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Ns-3 Simulation Model for Underground Networks

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Abstract

Underground communications networks have many interesting applications such as border surveillance, agriculture monitoring and infrastructure monitoring. The first networks used in these applications were wired networks, but recent studies have shown that wireless underground networks are feasible and have deployment advantages.

Wireless underground networks can have nodes buried in the soil, which establish communication between them or have some nodes aboveground as data sinks; in the later case, the communication is between aboveground and underground devices.

The goal of this dissertation is to study propagation models for the communication scenarios where at least one of the nodes is buried and then develop a simulation environment for wireless underground networks based on ns-3 simulator, using those propagation models as basis. As a final step the developed simulation environment will be validated by simulating some experimental scenarios found in literature and comparing the simulation results against the experimental results previously obtained. This will also be used to conclude about the accuracy of the simulator.

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Acronyms

A2U	Aboveground-to-underground
AODV	Ad hoc On-Demand Distance Vector
DSS	Direct Spread Spectrum
EM	Electromagnetic
FEC	Forward Error Correction
GRMDM	Generalized refractive mixing dielectric model
LTE	Long Term Evolution
MAC	Medium Access Control
MBSDM	Mineralogy-based soil dielectric model
MSc	Master of Science
Ns-3	Network simulator 3
OFDM	Orthogonal Frequency Division Multiplexing
OLSR	Optimized Link State Routing Protocol
OTA	Over-the-Air
SMDM	Semi-empirical dielectric model
U2A	Underground-to-aboveground
U2U	Underground-to-underground
WiMax	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Network
WUN	Wireless Underground Network
WUSN	Wireless Underground Sensor Network

Chapter 1

Introduction

1.1 Context

Underground communications are common in mines and tunnels. In the past years the research work has been increasing in this area. Although these scenarios are different from the aboveground over-the-air (OTA) communications, the propagation medium is still the air. Wireless communications through soil with applications such as agriculture and maintenance of playing fields are an emerging topic. Since this type of communications involve using the soil as the propagation medium, new propagation models have to be created and new challenges have to be addressed. The soil is characterized by several properties that we need to take into account, such as texture and water content. In particular, the water content is a property that depends on the weather and so it can vary from low water content in a sunny day to high water content in a rainy day.

A wireless underground network typically includes underground and aboveground nodes, as we can see in the Figure 1.1

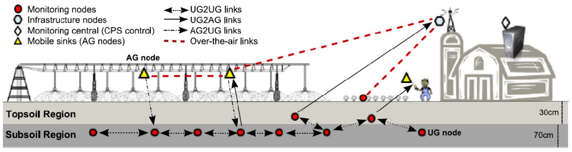


Figure 1.1: Example of a wireless underground network with aboveground and underground nodes. [1]

Although there is significant research work produced in the last years, wireless underground networks are an emerging topic and there are still many challenges and problems to be addressed.

1.2 Motivation

A number of research works have been made in the past few years regarding wireless underground communications because they revealed to be a good alternative to wired solutions. However, the propagation medium is the soil, the communications properties vary from soil to soil, and the amount of water also has significant influence in the propagation; for instance, the medium characteristics will vary a lot with weather conditions.

In order to overcome the difficulties to design a network of this type we need to be able to simulate the target network for several scenarios. Then, with the results we can determine, for example, the minimum distance between nodes that can guarantee connectivity between nodes for different amounts of water in the soil. Also, before doing field experiments, new wireless underground networking solutions need to be evaluated in simulations, for the sake of easy control of the tests. These difficulties in design a network are mainly due to the non-existence of simulators for these scenarios.

The Ns-3 will be the simulator chosen for implement the simulation environment for underground networks because it is widely used by the research community including our research group. This implementation in a network simulator is an important step when designing new networking solutions for this environment and also for research purposes.

1.3 Objectives

The goal of this dissertation is to develop a new simulation model for ns-3 that allows simulation of wireless underground networks for different frequencies, types of soils and depths of the nodes. The ns-3 model has to be able to simulate communications between buried nodes and between buried nodes and aboveground nodes. To achieve this goal the work was divided into some specific objectives:

- Study the major properties characterizing the soil and models;
- Study some experiments and the existing radio propagation models for underground networks;
- Study the ns-3 simulation environment, in particular the methodology that shall be used to implement and add new models to the simulator;
- Implement the propagation models in ns-3;
- Simulate the same experimental scenarios found in literature and compare the obtained results with the documented ones;
- Conclude about the accuracy of the implemented wireless underground simulation environment.

1.4 Document Structure

This document is organized in five chapters. Chapter 2 presents the state of the art in Wireless Underground Networks (WUN) and the ns-3 network simulator. Chapter 3 shows the methodology that will be used in order to achieve the goals described in this chapter. Chapter 4 describes the work plan. Finally, Chapter 5 draws the major conclusions.

Chapter 2

State of the art

In this chapter we present the state of the art on wireless underground networks. We start by defining some concepts about these networks, and point out some recent applications. Then, we present the major radio propagation models in underground networks, and also soil models for estimate the soil dielectric constant. We also make an introduction to wireless networks in tunnels and caves for the sake of completeness. Next, we present the ns-3 network simulator, since it will be the simulator used as a basis to develop the simulation environment for WUNs, and we discuss some important aspects of ns-3 in order to justify its use. Finally, we discuss the major topics presented in this chapter.

2.1 Wireless Underground Networks

Wireless Underground Networks (WUN) are networks in which some or all the nodes are located underground and use some wireless technology to communicate with each other. The communication medium is the soil or hybrid (soil plus air) when some of the nodes are located aboveground.

Since the medium in WUNs is different from the traditional wireless networks it requires the definition of new propagation models, which have been proposed in the past few years. This type of networks are mainly implemented with sensors that are monitoring some variable or process. For this reason they are also called Wireless Underground Sensor Networks (WUSN) because they are an extension of the traditional Wireless Sensor Networks (WSN). There are several applications of WUSNs to improve some sort of monitoring [8]:

- **Agriculture** — sensors can be used to monitor the soil parameters, such as water content, mineral content, salinity, and temperature, and then communicate these values in real time to a control station aboveground, in order to have soil parameters in optimal values. This type of monitoring can also be used in sports fields;
- **Security** — sensors buried at a shallow depth can detect movement at the surface. This is useful for home security as well as military applications such as border patrol. Although

this tasks can be done with aboveground sensors they benefit if they are underground since in this case they remain hidden;

- **Infrastructure Monitoring** — a WUN can be used to monitor underground plumbing leakage as well as electrical and communication wiring.

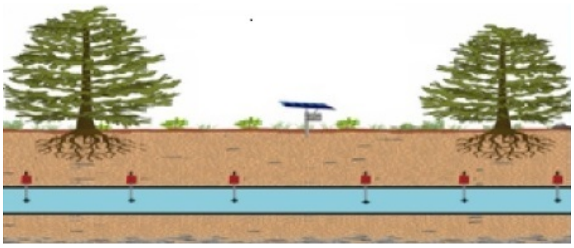


Figure 2.1: Example of WUN used in agriculture. [2]

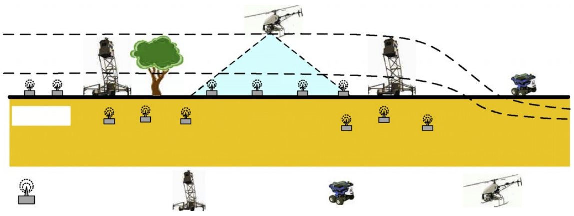


Figure 2.2: Hybrid wireless sensor network for border patrol. [3]

Compared to wired underground networks, WUN has some advantages: they are easier to deploy since the nodes don't require a physical connection with each other and they are harder to detect because there are no cables connecting the nodes.

2.2 Wireless Underground communication scenarios

In a wireless underground network there are buried nodes that communicate between them using the soil as propagation medium, but there are also aboveground nodes communicating with underground nodes; in the later case, the propagation medium is hybrid (the soil and the air). Assuming bidirectional communication we will see that between a node aboveground and a node underground the link aboveground-underground is different from the link underground-aboveground and, for that reason we consider three different scenarios as we can see in the figure 2.3:

- **Underground-to-underground (U2U)** — Communication between two nodes when both of them are buried underground. In this scenario the propagation medium is always the soil. This scenario is used in multi hop underground networks;
- **Aboveground-to-underground (A2U)** — Communication between an aboveground node (the sender) and an underground node (the receiver). In this scenario the propagation

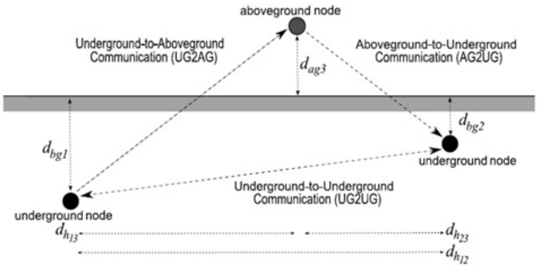


Figure 2.3: Types of communications in WUNs. [4]

medium is hybrid. This link is typically used to send control information to the underground nodes;

- **Underground-to-aboveground (U2A)** — In this link the underground node is the sender and the aboveground the receiver. The propagation medium is hybrid. This link is normally used to send the data measured to the aboveground data station that behaves as a data sink.

2.3 Underground channel models for WUNs

In this section we present the propagation models for the three different links referred in Section 2.2. Since the soil is a very different medium compared to the air we also present models to estimate its dielectric properties based on water content, percentage of sand and clay, and the frequency used for transmission. In turn, these models are important to estimate the parameters of the radio propagation models.

2.3.1 Dielectric soil properties model

In order to estimate the soil dielectric constant first we need to classify the kind of soil that we are using, which can be done by collecting a sample of that soil and analyse it in a laboratory to measure the percentage of sand, clay and silt. Based on these three parameters we can classify the soil using the texture triangle that is presented in the Figure 2.4.

Besides these three parameters the soil also has an amount of water which can be expressed as the Volumetric Water Content (VWC) that represents the fraction of water in the soil sample; as a final input parameter for the dielectric model, we need the operating frequency.

In [9] the authors compare the semi-empirical mixing dielectric model (SMDM) proposed by Dobson and the generalized refractive mixing dielectric model (GRMDM) in terms of their precision for determining the soil dielectric constant of several types of soils, including types of soils used to build the model and other types of soils. They conclude that the SMDM model is not very accurate for types of soils other than those used to derive the model. The GRMDM prove to be much more accurate in these tests, because it has the same accuracy to estimate the dielectric constant of the soils used to build the model but specially because it has much more accuracy when it comes to other soil types that are not the ones used to build the model.

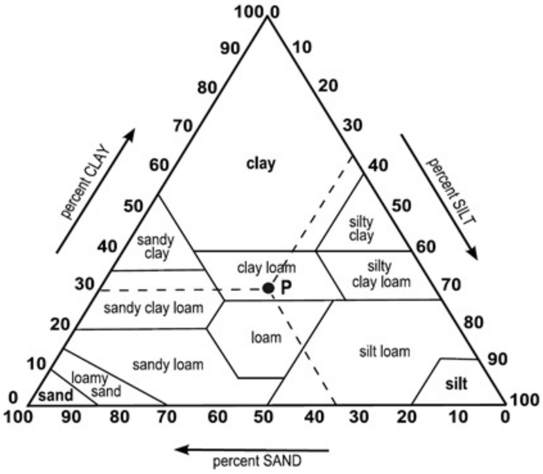


Figure 2.4: Soil texture triangle. [2]

The authors also present a model based on the GRMDM but with extra equations (Equation 2.9 to 2.17) to estimate some parameters that the GRMDM model requires to be measured. This model, named mineralogy-based soil dielectric model (MBSDM), is described below and is the one we selected to be our model to estimate the soil dielectric constant. The selection is based on the simplicity of the SMDM model, which uses only the percentage of clay as input [9] and [10].

$$\varepsilon' = n_m^2 - k_m^2 \tag{2.1}$$

$$\varepsilon'' = 2n_m k_m \tag{2.2}$$

According to this model the complex dielectric constant $\varepsilon = \varepsilon' + j\varepsilon''$ can be calculated using the Equations 2.1 and 2.2 respectively, where ε' is the dielectric constant and ε'' is the loss factor. The parameters n_m and k_m can be calculated as follows:

$$n_m = \begin{cases} n_d + (n_b - 1)m_v, & \text{if } m_v \leq m_{vt} \\ n_d + (n_b - 1)m_{vt} + (n_u - 1)(m_v - m_{vt}), & \text{if } m_v > m_{vt} \end{cases} \tag{2.3}$$

$$k_m = \begin{cases} k_d + (k_b - 1)m_v, & \text{if } m_v \leq m_{vt} \\ k_d + (k_b - 1)m_{vt} + (k_u - 1)(m_v - m_{vt}), & \text{if } m_v > m_{vt} \end{cases} \tag{2.4}$$

The parameters n_m, n_d, n_b, n_u and k_m, k_d, k_b, k_u are the values of the refractive index and normalized attenuation coefficient. The subscripts m,d,b,u stand for moist soil, dry soil, bound soil water and free soil water respectively. The rest of the n and k parameters can be calculated using the following equations:

$$n_{d,b,u}\sqrt{2} = \sqrt{\sqrt{(\varepsilon'_{d,b,u})^2 + (\varepsilon''_{d,b,u})^2} + \varepsilon'_{d,b,u}} \tag{2.5}$$

$$k_{d,b,u}\sqrt{2} = \sqrt{\sqrt{(\varepsilon'_{d,b,u})^2 + (\varepsilon''_{d,b,u})^2} - \varepsilon'_{d,b,u}} \tag{2.6}$$

The $\varepsilon'_{d,b,u}$ are the real part of the dielectric constant of dry soil, bound water and free water respectively. The imaginary part of the dielectric constants are expressed with the $\varepsilon''_{d,b,u}$. This model also present expressions for calculating the dielectric constant for bound water and free water which are present next:

$$\varepsilon'_{b,u} = \varepsilon_\infty + \frac{\varepsilon_{0b,0u} - \varepsilon_\infty}{1 + (2\pi f \tau_{b,u})^2} \tag{2.7}$$

$$\varepsilon''_{b,u} = \frac{\varepsilon_{0b,0u} - \varepsilon_\infty}{1 + (2\pi f \tau_{b,u})^2}(2\pi f \tau_{b,u}) + \frac{\sigma_{b,u}}{2\pi\varepsilon_0 f} \tag{2.8}$$

The f is the wave frequency, the values of $\sigma_{b,u}$, $\tau_{b,u}$ and $\varepsilon_{0b,0u}$ are the conductivities, relaxation times and low frequency limit of dielectric constant for bound water and free water respectively. The GRMDM model uses the equations present above from 2.1 to 2.8. With these equations we can estimate the dielectric properties of the soil we are considering, but for doing that we need the following soil parameters:

- Real (ε'_d) and Imaginary (ε''_d) parts of the complex dielectric constant for dry soil;
- Value of the maximum bound water fraction (m_{vt});
- Low frequency limits of dielectric constant for bound water (ε_{0b}) and free water (ε_{0u});
- relaxation times for bound water (τ_{0b}) and free water (τ_{0u});
- conductivities for bound water (σ_{0b}) and free water (σ_{0u}).

The value ε_0 is the dielectric constant for free space and ε_∞ is the high frequency limit which is equal to 4.9 for bound and free water.

Now that the GRMDM model was presented and we conclude that we need a significant number of parameters to use it, like the dielectric constant of the soil we are using without the presence of water (dry soil) we conclude that the model is not very easy to use when compared with the SMDM model proposed by Dobson, which requires only the sand and clay percentage of the soil.

After the analysis of this model and its requirements we will present next some equations that allow us to estimate the input parameters of the GRMDM model based only on the clay mass percentage of the soil so that this model (named MBSDM) can be as easy to use as the SMDM [9].

$$
\begin{aligned}
n_d &= 1.634 - 0.539 * 10^{-2}C + 0.2748 * 10^{-4}C^2 && (2.9)\\
k_d &= 0.03952 - 0.04038 * 10^{-2}C && (2.10)\\
m_{vt} &= 0.02863 + 0.30673 * 10^{-2} && (2.11)\\
\varepsilon_{0b} &= 79.8 - 85.4 * 10^{-2}C + 32.7 * 10^{-4}C^2 && (2.12)\\
\tau_b &= 1.062 * 10^{-11} + 3.450 * 10^{-12} * 10^{-2}C && (2.13)\\
\sigma_b &= 0.3112 + 0.467 * 10^{-2} && (2.14)\\
\sigma_u &= 0.3631 + 1.217 * 10^{-2}C && (2.15)\\
\varepsilon_{0u} &= 100 && (2.16)\\
\tau_u &= 0.5 * 10^{-12} && (2.17)
\end{aligned}
$$

With the complex dielectric constant of the soil estimated we can determine the propagation constant $\gamma = \alpha + j\beta$, where the α is the attenuation constant and β is the phase constant, using Equations 2.18 and 2.19.

$$
\begin{aligned}
\alpha &= \omega\sqrt{\frac{\mu\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}, && (2.18)\\
\beta &= \omega\sqrt{\frac{\mu\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1\right]} && (2.19)
\end{aligned}
$$

2.3.2 Underground-to-underground propagation model

The characterization of the underground channel is very important for designing new WUSNs and developing new protocols and mechanisms, such as new medium access control (MAC) optimized for underground communications. Here we present some models to estimate the underground-to-underground channel attenuation, which will then be used to create the ns-3 simulation model.

The simplest model is based on the Friis propagation model for free space and consists on taking into account the attenuation based only on the distance between the nodes. The Friis equation estimates the received signal strength at a distance d and can be written in the logarithmic form as follows [11]:

$$P_r = P_t + G_r + G_t - L_0 \tag{2.20}$$

where P_t is the transmission power, G_r and G_t are the gains of the receiver and transmitter antennas, respectively, and L_0 is the path loss in free space which is given by

$$L_0 = 32.4 + 20log(d) + 20log(f) \tag{2.21}$$

where d is the distance between sender and receiver and f is the operation frequency in MHz. For the propagation in soil we need to include a correction factor to take into account the soil medium, which adds some extra attenuation. As result the received signal strength equation is written as follow:

$$P_r = P_t + G_r + G_t - (L_0 + L_s) \tag{2.22}$$

where L_s is the additional path loss in the soil, calculated as follows:

$$L_s = L_\beta + L_\alpha = 154 - 20log(f) + 20log(\beta) + 8.69\alpha d \tag{2.23}$$

where β is the phase shifting constant and α the attenuation constant in soil.

The total path loss in dB for the direct propagation model can be expressed as follow:

$$\boxed{P_{sl}dB = 6.4 + 20log(d) + 20log(\beta) + 8.69\alpha d - 10log(G_a G_b)} \tag{2.24}$$

Using Equation 2.24 we can get an approximation of the attenuation in dBs between a sender and a receiver when both of them are buried. However, when estimating the total path loss in the underground channel we need also to take into account the reflecting wave that result from the underground surface, as shown in the Figure 2.5.

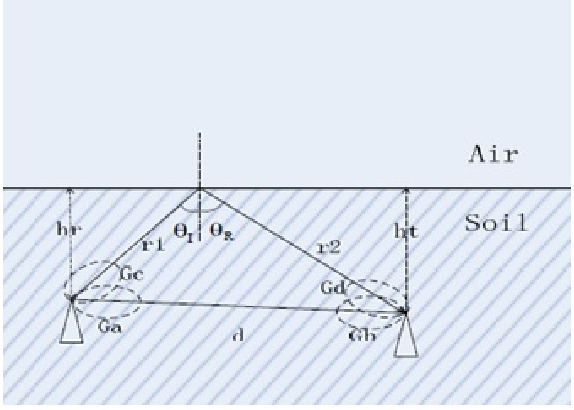


Figure 2.5: Two path channel model. [5]

This reflected wave has a greater effect when the buried depth of the nodes is lower, because in this case the reflected ray has a reduced distance to travel. For this reason, this signal component needs to be considered when estimating the path loss of the channel. The total path loss of the channel considering the two-ray model can be computed using Equation 2.25 [5].

$$\boxed{P_{fl}dB = P_{sl}dB - 10log\left|1 + \frac{\sqrt{G_c G_d} R d e^{\alpha \Delta r}}{\sqrt{G_a G_b}(r_1 + r_2)} e^{-j\Delta\phi}\right|^2} \tag{2.25}$$

Where P_{fl} is the 2-ray path loss, G_c and G_d is the antennas gain in the r_1 and r_2 directions, respectively, $\Delta r = (r_1 + r_2) - d$, $\Delta\phi = 2\pi(r_1 + r_2 - d)/\lambda$and R is the reflection coefficient of the soil-air interface and can be calculated as follow:

$$R = \frac{\frac{1}{\varepsilon_r}\cos\theta - \sqrt{\frac{1}{\varepsilon_r} - \sin^2(\theta)}}{\frac{1}{\varepsilon_r}\cos\theta + \sqrt{\frac{1}{\varepsilon_r} - \sin^2(\theta)}}(perpendicularly - polarixed) \tag{2.26}$$

$$R = \frac{\cos\theta - \sqrt{\frac{1}{\varepsilon_r} - \sin^2(\theta)}}{\cos\theta + \sqrt{\frac{1}{\varepsilon_r} - \sin^2(\theta)}}(parallel - polarized) \tag{2.27}$$

As we can see from Equation 2.25 this new model take into account the buried depth of the nodes.

2.3.3 Underground-to-aboveground propagation model

When building a WUSN we may also have aboveground nodes that can establish a bidirectional communication with underground nodes. The aboveground nodes may act as data sinks and/or as control stations. In this section we present a propagation model for the underground-aboveground communications link.

As we can see in the Figure 2.6 this situation differs from the underground-to-underground because now the propagated wave has to travel first in the soil, cross the soil-air interface, and then propagate in the air.

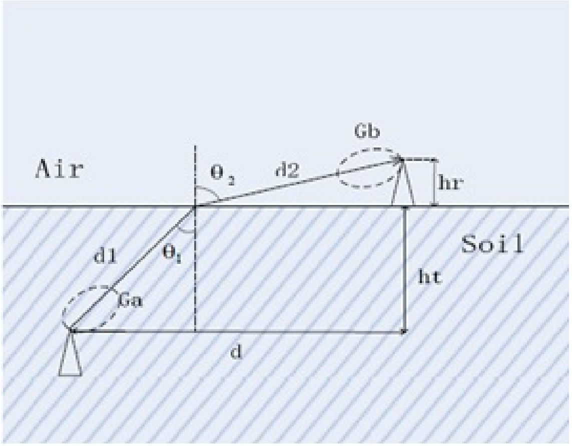


Figure 2.6: Underground-to-aboveground channel model. [5]

According to [5] the path loss can be calculated with the following equation:

$$P_{u-a}dB = P_u dB + P_a dB + 10log\left|\frac{1}{ve^{-j2\pi(d_1/\lambda + d_2/\lambda_0}}\right|^2 \tag{2.28}$$

$$P_u = 6 + 10log(d_1) + 20log(\beta) + 8.69\alpha d_1 - 10log(G_a) \tag{2.29}$$

$$P_a = 20log(f) + 20log(d_2) - 147.56 - 10log(G_b) \tag{2.30}$$

where v is the refraction coefficient from soil to air given by:

$$\nu = \frac{2cos\theta_1}{\sqrt{\frac{1}{\varepsilon_r}}cos(\theta_1) + \sqrt{1-\varepsilon_r sin^2(\theta_1)}}(perpendicularly - polarixed) \tag{2.31}$$

$$\nu = \frac{2cos\theta_1}{cos(\theta_1) + \sqrt{\frac{1}{\varepsilon_r} - sin^2(\theta_1)}}(parallel - polarized) \tag{2.32}$$

As we can see in Equation 2.28 the path loss is a sum of three components where the first is the attenuation in the soil medium, the second is the attenuation in the air medium, and the third is the attenuation in the soil-air interface.

In the underground-aboveground path we need to be aware that the relative dielectric constant of soil is greater than the air. So, if the incident angle (θ_1) is larger than the critical angle ($\theta_c = arcsin(\sqrt{\frac{1}{\varepsilon_r}})$) the ray will be completely reflected. In this case the refracted angle is approximately 90^o so the signal will propagates along the ground surface.

2.3.4 Aboveground-to-underground propagation model

This communication scenario is presented in the Figure 2.7. It is identical to the last one with the difference that this time we consider the link aboveground-to-underground.

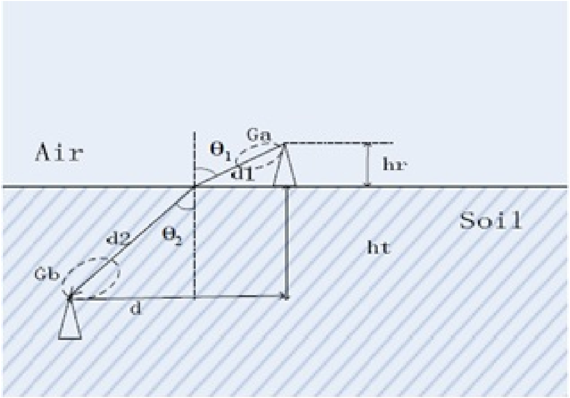


Figure 2.7: Aboveground-to-underground channel model. [5]

Since the propagation medium is air, air-soil interface and then soil, the equation that estimates the path loss is identical to the equation 2.28 presented in the last section and it can be written as follow:

$$P_{a-u}dB = P_a dB + P_u dB + 10log\left|\frac{1}{\nu e^{-j2\pi(d_1/\lambda_0 + d_2/\lambda}}\right|^2 \tag{2.33}$$

$$P_a = 20log(f) + 20log(d_2) - 147.56 - 10log(G_b) \tag{2.34}$$

$$P_u = 6 + 10log(d_1) + 20log(\beta) + 8.69\alpha d_1 - 10log(G_a) \tag{2.35}$$

where ν is the refraction coefficient from air to soil (different from the last one that was from soil-air) given by:

$$v = \frac{2cos\theta_1}{\sqrt{\frac{1}{\varepsilon_r}cos(\theta_1)} + \sqrt{1-\varepsilon_r sin^2(\theta_1)}}(perpendicularly - polarixed) \tag{2.36}$$

$$v = \frac{2cos\theta_1}{cos(\theta_1) + \sqrt{\varepsilon_r - sin^2(\theta_1)}}(parallel - polarized) \tag{2.37}$$

Now comparing Equations 2.33 and 2.28 we can see that they are basically identical. The only difference is that in the U2A link the interface is soil-air, which means that the ray goes from a higher refraction index to a lower refraction index; this leads to higher attenuation than in the A2U scenario. In the U2A scenario total reflection can also occur, as we concluded in the early section.

2.4 Wireless Underground Networks in mines and tunnels

When analysing wireless underground communications scenarios we can have another scenario which is the communication in a mine or a tunnel. In this case the communication medium is always the air, but the propagation characteristics of the EM waves is very different from those of the traditional aboveground communications, mostly due to the structure of the mine or the length of the tunnel and the dielectric properties of the walls.

There are also several mathematical models to describe this scenario and one of them is present in [1] and is named Multimode Model. This model is capable of characterizing completely the wave propagation on a tunnel in both near and far regions. However when we are dealing with caves the scenario can be different because in this case we need to consider the pillars that are disposed randomly. The multimode model overcomes this problem by combining their results with the shadow fading model in order to estimate the effects of reflections and diffractions suffered by the signal.

These networks have been the focus of many researches and are considered underground networks yet, since the medium is only the air they are out of scope for this MSc work.

2.5 Ns-3 Simulator

Ns-3, network simulator three, is an open-source discrete event network simulator targeted primarily for research and education purposes. It was written using the c++ programming language but the ns-3 library is wrapped to python thanks to the *pybindgen* library so if some users feels more comfortable with python they can use it instead of c++ to interact with the libraries.

The ns-3 is split into a couple dozens of modules and each implement one or more models for real world network devices and protocols such as Wi-fi, WiMax, LTE for layers one and two and also several routing protocols such as OLSR and AODV.

When compared to other network simulators the ns-3 has some distinguishing high level design goals such as [12]

- **C++ and Python emphasis** — instead of use a domain specific modelling language to describe the models ns-3 uses the c++ or python languages;
- **Callback-driven events and connections** — simulation events in ns-3 are simply function calls that are scheduled to execute at a prescribed simulation time by use of a callback function as in contrast to specialized "handler" functions that centralize the processing of events in each simulation object;
- **Flexible core with helper layer** — ns-3 has a low level API that gives the users a lot of flexibility to configure the objects. However it also has some helper classes with some default configurations and easier to use functions;
- **Alignment with real-world interfaces** — ns-3 nodes, interfaces and objects such us sockets and net devices are aligned with those found in a Linux computer which improves the realism of the models and makes the comparison with real systems easier.

Since ns-3 is an open-source simulator and is widely spread over the research community and due to the lack of simulation models for underground communications these will be implemented and tested in this simulator during the realization of this MSc dissertation.

2.6 Summary

In this chapter we started by analysing some of the applications for WUNs and defined the communication scenarios that will be the targeted in this MSc work. Then, we presented some mathematical models for describing the soil properties and propagation characteristics in each of the three communication scenarios that will be simulated. For the propagation characteristics the main equations that are important to notice are: Equation 2.25 for the U2U scenario; Equation 2.28 for the U2A link; and Equation 2.33 for the A2U link. For concluding the state of the art in wireless underground networks we also referred wireless networks in tunnels and mines because although they are beyond the dissertation objectives they still belong to the WUN group.

Since the main objective of this work is to implement the theoretical models into the ns-3 simulator we also went through an explanation of ns-3 and why we have chosen it. It is also important to notice that there is no simulation tool for these networks yet.

Chapter 3

Methodology

After identifying the main goal of the dissertation, which is to create a ns-3 accurate model capable of simulating wireless underground networks, and studying theoretical models for predicting the soil dielectric constant and signal attenuation, in this chapter we define the strategy that will be used to create the ns-3 model and validate it with experimental results. This chapter presents the methodology that will be followed during the development of this dissertation.

3.1 Ns-3 propagation model details

The simulation model that will be implemented should be able to predict the signal attenuation, the delay and the packet error ratio between two nodes in the cases of one or two buried nodes. Since the dielectric constant of the soil vary from one soil to another, based on the soil properties and volumetric water content, we identify another requirement for the model, which is, to estimate the complex soil dielectric constant based on the physical soil properties and the operating frequency of the connection nodes.

The class *ns3::TwoRayUndergroundModel* will be created in ns-3 to implement our model. In Figure 3.1 we can see the ns-3 architecture and the layer where our model will be focused which is the propagation layer.

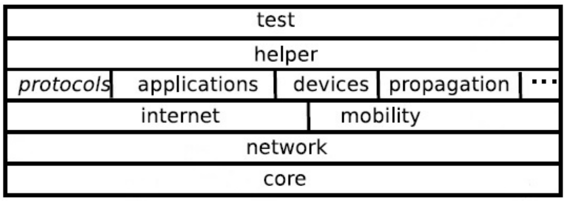


Figure 3.1: Ns-3 Architecture. [6]

For estimating the signal attenuation we will use the mathematical equations presented in Chapter 2. The important equations for the underground channel that will be the used are: Equation 2.25 for the U2U communication, Equation 2.28 for the U2A link and, Equation 2.33 for the A2U link.

For the delay calculation we will use one of the already implemented models which is the *ns3::ConstantSpeedPropagationDelayModel* that considers the delay constant along the path between the sender and the receiver. It is important to notice that this is true if we are only considering the U2U link, since in this case the electromagnetic wave will propagate exclusively in the soil. When we are considering one node aboveground there will be two propagation mediums. In this case we will use two instances of this model, one for the signal component that travels in the soil and another for the signal component that travels over the air; then we sum the two delays and have the total delay between the two nodes.

Another important property that is interesting to estimate when we are designing a new communication scenario is the packet error ratio, because above a threshold it is no longer possible to establish communication between the nodes. The error ratio has dependencies not only with the power receiver sensitivity but also with the frequency used, the modulation techniques (OFDM, DSS) and with the forward error correction (FEC) codes used (if any). In order to be able to take these variables into account we will use the already implemented *ns3::NistErrorRateModel* for the cases where we use the OFDM technique and the *ns3::DssErrorRateModel* for the cases where we use the DSS.

Another important property that needs to be estimated is the complex dielectric constant, which is evaluated using the soil physical properties and the amount of water. In Chapter 2 we presented two mathematical models to calculate the dielectric constant, which are the SMDM model and the MBSDM model. With some analysis between experimental and theoretical results found in literature we concluded that the MBSDM model is more accurate and so we focus on this model and implement it in ns-3. However, due to the simplicity of adding another dielectric model to our implementation, and since the SMDM model is widely spread in literature, we will also include this model. By adding more than one mathematical model we give the user a chance to choose which model he wants to use to compute the dielectric constant. During our investigation on previous experiments with these networks, with the objective of validating our model, we also found very common in these experiments the presence of the values for the dielectric constant instead of the physical soil properties. So, we decided to give another option for this constant which is the user be able to introduce it directly in our ns-3 model instead of estimate it with one of the two models described above. Besides the dielectric constant values we also find common to only characterize the soil using the terms in Figure 2.4, and, consequently we decided to include a table with several soil types like, for example, sandy or loam and their approximate dielectric constant. This table is a great help in obtain preliminary results before making an analysis to a soil sample.

3.2 Simulation scenarios

After the implementation of the ns-3 propagation model presented in the Section 3.1 is completed we will validate the model by simulating the scenarios presented in the state of the art (U2U, A2U and U2A) for several soil types and different water content, frequencies, depths of the buried nodes, lateral distance, and heights of the aboveground nodes. The simulations will be done using the 802.11 MAC, already implemented in ns-3, and the networks will be tested in both infrastructure and ad-hoc modes.

The accuracy of the model for the 2.4 GHz frequency will be concluded by simulating the experimental scenarios described in [13] and compare the practical results with the simulation results. The simulation tests will output the received signal strength, delay and packet error rate.

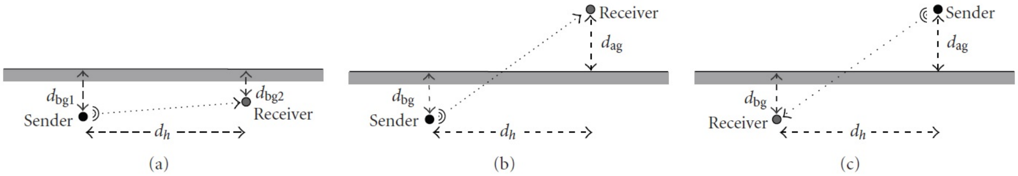


Figure 3.2: The basic simulation scenarios: (a) Underground-to-underground (U2U), (b) Underground-to-aboveground (U2A), (c) Aboveground-to-underground (A2U). [7]

Besides the 2.4 GHz frequency we will consider the 433 MHz to validate the ns-3 propagation model. This will be accomplished by replicating the experimental environment found in [2] for the U2U scenario and the [4] for the A2U and U2A scenarios. These simulation tests include several soil types and with different volumetric water content. For this particularly frequency we will also use the results from the testbed presented in [7] as another source of experimental values.

Upon the validation of the implemented model we will also show the potential of this model to study this type of networks by creating a complex network with several buried and aboveground nodes, and put some mobility in the aboveground nodes. For example, with this model we can simulate a golf field with several buried sensors and an aboveground mobile node that can retrieve the data measured by the buried sensors.

3.3 Summary

In this chapter we presented the strategy that will be carried out to develop the simulation environment enabling the simulation of wireless underground networks. We started by gathering the main requirements of the model, which are the estimation of the signal attenuation, delay, packet error ratio, and the complex dielectric constant of the soil and then showed how they will be implemented.

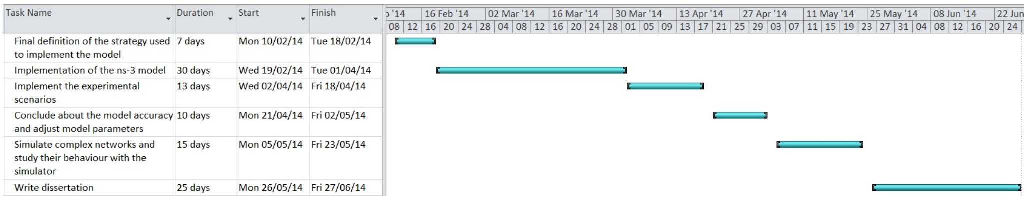
Since we also need to prove the accuracy of this model we defined some simulation scenarios that replicate experiments found in literature. After the simulations are completed we will compare the results and conclude about the accuracy of the implemented model. As a final step we will also design a wireless underground network with several nodes and use this model to simulate the network and show the importance of this model in future studies of these kind of networks.

Chapter 4

Workplan

In this chapter we present the workplan that will be carried out during the development of this dissertation. This plan is presented in figure 4.1 in a form of Gantt diagram and it presents the main activities that need to be done in order for us to accomplish the dissertation goals established in the first chapter.

- **10/02 - 18/02** - Define all the details in order to implement the ns-3 model;
- **19/02 - 01/04** - Implement the underground simulation environment in ns-3;
- **02/04 - 18/04** - Implement the experimental scenarios and simulate them;
- **21/04 - 02/05** - Conclude about the accuracy of the model based on the obtained results and adjust model parameters;
- **05/05 - 23/05** - Simulate a complex network to study their behaviour with our simulator;
- **26/05 - 27/06** - Write the final report.



Task Name	Duration	Start	Finish
Final definition of the strategy used to implement the model	7 days	Mon 10/02/14	Tue 18/02/14
Implementation of the ns-3 model	30 days	Wed 19/02/14	Tue 01/04/14
Implement the experimental scenarios	13 days	Wed 02/04/14	Fri 18/04/14
Conclude about the model accuracy and adjust model parameters	10 days	Mon 21/04/14	Fri 02/05/14
Simulate complex networks and study their behaviour with the simulator	15 days	Mon 05/05/14	Fri 23/05/14
Write dissertation	25 days	Mon 26/05/14	Fri 27/06/14

Figure 4.1: The workplan for this dissertation.

In this diagram it is possible to see the order in which the activities will be carried out and also the start and finish dates of each one and consequently their estimated duration in days.

Chapter 5

Conclusion

This dissertation arises in the context of establish wireless networks in the underground environment. The goal is to develop an accurate simulation framework for this kind of networks, which will be implemented over the ns-3 simulator.

Upon the review of the state of the art we have found several challenges in wireless underground communications. These challenges are mainly due to the fact that the EM waves propagates differently in the soil when compared to the over the air communications. The propagation parameters also vary from one soil type to another or even in the same soil if we have different amounts of water, which is dependent on weather conditions. These difficulties together with the fact that there are no simulation tools available for WUNs, upon the writing of this document, makes the design of wireless underground networks difficult.

After the characterization of the main objectives of the dissertation and reviewing the state of the art, we presented in Chapter 3 the strategy that will be used to implement the simulation model in ns-3 and to validate it by simulating some underground communications found in literature. After this validation is completed we will also design a complex network and demonstrate the power of this framework to study and design this type of networks.

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