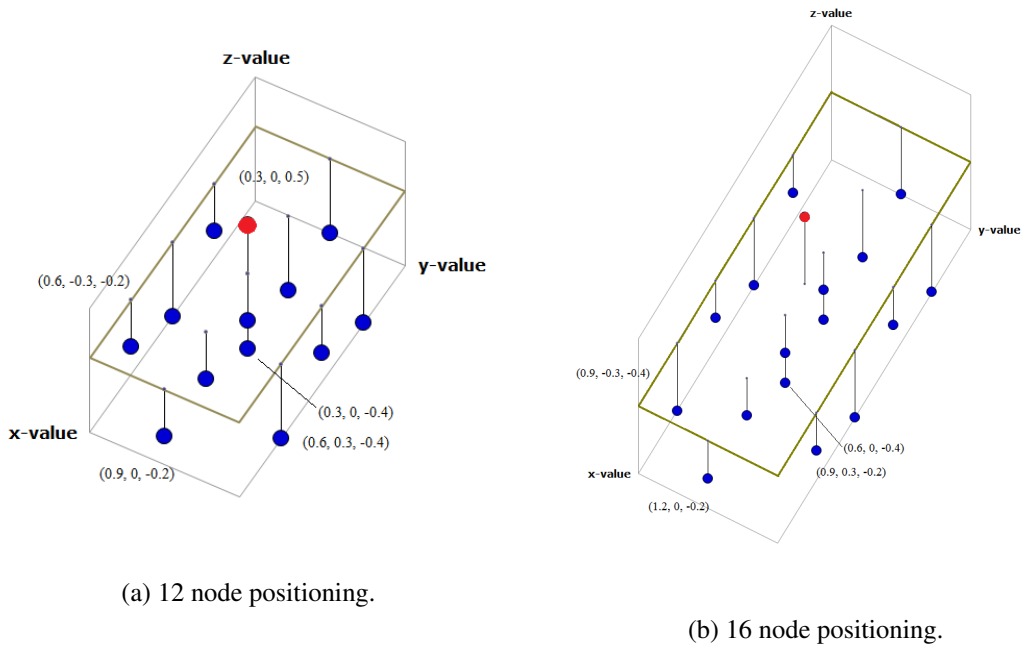


Figure 4.2: Positions for 12 and 16 nodes.

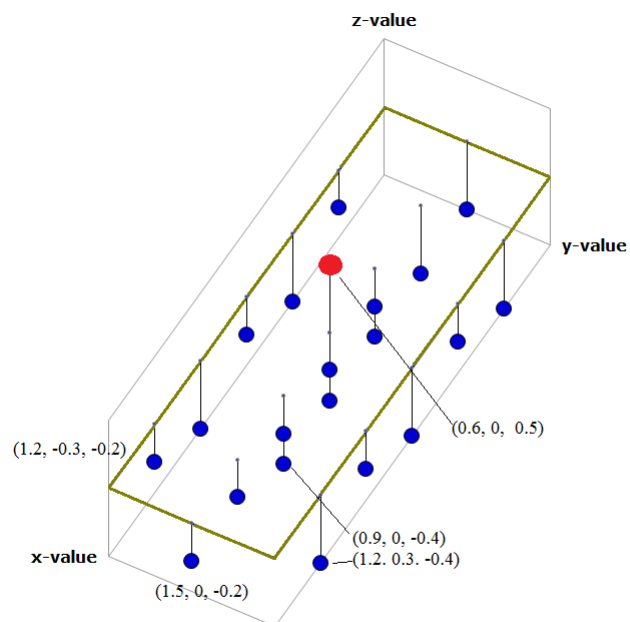


Figure 4.3: Positions for 20 nodes.

4.3 Simulation Results

In every simulation, all nodes have 512 bytes of data they want to transmit to the AMN. Each test was run 20 times with different seeds, giving the results presented in what follows. Simulation results for Delay, Packet Loss Ratio, and Aggregated Throughput are analysed for sand and loam soils. All simulation results for packet loss ratio and aggregate throughput are presented with a confidence interval of 95%.

4.3.1 Simulation Description

Assuming that a buried node has a range of 5 meters in loam soil [5] and that a tractor carrying the AMN is monitoring a field at 20 km/h (5.56 m/s), the buried nodes will have a 2 second time window to exchange all the messages needed to conclude the protocol.

The data collection begins with the AMN broadcasting a message with the Control field set to ASSOC_REQ. Each USN that is able to receive it will try to be elected as UMN by replying to the broadcast with the CF set to ASSOC_REP. The UMN node is then selected by order of arrival and receives confirmation from the AMN, which replies in unicasts a frame with CF set to ASSOC_REP. If the selected USN receives the ASSOC_REP message from the AMN, it becomes the UMN and broadcast a message with CF set to ASSOC_REQ informing its neighbours that they can now transmit data to him. It then waits for 2 seconds for the USN to transmit. All USN that received the broadcast will attempt to send any data they may have to the UMN, setting the CF to DATA. After two seconds, the UMN will send a message to the AMN with CF set to DATA and containing all the data that it received from USNs (Figure 3.3). Figure 3.4 represents the case when no data was received during the two second period, the CF will be set to NO_NEIGHBOURS, indicating that a new UMN must be chosen.

In order to have values to compare our DCM with, simulations using IEEE 802.11 MAC and UDP were performed. These simulations start with an aboveground sink node broadcasting a message and, in similar fashion to our solution, each underground node that successfully receives the broadcast will attempt to transmit its data to the aboveground sink. Note that in these simulations there were no changes made to the IEEE 802.11 standard.

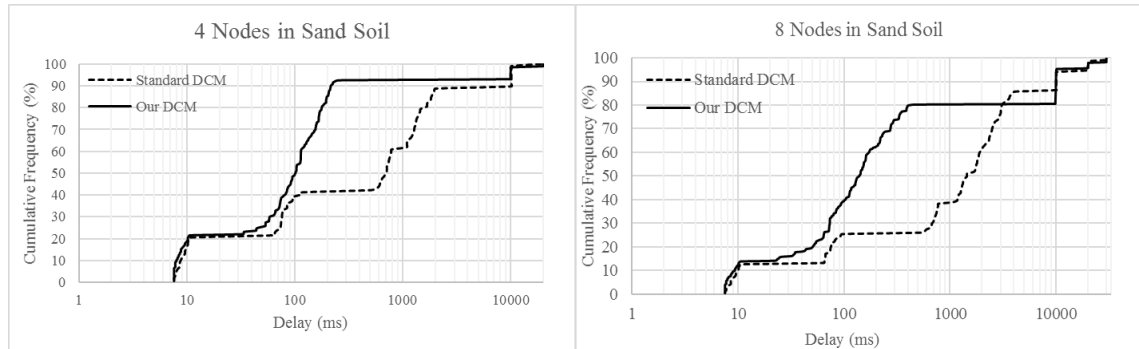
4.3.2 Delay

For each simulation, the delay values were obtained using ns-3's Flow Monitor module, which provides the end-to-end delay. Afterwards, the cumulative distribution function was plotted for each simulation scenario.

4.3.2.1 Sand Soil

Figure 4.4a shows us that 50% of the delay samples are smaller than 100 ms for our DCM against 700 ms for the standard DCM. When testing with 8 nodes our solution's median delay is 150 ms

while the standard DCM's was 1050 ms, as shown in 4.4b. Figure 4.5a shows that for 12 nodes our DCM has 170 ms of median delay and the standard DCM has 1900 ms. Figure 4.5b shows that for 16 nodes our DCM presents 192 ms of median delay while the standard DCM has 2085 ms. For 20 nodes our DCM's median is 241 ms against the 2656 ms of the standard DCM.

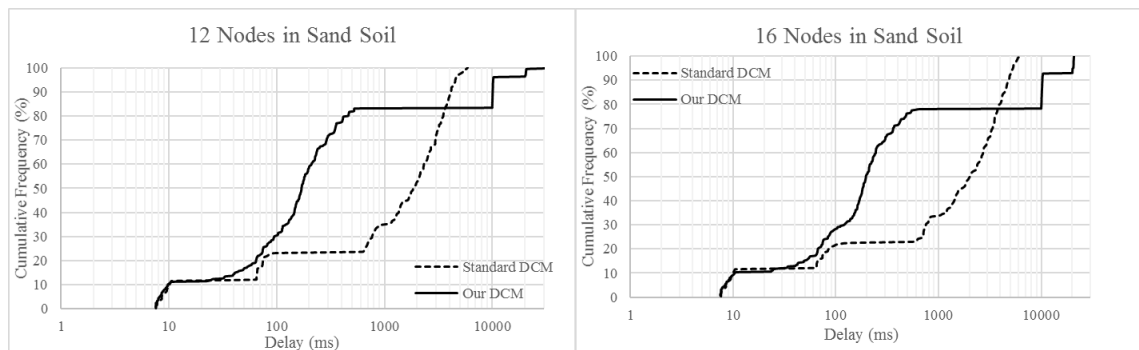


(a) Delay results for 4 nodes in sand soil

(b) Delay results for 8 nodes in sand soil.

Figure 4.4: Delay results for 4 and 8 nodes in sand soil.

From Figures 4.4a to 4.6 it can be observed that the median delay values for the standard DCM increase more than our solution. While the standard starts at 700 ms for 4 nodes and escalates up to 2085 ms for 20 nodes, our solution's lowest value is 100 ms and highest is 241 ms.



(a) Delay results for 12 nodes in sand soil

(b) Delay results for 16 nodes in sand soil.

Figure 4.5: Delay results for 12 and 16 nodes in sand soil.

The reason why the mean delay is so much lower for our solution when compared with the standard DCM is that the U2U links between the USNs and the UMN created by our protocol serve the same purpose as the direct U2A links in the standard DCM. As the U2U links created are shorter than the U2A links used in the standard DCM, it is expected for the mean delay to be lower.

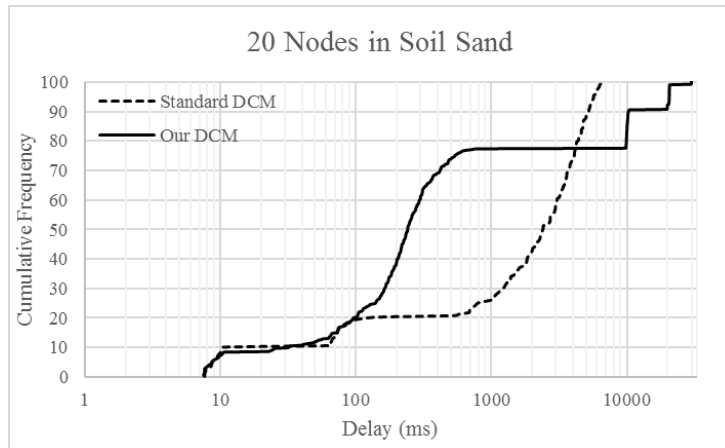
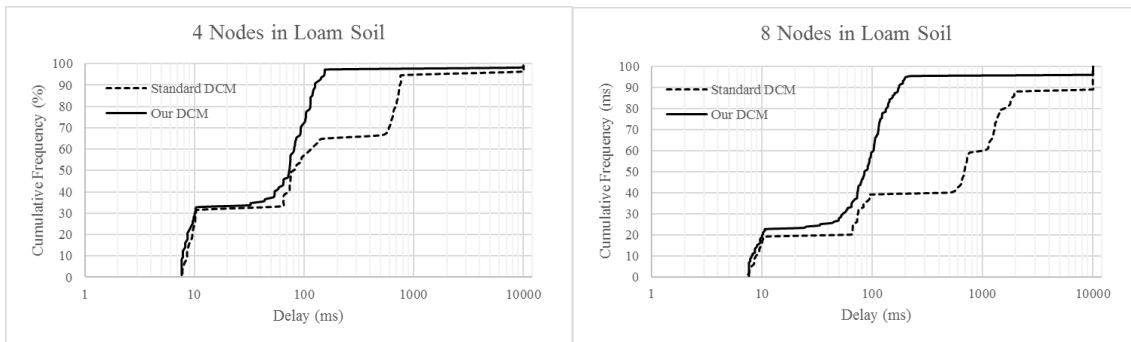


Figure 4.6: Delay results for 20 nodes in sand soil.

4.3.2.2 Loam Soil

The plot in Figure 4.7a shows that the median delay for both our solution and the standard DCM is 72 ms but the delay for the later increases rapidly, with 90% being under 740 ms against our solution's 125 ms.



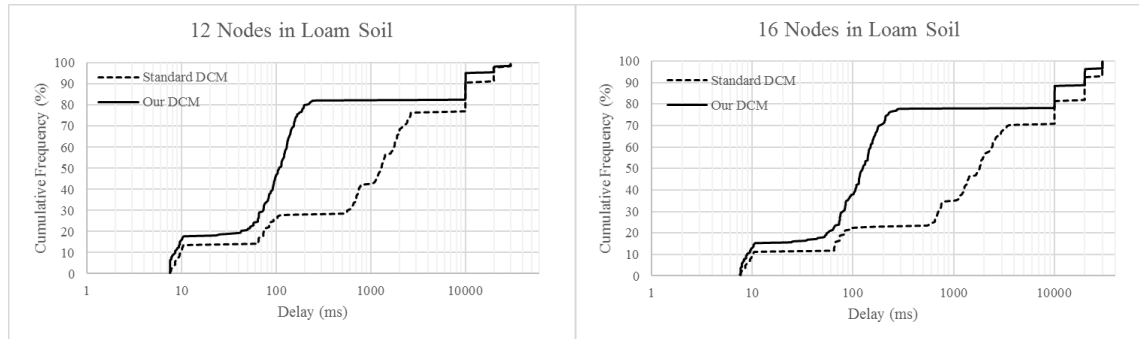
(a) Delay results for 4 nodes in loam soil

(b) Delay results for 8 nodes in sand soil.

Figure 4.7: Delay results for 4 and 8 nodes in sand soil.

For the 8 node test, our solution's median delay is 90 ms while the standard DCM's median delay is 682 ms. In the 12 node test the median delay increases slightly for our solution, being 112 ms, and almost doubles for the standard DCM, reaching 1258 ms. For the 16 and 20 node cases our solution reaches 125 ms and 144 ms respectively, against the 1800 ms and 1682 ms for the

standard DCM tests.



(a) Delay results for 12 nodes in loam soil

(b) Delay results for 16 nodes in sand soil.

Figure 4.8: Delay results for 12 and 16 nodes in sand soil.

The discrepancy in delay values for our solution and the standard DCM is due to the same reason pointed out for the sand soil tests. Still, the delay values for the loam soil are slightly better than the sand soil as opposed to expected. This happens due to the nodes buried deeper (40 cm), which are harder to reach in the loam soil than in the sand. As these nodes aren't reached sometimes the higher delay samples aren't obtained and thus the median delay is lower.

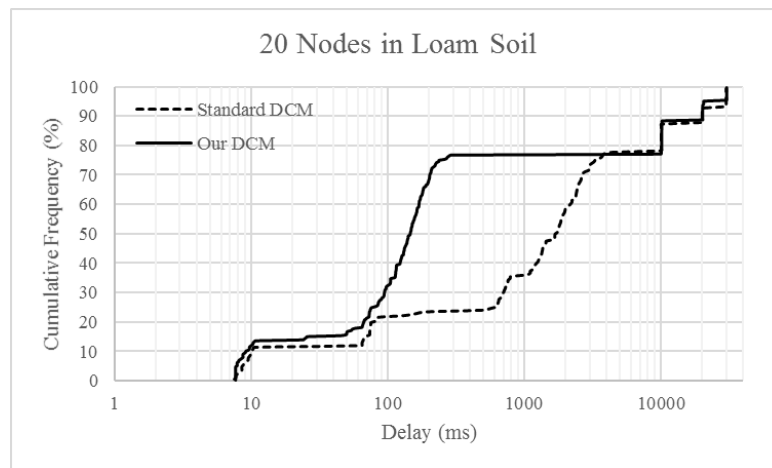


Figure 4.9: Delay results for 20 nodes in loam soil.

4.3.3 Data Collection Loss Ratio

The Data Collection Loss Ratio (DCLR) plots presented depict the percentage of nodes that were unsuccessful in transmitting their data.

4.3.3.1 Sand Soil

The DCLR results for sand presented in Figure 4.10 show that the standard DCM behaves better than our solution for topologies with less nodes, presenting only 4% DCLR vs. our solution's 8% for the 4 node case and 14% against 23% for the 8 node case. Further inspection of these results show that the number of nodes reached by each solution is the same, 2 nodes reached when 4 buried nodes are present and 4 when 8 nodes are present. Also, the cause for the extra DCLR presented by our solution is caused by the data packets sent from USN to UMN.

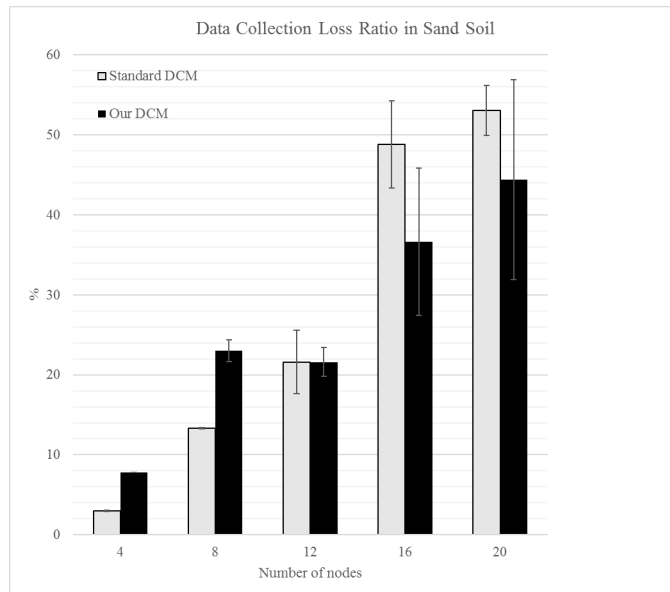


Figure 4.10: *Data Collection Loss Ratio results for sand.*

For the 12 node case the DCLR is the same for both mechanisms - 23% - increasing in the 16 node scenario to 48% for the standard DCM while our DCM obtains 36%. When testing with 20 nodes the standard DCM achieved 53% DCLR while our mechanism achieved 44%, though the standard deviation presented is quite high — 13%.

These results show that our DCM is arguably unnecessary for topologies with little nodes in sand soil, but shows a considerable gain when more nodes are present.

4.3.3.2 Loam Soil

Figure 4.11 shows the DCLR plot for loam soil. For the standard DCM, only the nodes least buried are reached, which is reflected by the 50% DCLR for 4, 8 and 12 nodes. For 16 nodes it increases to 55% and escalates to 75% for 20 nodes, situations when not even all the shallowest nodes are reached. The results presented by our solution are less predictable, starting at 50% for 4 nodes, 60% for 8 nodes and 44% for 12 nodes. From there on it jumps to 75% when 16 nodes are present and 77% for the 20 node test.

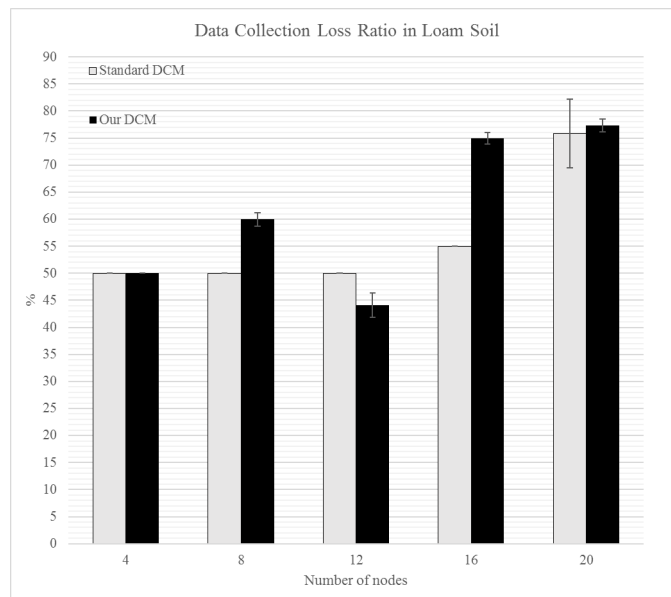


Figure 4.11: *Data Collection Loss Ratio results for loam.*

These results show that our DCM is on par with the standard DCM for the 4 and 20 node tests, being slightly better when 12 nodes are present. For the 8 and 16 nodes test the standard shows a 10 and 20% improvement, respectively.

4.3.4 Aggregate Throughput

The aggregate throughput for these experiments was calculated through the data provided by the Flow Monitor module, specifically through the TX bytes and Delay field. By converting the TX bytes to bits and dividing by the delay on each link we obtain the throughput relative to that link. An average of the throughputs in each simulation was obtained next. The plots presented in Figure 4.12 and Figure 4.13 relative to throughput are a representation of the average of the simulations average. The efficiency of both approaches can be observed in this representation; the more nodes reached the more traffic generated, hence more throughput is registered. Note that our protocol is expected to generate more traffic due to the Control messages exchanged and the data forwarding done from the UMN to the AMN.

4.3.4.1 Sand Soil

For the first simulation the standard DCM presents a throughput of 190 kbit/s while our protocol shows 390 kbit/s.

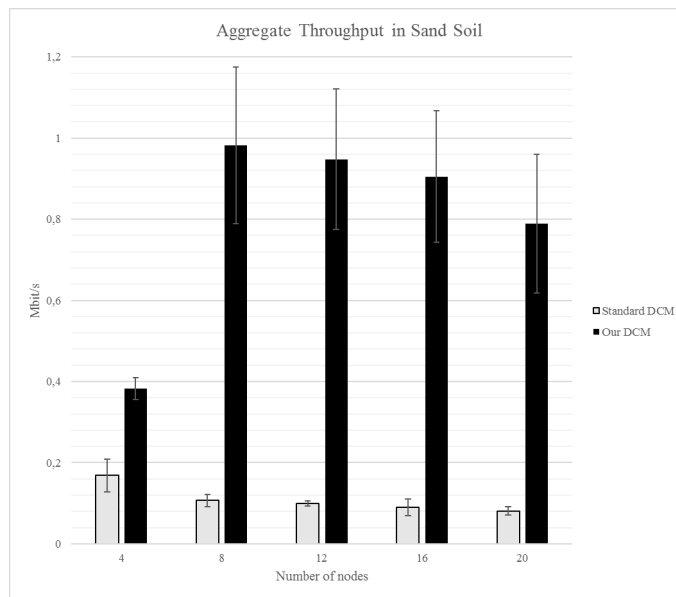


Figure 4.12: Throughput results for sand.

From here on the throughput obtained by our DCM starts at 980 kbit/s for the 8 node case and steady decays to 790 kbit/s. This represents a major increase in throughput and is a reflection of the protocols success due to using shorter links.

4.3.4.2 Loam Soil

The tests performed in loam soil show a considerable increase in throughput for our solution, outperforming the standard DCM in every scenario. Our solution starts at 450 kbit/s for the 4 node case and slowly descends to 390 kbit/s for the 16 node case while the standard DCM peaks at 290 kbit/s for 4 nodes and descends to 100 kbit/s. Although our solution shows an increase in the 20 node case, the standard deviation shows that it is likely that this value may lay between the 450 and 390 kbit/s range.

This confirms the conclusions first stated in section 4.3.3.2 that the nodes buried deeper aren't reached by the standard protocol. The throughput of our solution is lower due to the U2U channels, which have the worst propagation conditions, created from the USNs to the UMN.

4.4 Discussion

When analysing the results presented in this chapter the difference in performance between our solution and the standard DCM depend on the number of underground nodes. Testing with 4 nodes, our solution is arguably unnecessary for sand soil, as the DCLR is higher, but throughput and delay show major improvements. For loam soil our solution is better as it shows better delay and throughput, while the DCLR is the same. The results for 8 nodes tested in sand soil show that

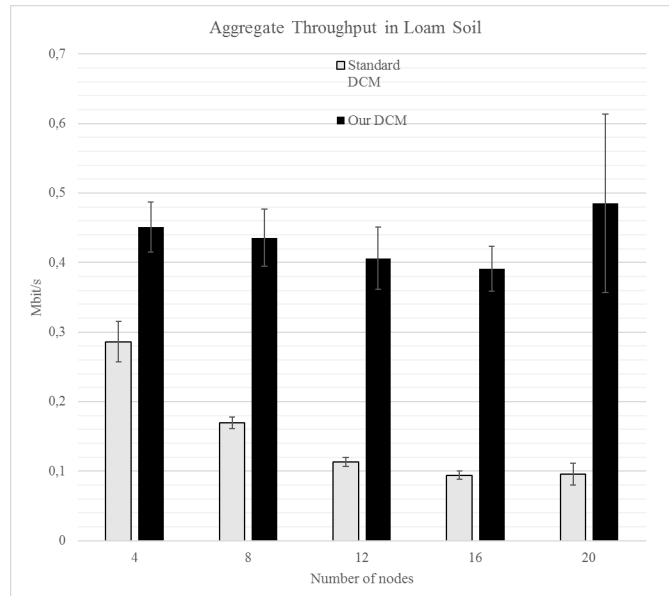


Figure 4.13: *Throughput results for loam.*

the delay is still better in our DCM and although the DCLR is worst, the throughput shows a significant increase. In the loam soil the delay and throughput are also better but the DCLR shows a 10% gain for the standard DCM. The 12 node test yields better results in the delay, throughput and DCLR metrics for our DCM in both soils. In the tests with 16 and 20 nodes our DCM outperforms the standard DCM in every metric, in both soils. We can then state that the 12 node scenario is the best for our solution, as it shows gains in all the metrics, in both soils. The fact that the links USN-UMN and UMN-AMN are shorter in our mechanism than the analogous USN-AMN in the standard solution are key to the improvement in delay achieved.

When considering a scenario with underground sensor nodes it is likely that a topology with high node density will be found. If we look specifically at an agricultural case, where the soil is normally loam-like, the advantages gained by our DCM are significant.

Chapter 5

Conclusions

As today's underground sensor applications increase in number, so does the importance of an adequate data collection mechanism for Wireless Underground Networks, as WUNs are cheaper and easier to maintain and deploy. Most of the research done so far focuses on using IEEE 802.15.4 and ZigBee technologies as a basis [3], which are more costly than Wi-Fi. So far, the contributions to this topic state that the Underground-to-Aboveground channel has better stability and range than its counterpart.

This MSc thesis proposed a multi-hop data collection mechanism adapted to these unique features, implementing a double-hop communications method without acknowledgements. The results obtained through simulation show a significant gains in Delay, PLR and Aggregated Throughput when compared to a single-hop data collection mechanism running over IEEE 802.11.

As future work, we still feel there is a plethora of behaviours displayed by EM waves in the underground medium that need to be better understood and that some aspects of the data collection mechanism can still be improved:

- **Add an adaptive rate algorithm for the first broadcasts**, starting with the highest rate and lowering it until an UMN is found. This would ensure that the node with the best possible data rate would become the UMN, increasing the throughput obtained and possibly reaching more neighbour nodes;
- **Adding a contention window to the SN to reduce the number of interferences when transmitting to the UMN**. As the node density increases, so does the probability of collision and of the hidden node problem occurring. A contention window can possibly reduce the occurrence of these problems;
- **Testing the application with a mobile AMN**. The simulations performed had the goal of testing the data collection mechanism at an early stage, and so the tests were ran with a fixed AMN. By testing with a moving AMN we expect to obtain better results when comparing with the standard DCM.

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