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Wireless Underground Sensor Networks: A Comprehensive Survey and Tutorial

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The Internet of Things has developed greatly over the last decade to cater for many diverse applications across almost all fields of life. Many of these applications can either profit or even explicitly require deployment underground, such as precision agriculture, but also land, pipeline or mine monitoring. Underground deployment offers many advantages, such as concealment of the devices for their protection. However, the underground environment is also very challenging, especially for wireless communications and energy harvesting. In this survey and tutorial, we offer a comprehensive view of the complete topic, from theoretical foundations of wireless communications underground, through system architectures and applications, to energy harvesting options. These topics cannot be viewed separately from each other, as they are deeply intertwined and all of them need to be considered before a possible deployment. We will show that wireless underground sensor networks have a great potential for a variety of applications and are an intriguing alternative to overground deployments. We will describe the state of the art in a tutorial style, so that beginners can also profit. Last but not least, we will identify remaining challenges to guide researchers in this area.

CCS Concepts: • **General and reference** → **Surveys and overviews**; • **Hardware** → **Sensor applications and deployments**; • **Applied computing** → *Telecommunications*.

Additional Key Words and Phrases: Internet of Things, Wireless Underground Sensor Networks, Wireless Communication, Signal Attenuation, Energy Harvesting

1 INTRODUCTION

Recent developments in the Internet of Things (IoT) and its software and hardware have led to a whole new sub-field, called the Internet Of Underground Things (IoUT) or Wireless Underground Sensors Networks (WUSNs) [86, 87, 152, 168]. Admittedly, there is no consensus among researchers on which term to be used, and many other terms are also possible. Industrial Internet of Things and sensor-based IoT, but also Cyber-Physical Systems share some properties and solutions with WUSN and IoUT. For the sake of simplicity, we will use WUSN and IoUT as synonyms throughout this paper, as they address specifically the underground environment.

The main difference between traditional over-ground WSNs and WUSNs is the propagation medium (soil), which is denser than air. Due to this feature, the theoretical communication range of a terrestrial sensor node decreases drastically when the node is buried [159]. Thus, various challenges arise at all networking layers.

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Additionally, the underground environment presents also a challenge for the energy supply since battery change is more complex, and energy harvesting with solar panels is not feasible. Basically, a WUSN is made up of several sensor nodes that are mainly located under the ground and communicate with each other or with fixed gateways, as Figure 1 shows. The gateway can either be connected to the Internet or any local network to which an end user can connect.

Three types of underground communications can be found [181] in WUSN:

- *Underground to Underground communication (UG2UG)*: The transmitter and receiver nodes are fully underground for this kind of communication. The emitting signal travels wirelessly through the ground in the topsoil (first 30cm after the surface) or in the subsoil (below 30cm depth) regions.
- *Underground to Aboveground communication (UG2AG)*: here, the transmitter sensor node is located under the ground (fully buried, topsoil or subsoil), and the receiver, which can be another node or the gateway, is located above the ground. The signal crosses successively underground and free surface regions.
- *Aboveground to Underground communication (AG2UG)*: This case is the opposite of the previous case. An aboveground node or a gateway communicates with an underground sensor node (receiver).

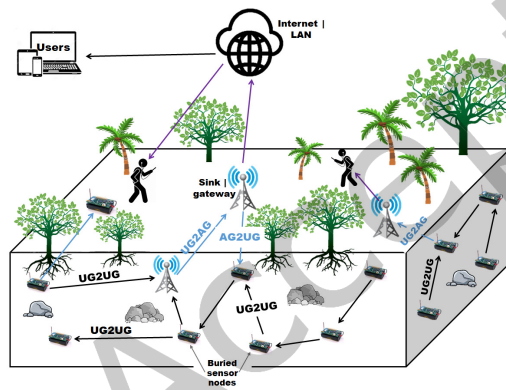


Fig. 1. Architecture of a WUSN which shows the different types of communication types.

Instead of focusing on the small number of IoUT protocols [197, 199], this study aims to provide a comprehensive survey on WUSN, its applications, challenges, communications, networking, and energy supply options. Our main contributions involve:

- **Analysis and comparison of related surveys:** We made an investigation of existing and related surveys. We presented each of them and compared them to our survey. A table comparison table that states the main contributions and identifies the topic addressed is provided to highlight their differences (Section 2).
- **A new taxonomy of WUSN applications:** Due to the diversity of WUSN applications, we propose a novel classification of these applications by considering three main types. The resulting taxonomy helps to better group the existing applications in terms of their properties and requirements (Section 3).
- **Review and comparison of existing testbeds:** After stating the difference between a real application and a testbed in WUSN, we investigate and present the relevant testbeds found in the literature (Section 4).
- **Review and comparison of wireless technologies used in WUSN:** We comprehensively describe the relevant wireless technologies for WUSN and compare them to each other (Section 5).
- **Review of existing path loss models in WUSN:** Underground signal attenuation is unique. Thus, we provide a technical and detailed tutorial on path loss models. After classifying them into 3 main categories, we compare the path loss models by taking into account 4 relevant parameters (Section 6).

- **Review of energy harvesting techniques applicable to WUSN:** Because of the limited lifetime of sensor nodes due to the use of batteries, we investigate relevant, promising, and innovative approaches that can enable the use of nodes operating without batteries in WUSN (Section 7).
- **Discussion of WUSN current challenges:** Last but not least, we identify open challenges and future research directions for WUSN (Section 8).

The paper is organized by our contributions, as discussed above.

2 RELATED SURVEYS ON WUSN

There are only few survey papers that present general issues for IoUTs or WUSN fields. Most of them focus on relevant applications or the wireless technologies used. Table 1 summarizes the survey papers from the last five years.

Vuran *et al.* [175] investigated the usage of IoUT for precision agriculture. Precision agriculture refers to a concept where sensors and actuators are installed to support agricultural activities and thus save resources such as water or pesticides. The authors discuss the types of sensors needed, relevant wireless technologies, and system architectures. This work was extended later in Vuran *et al.* [143] to cover more underground applications and to explore the size (scale) of the relevant applications.

Aalsalem *et al.* [1] investigated the recent technological advances and their challenges in using WSN for oil and gas monitoring. The authors point out the relevant challenges in monitoring underground pipelines. Indeed, underground wireless communication is shown as a very challenging issue for the real-time of underground pipelines. Slightly similar to [1], Muduli *et al.* presented a review of applications based on WSN to monitor underground coal mines in [110]. The authors first start by proposing three relevant questions useful in monitoring underground coal mines. More than 50 papers on this kind of application are classified in terms of the type of monitoring, the problem addressed, and the main approach used. Furthermore, the limitations of each paper are provided. Since the monitoring of underground coal mines can be divided into many monitoring or sensing activities, Muduli *et al.* discussed several solutions and techniques used in the literature for addressing these issues.

Another survey paper in WUSN has been proposed by Kisseleff *et al.* in [82]. The main contribution of this survey was the investigation of the WUSN application in which magnetic induction waves achieve wireless communications. The choice to focus on magnetic induction rather than traditional EM for wireless communication is justified by the high attenuation of EM in wet soil compared to MI. According to the authors, the applications of WUSN can be classified into four categories: environmental monitoring, infrastructure monitoring, localization, and security. The authors present the challenging issues highlighted by recent research, such as link quality estimation, the optimization of node positions, the use of relay points to increase the communication range, and energy harvesting.

Unlike previous surveys, Saeed *et al.* [141] present a systematic survey in IoUT field. Their main contribution consists of classifying the application of IoUT according to underground communication technology. The authors identify two types: five wireless technologies (EM, Acoustic wave, Mud Pulse, MI, and Visible Light Communication) and one wired underground communication. Each technology has been evaluated according to 8 different parameters. The authors provide an extensive discussion of relevant challenges, including deployment issues, robustness, and localization issues. Similarly to [141], Pal *et al.* investigated in [116] the mostly used wireless underground technologies in WUSN. Contrary to [141], the authors only consider three underground wireless technologies, which are radio frequency, acoustic waves, and magnetic induction. Since visible light cannot pass through the soil, the authors did not compare it to the other technologies. Additionally, Pal *et al.* have provided a brief presentation of underground energy harvesting.

A broad and detailed review of the detection of anomalies that can occur in WUSN is discussed in [150] by Sharma et al.. These anomalies, mostly known as holes, are classified into coverage holes, routing holes, and security holes. According to the authors, the holes widely affect the lifetime and the Quality of Service of the WUSN. An unavoidable hole can emerge in the network because of the random deployment of sensors, an external attack, or a restricted deployment field. For each anomaly presented in the survey, the main techniques used to solve the different problems are presented, discussing their advantages and disadvantages.

Table 1. Overview of related surveys paper.

Survey	Contribution	Application(s)	Topic	Year
Vuran et al. [175]	Investigation of IoUT applied to precision agriculture; main challenges and techniques related to precision agriculture are presented.	Precision agriculture	Application	2018
Vuran et al. [143]	Investigation of communication architectures used in agricultural applications. Review and classification of existing IoUT systems	All the underground applications	Wireless technologies	2018
Aalsalem et al. [1]	Presentation of recent technologies for underground monitoring of oil and gas reservoirs with the help of WSN.	Oil and gas monitoring	Application	2018
Muduli et al. [110]	Comparison of techniques used for the monitoring of underground coal mines. For each problem, the solutions used are discussed.	Coal mine monitoring	Application	2018
Kisseleff et al. [82]	Investigation of WUSN's applications based of MI communication. For each application, the main limitations are briefly discussed.	All the underground applications	MI communication	2018
Saeed et al. [141]	Classification of IoUT applications in terms of the wireless technology used. A comparison of wireless technologies is provided.	All the underground applications	Wireless technologies	2019
Pal et al. [116]	Classification of IoUT applications in terms of the wireless technology used. Harvesting techniques used to power sensor devices are also presented.	All the underground applications	Wireless technologies Energy harvesting	2020
Sharma et al. [150]	Investigation and classification of anomalies that may occur in a WUSN.	All the underground applications	Hole detection	2022
Wohwe and Förster	In-depth investigation and classification of applications and testbeds in WUSN. Description and comparison of wireless communication technologies used in WUSN. Detailed analysis and comparison of path loss models and energy harvesting techniques in WUSN/IoUT.	All the underground applications Existing testbeds	Application Testbeds Wireless tech. Pathloss models Energy harvesting	2023

As we can see in Table 1, our survey covers a broader area of topics in the area of WUSN/IoUT and more up-to-date research. For example, the works of Vuran *et al.* in [143] and [175] together can be considered the most comprehensive existing surveys. However, they describe the state of the art from 2018. Compared to the works of Vuran, we have included around 75 references after 2018. Compared to the other, later, surveys, we offer a more comprehensive view of the complete area, which is very helpful, especially for young researchers entering the field.

3 APPLICATIONS OF WUSN

In this section, we present a review of existing applications in WUSN or IoUT. We have organized them into three categories, which have some properties and requirements in common (Figure 2): (i) Environmental and agricultural monitoring; (ii) Underground structural monitoring; and (iii) Infrastructure monitoring and intrusion tracking.

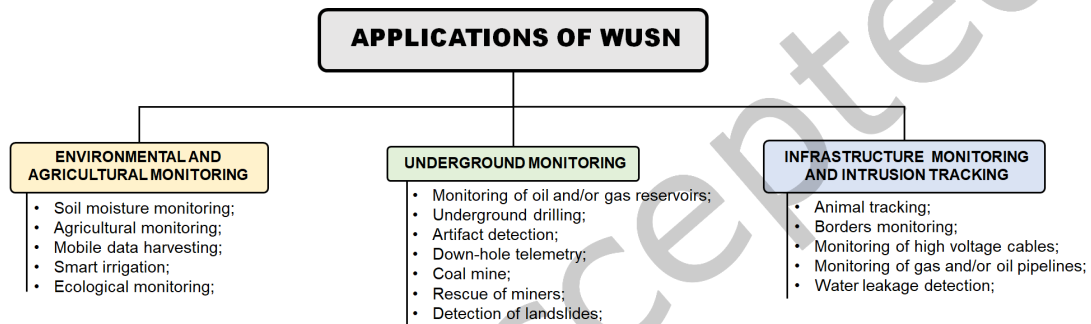


Fig. 2. Classification of WUSN applications into three different categories.

The details of all applications are presented in Tables 2, 3 and 4. For each application, the hardware used, the frequency range, the main contribution, the wireless communication technology, and the type of wireless communication are presented. In the following sections, we step through the three categories individually.

3.1 Environmental and agricultural monitoring

The most prominent and well-known usage of WUSN is for agricultural or environmental monitoring applications, including smart or autonomous irrigation systems. Precision agriculture takes into account the variation and the variability of numerous components such as irrigation, pesticide spraying, soil composition, nutrients, drainage, etc. [158]. However, traditional WSNs hinder the deployment of sensors and sensor nodes due to continuous agricultural activities like plowing or irrigation. WUSN overcome these shortcomings by burying the sensor nodes underground and allowing the farmers to continue their regular agricultural activities. The purpose of the buried sensors is to control the proper growth of the plants by monitoring the level of water and nutrients needed.

The success of these methods depends on the accuracy and timeliness of the monitoring techniques. For example, in the case of irrigation, we need to know *when*, *where*, and *how much* water to apply in order to optimize the output of the crops. Furthermore, we also need the minimum and the maximum amount of soil water necessary for the proper growth of certain crops. Thus, precision agriculture techniques cannot be limited to monitoring only and require sophisticated data and data processing techniques. Good management of irrigation techniques will greatly reduce the economic loss (the quality and the quantity of the yield) that can occur in case

of over or under-irrigation, as well as not taking into account other factors such as the movement of nutrients, pesticides, and chemicals in the groundwater.

One example of ecological monitoring is the ReviTec initiative [77] in the north of Cameroon, which targets to revitalize parts of the desert through reforestation. A unique property of such ecological monitoring applications is that they only monitor the environment without taking actions such as irrigation or pest control. In the case of ReviTec, the objective was to observe the efficiency of different reforestation techniques in an autonomous and remote way [195]. The main observed parameter was the volumetric water content (VWC) of the soil. Another important requirement in open public environments is also protection from vandalism, which is easily achieved with buried sensor nodes. A sample deployment of the self-developed underground sensor node called MoleNet¹ is shown in Figure 3a. Similar to [195], the authors of [136] also measured the VWC in UG2AG and AG2UG links. With the help of sensed soil moisture, the authors of [120] have developed a complete irrigation system.

An example of a monitoring application with both ecological and agricultural elements is the Ridgefield Farm monitoring project in Western Australia [32]. The authors have gathered and published a very large database of soil moisture and temperature data enriched with weather data.



Fig. 3. Buried sensor nodes for ecological and agriculture monitoring. (a) Deployment of the MoleNet sensor node enclosed in a waterproof box in Ngaoundéré, Cameroon. (b) Application of a WUSN for onion culture within the Botanical Garden of the University Cheikh Anta Diop of Dakar in Senegal

The authors of [183] have performed an experimental deployment of a WUSN at the botanical garden of the University Cheikh Anta Diop of Dakar in Senegal. A 450m² area for an onion's plantation is considered; the present soil is a sandy clay type in which the clay proportion increases with the depth. Before putting the onion plants under the ground, the top 20cm of soil is plowed. Then, a drip irrigation system is installed, and young onion seedlings are planted two days after the soil plowing while the ground is still soft enough. As it is shown in Figure 3b, the transmitter (green lid) and receiver (red lid) have been buried at different depths. The main objective of these studies was not only to show the feasibility of WUSN for agricultural applications in developing countries but also to make systematic measurements of the wireless channel and to validate a new path loss model, which is discussed in greater detail in Section 6. Similar studies have been achieved in [47, 171, 173, 185]. The latter work added a mobile harvesting solution to avoid batteries.

Some works propose also the use of ACW and MI wireless technologies for agricultural monitoring solutions [151, 165]. Yet another solution was proposed for underground pest control with acoustic sensors [21].

The Center Pivot system is a significant achievement in smart agriculture [164]. It aims to reduce operating costs while increasing agricultural yield. The Center Pivot System is basically a system with a pipe and a central pivot that spins in place and irrigates the area around and underneath it. Sprinklers are placed along the pipe.

¹molenet.org

The big advantage of the pivot system compared to other existing systems, such as surface irrigation systems, is that surface run-off losses can be greatly reduced or totally removed if the system is properly managed. Such systems also require less water (up to 40% less compared to surface irrigation) to produce the same results. This system can also be used to apply nutrients directly to the crop canopy (chemigation). Applying most nutrients, fertilizers, pesticides, insecticides, and herbicides directly to the canopy can greatly increase the absorption rate compared to surface (or granular) application. Due to the cost of such Pivot systems, they are generally used to irrigate large areas between 3.5 and 65Ha.

Table 2. WUSN's applications in environmental and agricultural monitoring

Ref.	Application	Hardware	Freq.	Contribution	Tech.	Comm.	Year
[136]	Soil moisture monitoring	nRF905	868MHz	Network architecture for continuous soil moisture monitoring, asymmetric UG2AG and AG2UG links.	EM	UG2AG AG2UG	2009
[151]	Agricultural monitoring	Microphone ATP-20M	<900Hz	Investigation of the dependence of sound speed in the silt loam and sand soil types with the water content in soil using continuous wave (CW).	ACW	AG2UG, UG2AG	2010
[173]	Agricultural monitoring	Mica2	433MHz	Empirical Analysis of Packet Size and error control for underground communication.	EM	UG2UG UG2AG AG2UG	2012
[185]	Agricultural monitoring	MSP430 nRF905	433MHz 868MHz 915MHz	Empirical evaluation of the signal attenuation regarding the variation of the burial depths of sensor nodes and the volumetric water content of the soil.	EM	<i>unknown</i>	2012
[120]	Smart irrigation	<i>unknown</i>	10MHz	A WUSN system to regulate soil moisture level in a pecan farm. Exploration of an optimal number of relay coils for reliable wireless communication.	MI	UG2UG	2012
[47]	Agricultural monitoring	Mica2	433MHz	Experimental and Empirical analysis of UG2AG channel.	EM	UG2AG	2013
[171]	Agricultural monitoring	Soil Scouts	869.4MHz	Real-time monitoring of soil parameters, single hop communication. The sensor node (Soil Scout v2) has a calculated lifespan of 42 years.	EM	UG2AG	2013
[195]	Ecological monitoring	MoleNet	434MHz 868MHz	Design and evaluation of a cheap and powerful new underground mote. Deployed for reforestation monitoring in Ngaoundéré, Cameroon.	EM	UG2UG	2016
[165]	Smart irrigation	<i>unknown</i>	10MHz	A novel MI waveguide for wireless underground communication. Coil parameters are optimized for the efficient use of energy.	MI	UG2UG	2017

[32]	Ecological and agri-cultural monitoring	RFM98PW-169S2	174MHz	Establishment and publication of a 10-month data set from a farm site in Western Australia. The WUSN consists of 5 transmitters and 2 receivers.	EM	UG2UG	2019
[21]	Agricultural monitoring	<i>unknown</i>	350MHz 700MHz	Proposal and evaluation of a mathematical model for detecting underground insect pests in crops.	ACW	UG2UG UG2AG	2019
[183]	Agricultural monitoring	Arduino UNO R3 + Sx1278 / nRF905	433MHz	Design and proposition of a new path loss model for precision agriculture. Analysis within an agricultural field at Cheikh Anta Diop University, Senegal.	EM	UG2UG UG2AG AG2UG	2020

The existing applications presented in Table 2 are mostly designed for UG2UG or UG2AG/AG2UG communications due to the fact that soil sensors are always underground and required for all these applications. Various wireless technologies are used, with 66.67% using electromagnetic waves.

3.2 Underground Monitoring

Natural resources such as oil and gas are located deeper into the ground and their extraction is complex. Drilling such wells requires constant monitoring. In this kind of system where the purpose is to allow transmission in boreholes, the lower section of the drill is equipped with measuring and recording sensors. The Measuring While Drilling system (MWD) and the Logging While Drilling system (LWD) are the two main parts of the bottom hole assembly [23]. In order to collect data from the borehole, sensors are fixed at the bottom of the borehole and the measured data are transmitted over several kilometers with Mud Pulse Telemetry (MPT) from the bottom to the surface [59, 128]. An example of a typical LWD/MWD system based on MPT is depicted in Figure 4a[17, 84].

There are numerous applications for underground drilling in the literature. Harrel *et al.* [61] proposed a new solution that allows the detection of MPT signals, especially when measuring the flow rate at the top of the well-bore. The same idea has been improved in [133] by measuring the variation of the flow rate closed of the drill bit. In [145], authors considered a geophone for wireless communication perspective with ultra-wideband for the monitoring of underground oil and gas reservoirs. Another previous study showed that ACW can be used effectively to monitor underground resources such as the presence of gas in a coal mine [157]. Other solutions based on VLC have been proposed in the literature to monitor gas reservoirs[94]. However, they cannot be applied to oil, as it is not opaque.

An example of landslide monitoring is presented in [49]. There, authors have developed an early-warning system, which monitors soil moisture underground and rainfall overground to predict landslides. Based on the collected data, the system informs in real-time the end-user through a web server and an application if there is a risk of landslide.

A fire monitoring system for coal mines has been proposed in [20]. The proposed system takes the values (temperature, CO , CO_2 , O_2) provided by the sensor nodes to check in real-time the presence of fire. The proposal's accuracy is achieved by the Mamdani type-2 fuzzy Logic system for final decision-making.

Underground mines are generally monitored using communication infrastructures based on wired, through-the-earth, or wireless sensor systems. In case of an incident (rockfall or explosion), traditional communication systems may break down or be damaged, this results in a loss of communication with miners working underground. The lack of communication with the trapped miners makes it difficult for the rescuers to reach out to them. Zaman *et al.* [194] performed several experiments in the mock mine at the University of Witwatersrand, South Africa to analyze the performance of the WUSN in underground mines, particularly in a disaster scenario. Different

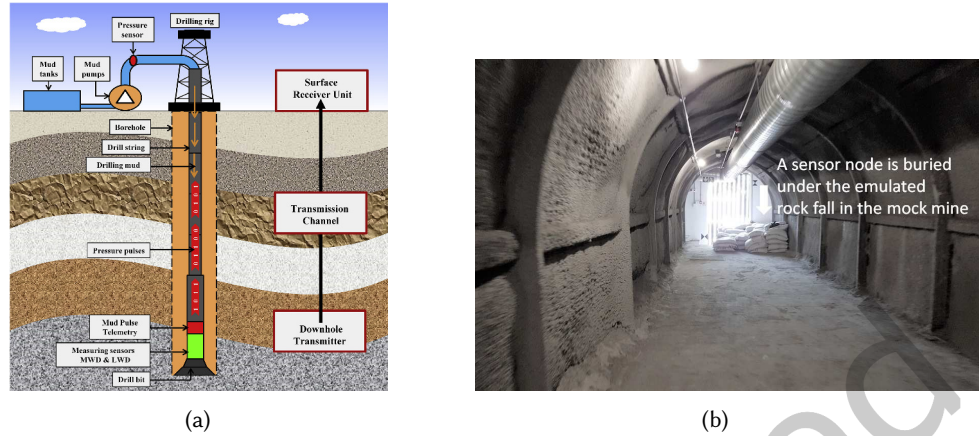


Fig. 4. Example of underground monitoring applications. (a) The architecture of a typical LWD/MWD system [23]. (b) An emulated disaster scenario in the mock mine at the University of Witwatersrand, South Africa [194].

disaster scenarios are emulated in the mock mine and the performance is compared with the traditional WSNs operating at 2.4GHz and 868MHz. Figure 4b shows an emulated disaster scenario, where a sensor node is buried under the rockfall. The MoleNet sensor node [195] operating at 433MHz proved to establish communication with the trapped miner in all emulated disaster scenarios. The rescue of miners has been the main motivation in others solutions; [102] allows the transmission with a high rate of data through rock and soil thanks to magnetic transceiver nodes. [117] proposed a novel solution to detect underground miners with VLC by taking into account the shadowing and the mine dust effects. In the same way, [74, 75] presented a novel solution for the detection of miners thanks to light communication and by considering dust effects to improve detection accuracy.

Another application of WUSN in underground monitoring consists of the detection of underground artifacts [114]. The authors used acoustic waves and investigated the speed of sound in the soil to detect the presence of artifacts. Acoustic signals were transmitted through different samples of soil and received by hydrophones. The proposed empirical solution was able to detect an object buried at 40cm.

Table 3. WUSN's applications in underground monitoring

Ref.	Application	Hardware	Freq.	Contribution	Tech.	Comm.	Year
[17]	Monitoring of oil and gas reservoirs	unknown	1Hz - 1000Hz	A telemetry system for continuous receipt of underground data at the surface while drilling a well. It supports alert management and control.	MPT	AG2UG, UG2AG	1964
[61]	Underground drilling	unknown	unknown	A new system to detect mud pulse telemetry signals in under-balanced drilling by measuring flow rate at the top of the well-bore.	MPT	AG2UG, UG2AG	2000
[114]	Artifact detection	NRLF42C28 + NRLF5658	2 - 6KHz	Investigation of the speed of sound in the soil to detect the presence of buried artifacts in a wide range of soil samples.	ACW	AG2UG, UG2AG	2002

[84]	Monitoring of oil and gas reservoirs	<i>unknown</i>	30Hz	A novel mud pulser that allows generation of baseband and carrier modulated to assure real-time drilling data at the surface.	MPT	UG2AG	2008
[59]	Down-hole telemetry	<i>unknown</i>	40Hz	A new method for transmitting pressure pulses from the downhole through a linear actuator. The system can also generate pressure pulses in a fluid flowing in a well-bore.	MPT	UG2AG	2008
[133]	Underground drilling	<i>unknown</i>	<i>unknown</i>	A novel measurement process that cancels pressure variations due to drilling noise by using a pressure sensor in the proximity of the drill bit.	MPT	UG2AG	2008
[92], [93]	Coal mine / Rescue of miners	Mica2	868/916MHz	Design of the monitoring system called SASA to detect holes in underground coal mines.	EM	UG2UG	2009
[102]	Rescue of miners	<i>unknown</i>	2.5KHz	Design of magnetic transceiver nodes for underground sensor networks. They are able to transmit data through rock and soil at higher data rates.	MI	<i>unknown</i>	2012
[157]	Coal mine	<i>unknown</i>	40KHz	Detection of gas leaks by the change of the sound velocity and amplitude. A novel acoustic signal processing to measure the attenuation of an acoustic signal.	ACW	UG2UG	2012
[145]	Monitoring of gas and oil reservoirs	Geophones	500MHz	A novel study that introduces the basic principles of seismic acquisition systems from the wireless communication perspective with ultra-wideband.	ACW	<i>unknown</i>	2013
[94]	Monitoring of gas and oil reservoirs	LED (transmitter)/SPAD (receiver)	<i>unknown</i>	A novel VLC system that uses SPAD instead of traditional PDs as a receiver. The proposed system saves energy by using only 8 dBm power to send a signal with a 4,000 meters long gas pipeline.	VLC	UG2AG	2014
[67]	Monitoring of oil and gas reservoirs	<i>unknown</i>	<i>unknown</i>	Method to detect pressure changes for MPT systems due to over-pressurization that leads to stress and to crash the mud pumps or expensive drill bits.	MFT	UG2AG	2016
[69]	Coal mine	LED / PhotoDetector	<i>unknown</i>	A novel system to localize workers in underground mines using VLC and the trilateration technique.	VLC	<i>unknown</i>	2017
[194]	Rescue of miners	MoleNet	433MHz	A novel sensor node to monitor and localise. The hardware validation of the proposal considers several scenarios in a mock mine.	EM	UG2AG	2018
[8]	Coal Mine	<i>unknown</i>	615MHz 2.216GHz	Analytical path loss model for coal mines, Single and two path, BER.	EM	UG2UG	2018

[55]	Coal mine	Vibration sensors (receivers)	100Hz	Data transmission through an acoustic wave in underground coal mine verified by mathematical analysis of the acoustic wave propagation characteristics in the drill pipe column.	ACW	UG2AG AG2UG	2018
[128]	Underground drilling	<i>unknown</i>	12 - 24Hz	An adaptive noise canceling structure for estimating the channel characteristics between two pressure transducers helps by the Recursive Least Squares (RLS) algorithm to optimize its output.	MPT	UG2AG	2018
[179], [178]	Coal mine	LED / Optical receiver	<i>unknown</i>	Investigation of the propagation channel in underground mining based on VLC technology.	VLC	<i>unknown</i>	2018
[20]	Coal mine	<i>unknown</i>	2.4GHz	Real-time detection of fire in coal mines with the help of sensor nodes. The final decision-making is based on a Mamdani type-2 fuzzy logic system.	EM	<i>unknown</i>	2019
[49]	Detection of landslides	Arduino MEGA 2560	<i>unknown</i>	Proposition of a landslide prediction system based on real-time data collected by nodes. An end-user application to issue warnings.	EM	<i>unknown</i>	2019
[74]	Rescue of Underground miners	LED / Optical receiver	<i>unknown</i>	Empirical modelling of VLC path loss in underground mines. For a realistic model, the proposed system considers the gain during Line-of-Sight (LoS) and Non-Line-Of-Sight (NLoS) propagations.	VLC	<i>unknown</i>	2020
[75]	Rescue of Underground miners	LED / Optical receiver	<i>unknown</i>	Study of the underground factors that affect the performance of VLC systems: rotation and inclination of the LEDs and the photodiode, aspects of the walls, shadowing and dust particles.	VLC	<i>unknown</i>	2020
[117]	Rescue of underground miners	LED / Photodiode	430-790THz	Modelling the VLC channel by taking into account the shadowing and the mines dust effects on the light.	VLC	<i>unknown</i>	2022

As shown in Table 3, WUSN's applications in underground monitoring are mostly based on MPT communications, and only one application considers MI as wireless technology. The higher operating depth explains the use of MPT in this type of WUSN application than in environmental and ecological monitoring applications. Moreover, for UG2UG communications, only EM and ACW are used for applications in underground monitoring.

3.3 Infrastructure monitoring and intrusion tracking

In developing countries, the infrastructure of the railway does not always meet safety standards. In many places, the railway crossings for vehicles and humans are left unattended, which leads to dreadful incidents. Figure 5a shows an example scenario in Sri Lanka, where the railway crossing has no barrier protection. A sensor node equipped with a geophone sensor can be buried on the side of the railway track. The geophone (seismic sensor) can sense the vibrations of a train from 2-3km [36], and send the notification to the sensor node at the railway

crossing point. So without any existing infrastructure, the setup can be deployed anywhere, resulting in an inexpensive solution for the notification of train arrival.

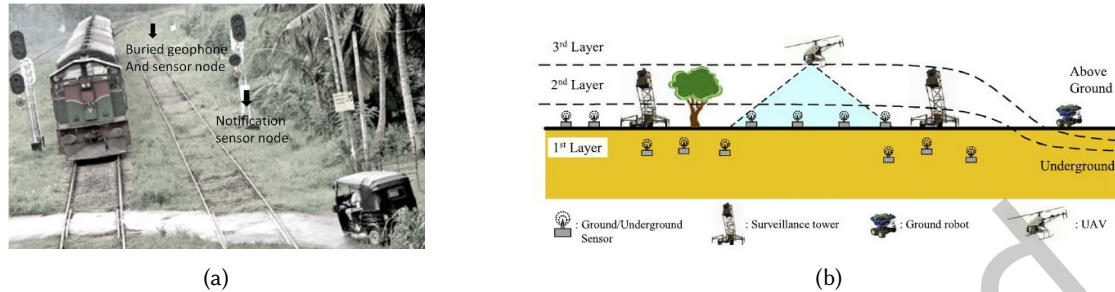


Fig. 5. Application of WUSN for infrastructure and intrusion monitoring. (a) Unprotected level crossing in Sri Lanka [112]. (b) Overview of the BorderSense's architecture [164].

Similarly, in recent years, many agricultural fields in Sri Lanka have been damaged by wild elephants [19]. Usually, the elephants are scared off using electric fences, torches, or firecrackers. However, electric fences are costly, inactive during frequent power outages, and can be destroyed by elephants. The same approach as for train notification can be used to notify the farmers about approaching elephants. The system can also be equipped with flashlights or firecrackers to disperse the herd of approaching elephants. Another solution for tracking underground animals with the help of MI has been proposed in [103]. The presented solutions help zoologists to have a better view of their subterranean animals.

Border security has always required a lot of manpower to do properly, which is the main challenge that current systems are sometimes unable to cope with [148]. Conventional systems consist of checkpoints on the main international roads in order to monitor the vehicle traffic and patrols which cover the areas between the checkpoints. However, those patrols have a predetermined route and timing. The problem is, as stated before, that even modestly sized areas require a lot of personnel to properly monitor. The potential of WUSN is investigated for border security. Sun *et al.* [164] have proposed a modern approach to border control called BorderSense. This project aims to make use of Wireless Underground Sensor Network Systems with a Hybrid topology in order to monitor and accurately detect intrusion over large areas with minimal human involvement. The proposed system makes use of Wireless Multimedia Sensor Networks as well. During the deployment phase, three types of nodes are used: multimedia sensor nodes (equipped with cameras and/or night vision equipment); scalar sensor nodes (equipped with vibration/seismic detectors and deployed under the ground or above the ground to detect terrestrial movement); and mobile sensor nodes (equipped on surveillance drones between surveillance towers). The overall architecture of the proposed system is given in Figure 5b.

Underground pipelines are commonly used to transport several types of fluids from an extraction point to a distribution point. Meanwhile, many of these fluids can be toxic, hazardous products, or useful such as drinking water. After a certain amount of time, leaks will cause harmful losses to the economic resources, raw materials and wastage that can affect the population of a city [88]. The authors of [107] investigate to use of VLC in monitoring methane pipelines. To reach an acceptable bandwidth and the lowest signal attenuation, they used blue LEDs instead of the other colors. Due to the opaque capacity of oil, the monitoring of oil pipelines with VLC solutions remains challenging, however, [7] proposed a cost-effective system for real-time monitoring of underground gas and oil pipelines based on MI communications. To increase the communication range, passive relay points are needed along the pipeline. A novel system for the detection of pipeline leaks based on a WUSN is discussed in [70]. The proposed model assumes that underground nodes equipped with humidity and water

pressure sensors are deployed over the pipeline at the deterministic point. Leaks occur when the value of the water pressure drops sharply. The sensed data travel from source to destination nodes through the Dynamic Source Routing (DSR) protocol implemented in NS-3. In the same vein, Anwad et al. [18] proposed a new solution to detect underground pipeline water leakages by using ACW. To detect a leak, the recorded audio file is sent to cloud storage without any compression and then analyzed. The acoustic solution can also be used in monitoring the good functioning of underground high voltage cable [34].

Table 4. WUSN's applications in infrastructure monitoring and intrusion tracking

Ref.	Application	Hardware	Freq.	Contribution	Tech.	Comm.	Year
[103], [104]	Animals tracking	Zigbit A-2	433MHz	A novel approach for automatically tracking the location of burrowing animals when they are underground. The method help zoologists to have a better view of their subterranean animals.	MI	UG2AG	2010
[164]	Borders monitoring	<i>unknown</i>	<i>unknown</i>	A novel concept of a hybrid wireless sensor network architecture for border patrol systems called BorderSense.	EM	UG2AG	2011
[34]	Monitoring of high-voltage cables	Electro-acoustic sensor	1-5000KHz	Evaluation of Partial Discharges (PD) that occur in the interior of high voltage (HV) cable buried under the ground. Acoustic waves are insensitive to the noises due to EM waves.	ACW	<i>unknown</i>	2012
[70]	Pipeline leakage detection	<i>unknown</i>	<i>unknown</i>	Modelling of a system for the detection of leaks in water pipelines. Underground nodes are located at specific points in the water distribution system.	EM	<i>unknown</i>	2018
[107]	Monitoring of gas and/or oil pipelines	Cree® LEDs (white, blue and red)	2.5MHz 10MHz	Exploration of using visible light as a communication channel in gas pipelines (methane). The blue LED is preferred to other LEDs because it has the highest bandwidth and the lowest path loss.	VLC	UG2UG	2018
[7]	Monitoring of gas and/or oil pipelines	<i>unknown</i>	125KHz 522KHz	Proposition of a cost-effective system for real-time monitoring of pipelines. To increase the communication range, passive relay points are needed.	MI	UG2UG	2019
[18]	Water leakage detection	Ultrasonic detector	20-40KHz 40-60KHz 60-80KHz 80-100KHz	Use of ultrasonic waves for leakage detection in underground water pipeline by using 4 frequencies. For each one, a WAV audio file is recorded and sent to cloud storage without any compression.	ACW	AG2UG UG2AG	2020

Contrary to applications for underground monitoring (Table 3), none of the applications for infrastructure monitoring and intrusion tracking found in the literature use MPT for wireless communications. Furthermore, this type of WUSN application usually uses UG2UG or AG2UG/UG2AG communications.

4 EXISTING WUSN TESTBEDS

The difference between testbeds and real deployments is not trivial. However, while testbeds are used for validation and measurements in relevant environments, real deployments go beyond the implementation details and access also the data yield and its relevance for the application scenario. In this section, we discuss some WUSN testbeds (Table 5).

In order to establish a new relationship between the soil moisture proportion and the sound speed in soil, Adamo *et al.* [2] provided a testbed made up of different types of soil samples. Their proposed model aims at designing UG2AG/AG2UG links and is based on the Brutsaert's model for elastic waves. The soil moisture level is monitored by the testbed designed. A new testbed to monitor soil moisture using wireless magnetic communications in an agricultural field has been proposed by [121]. Their study showed that the angle of coils used as relays highly affects the quality of data transmission. In addition to the soil moisture, [167] looks at finding the composition of soil by considering the use or not of waveguides widely used as passive relay points. An agricultural testbed to see the relationship between soil parameters such as the universal soil loss and the sound absorption coefficient in the soil is proposed by [52]. To monitor the temperature and the moisture parameters of soil, a testbed based on sharing images or texts is proposed in [134]. Their proposal uses MI to transmit up to 64Kb without delay.

Knowing that most of the common types of wireless equipment work at 2.4GHz, the authors of [159] studied the impact of conventional sensor nodes such as Mica2 (terrestrial) within underground environments. Their testbeds revealed that wireless terrestrial communications are widely attenuated by soil and the communication range highly reduce when using such frequency bands. Furthermore, this study showed that the use of wireless sensor nodes in underground applications must consider long-range communication technologies and has to find a trade-off between the communication rate and the communication range. An interesting method that reduces noise while drilling is proposed in [73]. The technique describes the different noises that can occur and affect the initial signal and recover the valuable signal from the surface. [156] and [172] change the frequency of the well-known terrestrial sensor node Mica2 to 433MHz in order to increase the communication range with soil as the communication medium. The testbed designed by the authors of [156] aims at analyzing the underground channel whereas in [172], the proposed testbed is used to control dynamically a center pivot widely used in smart irrigation systems.

In order to investigate the channel quality in wireless UG2UG MI communication, Zungeru *et al.* [200] proposed a new approach that combines pulsed power with MI. Underground acoustic waves have been investigated in [186] where the sent data between nodes are low-resolution images. Another similar study has been conducted with a low-cost wireless acoustic system in [187]. The proposed system was able to reach an acceptable rate without relays. More recent works for underground channels based on EM and VLC are described in [97] and [109].

Hossain *et al.* [62] evaluated the link quality of EM communication between a fully buried sensor node and an Uncrewed Aircraft System (UAS). To obtain a large communication range (more than 36.5m for a 30cm depth) the buried transmitter and the mobile receiver communicate through LoRa modulation operating at 916MHz. Additionally, the authors showed that reliable communication can be achieved regardless of the orientation angles of the antennas of the buried node or the mobile UAS. Thus, the designed testbed helps in monitoring the soil moisture sent by a buried node to a mobile LoRaWAN gateway. Despite the good communication distance obtained in this testbed, the impact of soil moisture on the attenuation of underground EM communications remains a key issue to be addressed. A similar study has been proposed by Cariou *et al.* [33] in which the unmanned aerial vehicle (UAV) is able to collect data from a buried node while moving. Contrary to [62], the LoRa communication between the gather node and the UAV is achieved at 868MHz and the buried are located at

a 15cm depth. Furthermore, an additional Zigbee module is added to the UAV in order to communicate in 2.4GHz with the gateway.

Table 5. Review of existing testbeds for Wireless Underground Sensor Networks.

Ref.	Hardware	Freq.	Contribution	Tech.	Comm.	Year
[2]	MC68HC908GP32 & RS232/485	433.92 MHz	A relationship between the soil moisture and the sound speed in different soil samples based on Brutsaert's model for elastic waves.	ACW	AG2UG, UG2AG	2004
[159]	MicaZ	2.4GHz	Experimental analysis of underground channel when using conventional terrestrial sensor nodes.	EM	UG2AG	2006
[73]	<i>unknown</i>	1-20Hz	Description of a new method that can filter several kinds of noises (pump, reflection, and random noises) and recovers the useful signal sent from the surface.	MFT	AG2UG	2007
[156]	Mica2	433MHz	Repeatability, Underground channel analysis.	EM	UG2UG, UG2AG	2010
[172]	Mica2	433MHz	Dynamically control a center pivot irrigation system.	EM	UG2AG	2012
[121]	Motorola MC68HC811 E2FN	13.56MHz	Soil moisture monitoring under different climatic conditions. The angle of the coils largely affects the quality of the data transfer.	MI	UG2UG	2013
[167]	USRP N210 + Xilinx Spartan-3A DSP 3400	8MHz	Underground testbed based on MI. Investigation of soil composition and water content by considering or not waveguide received power and bandwidth.	MI	UG2UG	2015
[52]	speaker NATTS, 200W RMS	16kHz	Establishment of the relationship between the sound absorption coefficient and factors of the Universal Soil Loss Equation by using 04 experimental plots.	ACW	AG2UG, UG2AG	2015
[200]	<i>unknown</i>	2.5KHz	Improvement of wireless underground communication range by combining pulsed power with MI.	MI	UG2UG	2016
[186]	<i>unknown</i>	<i>unknown</i>	A scheme for wireless data communication through soil employing acoustic waves. The sent data are ranged from sensor readings to low-resolution images	ACW	UG2UG	2018
[134]	PCB based on PIC16F877A	4-16MHz	Use of MI to transfer data in the form of text or image in soil medium. During image transmission, up to 64Kb can be sent without delay.	MI	UG2UG	2020
[187]	Arduino Uno + 9W motor controller	20-80Hz 500-1500Hz	Practical implementation of a low-cost wireless acoustic system for communication through the soil. The proposed system is able to get a 50m range with a 20bps data rate without relays.	ACW	UG2UG	2020
[97]	Nucleo-L073RZ + RFM95/SARA UBe	863-870MHz	Comparison of transmission performance within critical environments such as underwater, underground, and through-metal box. The measurement of losses due to media in LoRaWAN and NB-IoT is performed.	EM	UG2AG	2021

[109]	Arduino Pro Mini + RFM98W	<i>unknown</i>	Study of the characteristics of the underground mining external factors that affect the performance of VLC systems. These factors are the rotation and inclination of the LEDs and the photodiode, aspects of the walls, shadowing, and dust particles.	VLC	UG2AG	2022
[62]	Raspberry Pi-4 + RFM95W	916MHz	Monitoring system of the soil moisture by an UAS. A stable and reliable communication between the buried node (30cm depth) and the mobile LoRaWAN gateway (UAS) is achieved over a distance of more than 36.5m.	EM	UG2AG	2022
[33]	Atmega328 MCU + RFM95W	868MHz	Study of data collection from a buried sensor node by a drone (UAV) using LoRa 868MHz communication.	EM	UG2AG	2022

As can be seen in Table 5, from the 16 testbeds found in the literature, around 37.5% are designed for UG2AG or UG2UG wireless communications, and the largest number is based on EM technology. Only a few testbeds are available for VLC or MPT, which can be explained by their complexity and the high cost of equipment needed.

5 WIRELESS UNDERGROUND COMMUNICATION TECHNOLOGIES FOR WUSN

The underground environment is not optimal for wireless communication due to its high density. Therefore different wireless technologies have been investigated, aiming at providing low complexity, high data rate, and scalable solutions [141]. The leading wireless communication technologies in the literature are Electromagnetic Waves (EM), Magnetic Induction (MI), Acoustic waves (ACW), Mud Pulse Telemetry (MPT), and Visible Light Communication (VLC).

5.1 Electromagnetic Waves

EM waves are produced when an electric field comes in contact with the magnetic field. Electromagnetic waves are solutions of the equations of Maxwell, which are the fundamental equations of electrodynamics [30].

EM is widely used for WUSN and WSN. The EM waves are the best choice for classical wireless communication since radio waves propagate well through the air. However, when the communication channel is different from the air, the propagation of EM waves changes significantly. When the communication channel becomes the soil, the radio wave is highly attenuated due to dielectric modification in the soil. Thus, EM waves encounter much higher attenuation in soil compared to air [159]. This attenuation seriously impairs the quality of communication. Moreover, the ground surface causes reflection, as well as refraction, which requires a comprehensive investigation of the channel model [137, 146]. Multipath fading is another essential factor that affects EM waves underground [46]. Unpredictable obstacles in the soil, such as rocks and soft root trees, cause severe refraction and scattering of the EM wave. Low frequencies are used to address this issue [95, 144, 175, 192].

In short, EM waves encounter three significant problems in soil medium: high path loss, dynamic channel condition, and large antenna size [155]. Moreover, EM waves experience high levels of attenuation due to absorption by soil, rock, and water absorption in the underground medium. Thus, the propagation of EM waves in soil highly depends on several soil properties such as water content, soil proportions (sand, silt, and clay), and bulk density. Furthermore, these parameters change with time (e.g., the increase of soil water content after rainfall) and space (e.g., soil properties are not uniform over short distances) [161].

5.2 Magnetic Induction

In order to address issues of EM waves in WUSN, interest in Magnetic Induction (MI) solutions has grown considerably over the last decades. MI is a wireless communication technology that enables wireless communication by inducing a magnetic field between a transmitter and a receiver device. The technology uses small MI coils instead of an extended antenna, as it is with EM waves [10, 134, 162].

WUSN based on MI was first introduced in [162] and made use of coils as magnetic antennas. Furthermore, due to the low communication range of MI, they are combined in waveguide structures with several passive relay devices between two transceiver nodes (Figure 6). The coil parameters include the number of turns, coil radius, wire resistance, and coil angle [165]. The research areas of MI are in data transfer (Near Field Communication commonly known as NFC) and in wireless power transfer, both depending on the operating frequency [5, 6, 89]. Additional parameters must be considered to allow underground wireless communications based on MI, including the background medium, the geometry, the relative distance between the transceivers, and the orientation of coils (Figure 6a), as they can affect the transmission distance [57].

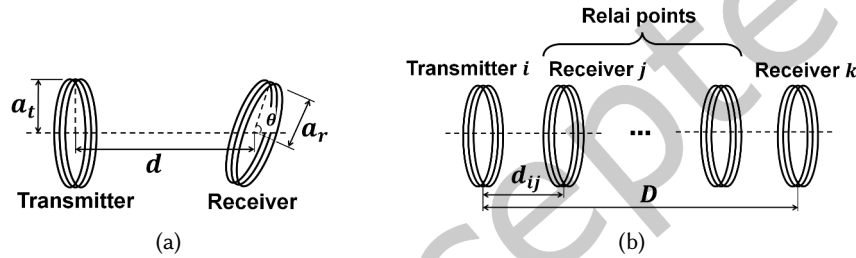


Fig. 6. Overview of MI communications. (a) MI transceivers with an inclined coil (receiver). (b) MI Waveguide with relay points.

For data transfer, transceivers based on MI need to be closed [81]. As it is shown in Figure 6b, in order to allow a higher communication range, coil parameters, and passive relay intervals must be well managed [165]. As it was shown in [162], a signal transmission range of 400m is achieved at 10MHz with a relay distance of 4m and unit length resistance of $0.01\Omega/\text{m}$. Furthermore, by using a low resistance loop with a high number of turns and a high signal frequency ($\omega\mu N_t \gg R_0$), Sun *et al.* [162] showed that the ratio between the received power P_r and the transmission power P_t can be reduced by (1).

$$\frac{P_r}{P_t} \approx \frac{\omega\mu N_r a_t^3 a_r^3 \sin^2 \theta}{16R_0 d^6} \quad (1)$$

Where N_t and N_r are the number of turns on the transmitter and receiver coils, respectively. θ is the inclination angle of the coil to the vertical axis, a_t and a_r are the radii of the transmitter and receiver coils. R_0 is the resistance of a unit length of a coil, μ is the permeability of the medium, and ω is the angular frequency of the transmitting signal ($\omega = 2\pi f$). R_0 is the wire resistance (in ohm/m), and d is the transmission range between neighbor coils. When the transmission between the transmitter and the receiver needs additional relay points, the transmission between transmitter i and receiver k becomes D (Figure 6b). a_t and a_r are the radii of transmitter and receiver coils.

As it was discussed in [30, 105, 165], the channel capacity of an MI-based link depends on the choice of the system parameters, like the size of the coils (radius a), resonance frequency f_0 , and the number of coil windings N . These works provide some insight into the design aspects for point-to-point MI-based signal transmissions [105]. Thus, using a MI system and a high operating frequency seems to be a better solution for low path loss. However, the frequency directly impacts the capacitor value and the number of turns on the coil. As for EM

applications, in order to use MI in WUSN, a trade-off between the communication range and the data rate must be fixed [102].

5.3 Acoustic Waves

Acoustic waves (ACW) are mechanical and longitudinal waves (the same direction of vibration as the direction of propagation) that result from an oscillation of pressure that travels through a solid, liquid, or gas in a wave pattern. This type of wave has the same characteristics as the EM and MI (velocity c in m/s , the frequency f in Hz , and the wavelength λ in m). Longitudinal waves are commonly known as compression waves because during the propagation of particles, compression, and rarefaction regions appear. Compression region denotes the areas where the particles are closest together, and rarefaction regions are regions where particles are furthest apart [22, 28]. The sound is the generalized name of ACW that has frequencies within the range of one to tens of thousands of Hertz. In other words, a sound is an ACW that humans can hear (20Hz to 20000Hz) [44]. ACW with a frequency below 20Hz is called infrasonic waves (infrasound), while ACW with higher frequencies above 20000Hz are known as ultrasonic waves (ultrasound) [22]. Frequencies range of ACW and average hearing ranges of some animals are given in Figure 7. Several aquatic animals such as whales or dolphins can communicate through sound and ultrasonic acoustic waves. Based on these animal capabilities to communicate with each other under the water, several types of research have been achieved for underground communication by studying the propagation of ACW in water [90, 147, 154].

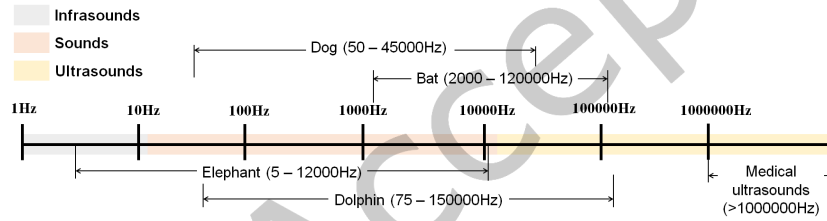


Fig. 7. Frequencies of ACW and average range of hearing.

Animals such as elephants, rodents, and a wide variety of insects use ACW for communicating through soil [187]. The ACW can either be an infrasonic wave or a sound; thus, the frequencies can vary from 1Hz to 20000Hz (Figure 7). It is why researchers widely use ACW to transfer data through the soil to allow reliable underground communication. Kostarev and Markhorthykh investigated in [85] the propagation speed of ACW in the soil. They assumed the speed of ACW depends on a vertical coordinate, and the proposed three layers model is presented in (2). Where $v(z)$ is the velocity of ACW at hm depth in the soil, h is the proper layer's boundary depth. The value of parameters h , h_1 , h_m , c_0 , c_1 , c_{min} and c_{l_0} are: $h = 10m$, $h_1 = 2m$, $h_m = 4m$, $c_0 = 700m/s$, $c_1 = 900m/s$, $c_{min} = 420m/s$ and $c_{l_0} = 910m/s$.

$$v(z) = \begin{cases} c_0 + z \frac{c_0 - c_1}{h_1} & \text{if } -h_1 < z < 0; \\ c_1 + \frac{h_1}{h_m - h_1} (c_{min} - c_1) + z \frac{c_{min} - c_1}{h_m - h_1} & \text{if } -h_m < z < -h_1; \\ c_{min} + \frac{h_m}{h - h_m} (c_{l_0} - c_{min}) + z \frac{c_{l_0} - c_{min}}{h - h_m} & \text{if } -h < z < -h_m. \end{cases} \quad (2)$$

Oelze *et al.* [114] performed an empirical analysis of the speed of acoustic waves ranging from 2-6Khz in a variety of soils. Another application of AWC is in precision agriculture in which the sound speed in the soil is used to estimate the soil moisture or its temperature [52], in coal mine application [55], and underground monitoring [12, 50, 145, 187], [65]. The communication distance of ACW in the soil is greater than the previous technologies. However, it also implies higher delay, and low data rate.

5.4 Mud Pulse Telemetry

The Mud Pulse Telemetry (MPT) is a method of transmitting Logging While Drilling (LWD) and Measurement While Drilling (MWD) data acquired downhole to the surface, using pressure pulses in the mud system [68]. The measurements are usually converted into an amplitude or frequency-modulated pattern of mud pulses. The mud goes through this valve, and pressure waves are controlled [59]. To modulate the amplitude, phase and frequency of the mud pulse signal, the same telemetry system is used to transmit commands from the surface [56]. MFT is widely used for exploration and drilling operations which are the most costly and risky activities that require LWD. The main advantage of the MFT technique during real-time deep underground monitoring is rapid decision-making. Furthermore, the MPT appears as the standard low-cost technology that provides reliable two-way *in situ* data transmission between the downhole system and the surface receiver [68, 96]. MPT signals can be classified into three types: positive, negative and continuous. To send a stream of data, these three types can be generated (Figure 8) to transmit and control at the surface the pressure pulses [141]. Various signal processing modules are used at the surface for this purpose. These pressure signals are encoded to carry the information which is essential for the application [131]. For example, it can carry the temperature, conductivity and pressure of the well. Even though MPT technology is widely used, many challenges remain [132, 142].

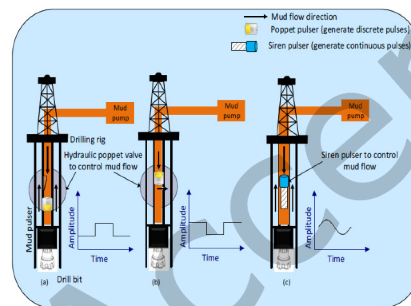


Fig. 8. Types of Mud Pulse Telemetry (MPT) systems. (a) Positive pulses through fluid, (b) Negative pulses through drill string (c) Continuous pulses through rotor [141].

The systems based on the MPT work on the concept of mud circulation in the pipes for data transmission [169]. Another application of MPT is for oil and gas monitoring [67, 84]. A review of MPT technologies is conducted by Mwachaka *et al.* [111]. MPT is suitable for underground monitoring and provides a higher communication range than ACW. However, the devices used in MPT are expensive, and their use within a WUSN would increase the deployment cost. Furthermore, MPT has a low data rate compared to the previous wireless technologies.

5.5 Visible Light Communication

Visible light communications (VLC) is part of optical wireless communications, also known as a technology that involves the transmission of information in free space through optical radiation in a channel [37]. In recent years, the idea of using LEDs for illumination and data communications became widespread [117]. The lighting and data communication functionalities provided by VLC has created a wide range of interesting applications, including intelligent lighting, communication in hazardous environments, high-speed data communication through lighting infrastructures, vehicular communications, underwater communications, high-speed communications in hospitals and aeroplanes, etc. [45, 64, 66, 129]. Since light cannot pass through opaque mediums such as soil, VLC is not feasible for the soil medium. Nevertheless, it is relevant for down-hole monitoring in gas fields or in the rescue of persons in mines [74, 75, 177, 179].

Usually, LEDs are used to transfer data in VLC. The detection of very soft light changes needs a photodetector (PD). An example of the usage of VLC to rescue miners is presented in Figure 9, where LEDs are fixed on the roof of a mine, and the miner carries the PD fixed on their helmet. The incident light beam makes a ψ angle with the vertical axis [118]. Recent research focused on exploring the propagation channel during VLC data transfer. Yasir et al. [190] show that the ratio between the received power and the transmitter power can be reduced to (3).

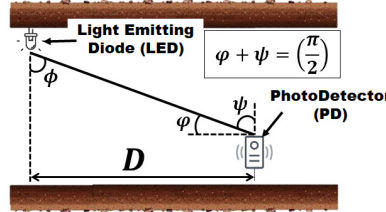


Fig. 9. An example of a VLC using LED as a transmitter and Photodetector (PD) as an optical receiver.

$$\frac{P_r}{P_t} = \begin{cases} \frac{A(m+1)}{2\pi D^2} \cos^2\left(\frac{\pi}{2} - \psi\right) \cos^m(\phi) T(\psi) \cos(\psi) & \text{if } 0 < \psi < \psi_c \\ 0 & \text{else} \end{cases} \quad (3)$$

$$m = \frac{-\log 2}{\log(\cos(\phi_{1/2}))} \quad (4)$$

Where P_r is the power received by the PD carried by a miner and P_t is the transmit power of the LED. A denotes the physical area of the PD in the receiver, D is the distance that separates the LED to the PD (miner) and depends on the irradiance angle ψ of the LED. From Figure 9, we observe that ϕ and ψ are two alternate interior angles, thus $\phi = \psi_c$. m is the Lambertian parameter of the LED, and its value is given in (4). $\phi_{1/2}$ denotes the half-power angle of irradiance of the transmitting LED, and $T(\psi)$ is the filter gain of the PD. ψ_c denotes the width of the field of view of the PD.

5.6 Comparison of wireless underground technologies for WUSN

This section summarises the wireless technologies we have presented so far and the comparison is presented in Table 6. The evaluation of these technologies has been conducted in 9 parameters: the burial depth, the communication range, the frequency range, the data rate, the attenuation, the deployment cost, the applications in which they are used, and their advantages and disadvantages.

Table 6. Comparison of wireless technologies used in WUSN.

Parameters	EM	MI	ACW	MPT	VLC
Burial depth	Low (few meters)	Low (few centimeters)	High (hundred of meters)	High (hundred of meters)	High (hundred of meters)
Communication range	Low (few meters)	Low (few meters)	High (hundred of meters)	High (hundred of meters)	High (hundred of meters)
Frequency range	High (433MHz-2.4GHz)	Medium (4MHz-16MHz)	Low (100Hz-16KHz)	Low (100Hz-1kHz)	Very high (400THz-800THz)

Data rate	Medium (in hundreds bytes/s)	Medium (in hundreds to thousands bytes/s)	Low (in tens bytes/s)	Low (in bytes/s)	High (in thousands to millions bytes/s)
Attenuation	High	Low	High	Medium	High (in the soil)
Deployment cost	Low(depends on the area's size)	Low (Depends on number of relays)	Average	Low	Low
Applications	Precision agriculture; Test-beds; Coal mine; Pipeline monitoring	Precision agriculture; Health care; Data transfer (NFC)	Precision agriculture; Coal mine; Test-beds; Monitoring of underground resources (oil, gas)	Oil and gas monitoring; Underground drilling; Down-hole telemetry	Down-hole monitoring (gas); Coal mine.
Advantages	1)Easy deployment and installation; 2)A high scalability due to the easy implementation of multihop communications	1)A high data rate; 2)Enable multihop communications for a better field's coverage; 3)A low sensitivity to buried;	1)A long transmission range for high depth; 2)Detection of sensed data according to the sound speed.	1)Low installation cost; 2)High communication range; 3)Suitable for real-time monitoring (low latency).	1)Low installation cost and small size of devices; 2)Low interference; 3)Lighting and data transmission functionalities.
Disadvantages	1)The high path loss problem; 2)The dynamic behaviour of the underground channel due to the ever-changing environment; 3)The antenna size is inversely proportional to wave frequency (lower transmission frequencies)	1)The limited communication range include the need of a dense deployment (relay points); 2)The transmission between transceivers are not omnidirectional, the direction between coils need to be well done; 3)Only for UG2UG communications.	1)The high delay, low bandwidth and high bit error rate during wireless communication; 2)The high wave attenuation in soil; 3)Lower data rate than EM and MI technologies; 4)Calibration of the sensed data according to the sound speed.	1)The location of the measurement point for better results; 2)The vibration during drilling applications introduce noises; 3)Low data rate 4)The high cost of devices and their high complexity	1)Available only when the underground communication channel is air; 2)Cannot be used effectively in an opaque medium.

In the following sections, we will analyze in-depth the EM waves because they are widely preferred compared to the others (Tables 2-5). Despite its drawbacks, EM wave is a good candidate for wireless communication in WUSN because it is easy to implement in a natural environment, easily reusable, and allows a rapid scaling up. Furthermore, devices for EM communication are readily available and cost-efficient.

6 PATH LOSS MODELS FOR WUSN

The wireless underground channel's characteristics differ greatly from the conventional free-space wireless communication channel. The wave propagation mechanism in the underground channel causes these differences. Waves interact with the soil medium, exhibit distinct characteristics and experience higher attenuation. The physical properties of the soil (texture, moisture proportion, temperature, and bulk density) impact the wave propagation. These interactions introduce channel impairments, which vary with space and time. This section presents path loss models designed for predicting the attenuation of EM waves in the soil. We classified path loss models into three groups: (i) underground path loss models designed for full underground communication; (ii) mixing path loss models, which aim to predict the EM wave attenuation for communications between the surface and the ground (UG2AG and AG2UG); and (iii) complete path loss models for all three types of communication.

6.1 Underground Path Loss Models

6.1.1 Complex Refractive Index Model-Fresnel: Bogena et al. [25] proposed a semi-empirical path loss model based on the famous Refractive Index Model (CRIM) [138] and Fresnel equations [98]. The radiations of the transmitter are assumed to be equal in all directions. Thus, the loss due to spherical divergence is reported. Furthermore, the authors consider additional losses due to optic phenomena (reflection, refraction and diffraction) and the signal attenuation that is related to the soil attenuation constant (5).

$$\alpha = 8.68 \frac{60\pi(2\pi f \epsilon_0 \epsilon'' + \sigma_b)}{\sqrt{\frac{\epsilon'}{2} \left\{ 1 + \sqrt{1 + \left[\left(\epsilon'' + \frac{\sigma_b}{2\pi f \epsilon_0} \right) / \epsilon' \right]^2} \right\}}} \quad (5)$$

f is the frequency in Hertz, $\epsilon_0 = 8.85 * 10^{-12} F.m^{-1}$ is the dielectric permittivity in free space, σ_b is the bulk density, ϵ' and ϵ'' the real (Dielectric Constant DC) and imaginary (Loss Factor LF) parts of the mixing model respectively. The CRIM is used to find the complex dielectric permittivity of the soil based on the permittivity of solid, the complex permittivity of water and the permittivity of the air. However, the authors assume that water is the unique element responsible for the dielectric losses; thus, the air and solid permittivity do not depend on the operating frequency.

The CRIM-Fresnel model adds the loss due to the wave reflection to the signal attenuation in the soil. It uses the Fresnel equation to calculate the reflection coefficient R . The proposed model neglects the effect of the magnetic permeability; therefore, R is simplified by (7). The total signal attenuation A_{tot} proposed by Bogena et al. [25] depends on the signal attenuation due to reflection R_c , the soil attenuation and the distance d between the two nodes.

$$A_{tot} = \alpha d + R_c \quad (6)$$

$$R_c = 10 \log \left(\frac{2R}{1+R} \right); \quad R = \left(\frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}} \right)^2 \quad (7)$$

Meanwhile, the semi-empirical CRIM-Fresnel model is not an accurate model because the type of soil used (sieved sand) is different from natural soil conditions. The results of the comparisons presented in [25] are very different from the real experiments. Roth et al. [138] extended the original CRIM model by assuming that the dielectric constant of moist soil depends on the dielectric constants of dry soil, free water and air (8).

$$\epsilon = (\theta \epsilon_w^\alpha + (1 - \eta) \epsilon_s^\alpha + (\eta - \theta) \epsilon_a^\alpha)^{1/\alpha} \quad (8)$$

where η is the porosity of the soil, θ , $1 - \eta$ and $\eta - \theta$ are the volume fractions of dry soil, free water and air respectively. ϵ_s , ϵ_w , ϵ_a are dielectric values of the dry soil, free water and air respectively. Moreover, Rhoades et al. [135] derived its value according to (9).

$$\sigma_b = \sigma_w(a\theta^2 + b\theta) + \sigma_s \quad (9)$$

where σ_w is the electrical conductivity of the soil water solution, a and b are fitting parameters, and σ_s is the surface conductivity of the soil matrix.

6.1.2 Modified Friis Model: The Modified Friis or the Conventional Modified Friis is a path loss model based on the Friis transmission equation initially designed for Free Space communication [53]. The Friis equation shows that the received power is inversely proportional to the square of the distance between a receiver and a transmitter (10).

$$P_r = \frac{K}{d^2}; \quad K = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2} \quad (10)$$

Where P_r and P_t denote the received and the transmit powers respectively; G_r and G_t are the antenna gains of the receiver and the transmitter respectively; $\lambda = \frac{c}{f}$ is the wavelength; c the velocity in vacuum and f the operating frequency. The value of the P_r in dBm is can be given by the link budget equation (11) as a function of the path loss in free space L_0 (12).

$$P_r(dBm) = P_t(dBm) + G_r(dB) + G_t(dB) - L_0(dB) \quad (11)$$

$$L_0(dB) = 32.4 + 20 \log(d(km)) + 20 \log(f(MHz)) \quad (12)$$

However, the Modified Friis model proposed in [91] takes into account the path loss due to wave attenuation in soil $L_s = L_{s1} + L_{s2}$. L_{s1} (13) denotes the attenuation loss due to the difference between the wavelength of the signal in soil and the wavelength of the signal in the air. L_{s2} represents the transmission loss caused by attenuation. Total attenuation L_{tot} considers the attenuation in free space [53] and the wave attenuation in soil L_s .

$$L_{s1}(dB) = 154 - 20 \log(f(Hz)) + 20 \log(\beta); \quad L_{s2}(dB) = 8.69\alpha d \quad (13)$$

The computed path loss L_{tot} (in dB) by the Modified Friis is simplified in Equation (14) below. The values α (1/m) and β (radian/m) depend on soil conditions. They are the attenuation due to material absorption and phase-shifting, respectively.

$$L_{tot} = 6.4 + 20 \log(d) + 20 \log(\beta) + 8.69\alpha d \quad (14)$$

The constants α and β (16) are the key elements of the Conventional Modified Friis path loss model and constitute the real and the imaginary parts of the complex propagation constant γ (15).

$$\gamma = \alpha + j\beta = 2\pi f \sqrt{\mu_0 \mu_r \epsilon_0 (\epsilon' - j\epsilon'')} \quad (15)$$

$$\alpha = 2\pi f \sqrt{\frac{\mu_0 \mu_r \epsilon_0 \epsilon'}{2} \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right)}; \quad \beta = 2\pi f \sqrt{\frac{\mu_0 \mu_r \epsilon_0 \epsilon'}{2} \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1 \right)} \quad (16)$$

α is the attenuation due to material absorption and β is the phase shifting constant. The permeability in vacuum μ_0 and the permittivity in free space ϵ_0 are related to the light velocity in vacuum by $\epsilon_0 \mu_0 c^2 = 1$. Most soils do not contain metal elements; the magnetic permeability is neglected ($\mu_r = 1$). The CDC depends on the semi-empirical mixing dielectric model proposed by Peplinski that uses the Debye relaxation spectrum of free water located out of the soil [122, 123]. Moreover, Li et al. [91] investigated the effect of burial depth on EM wave attenuation. Thus,

if sensor nodes are located close to the surface, the reflection loss due to the surface is considered. In addition to the direct path considered in (14), the wave will follow the reflected path (Figure 10). For such a case the resulting path loss L_f is (17).

$$L_f(dB) = L_{tot}(dB) - V_{dB}; \quad V_{dB} = 10 \log V \quad (17)$$

Where L_{tot} is given by (14) and V_{dB} is the attenuation that occurs due to the existence of the second path (reflected wave). Its expression is resumed by (18).

$$V^2 = 1 + (\Gamma \exp(-\alpha \delta(r)))^2 - 2\Gamma \exp(-\alpha \delta(r)) \cos\left(\pi - \left(\phi - \frac{2\pi}{\lambda} \delta(r)\right)\right) \quad (18)$$

$$\Gamma = \frac{\frac{1}{n} \cos(\theta_{ri}) - \cos(\theta_{rt})}{\frac{1}{n} \cos(\theta_{ri}) + \cos(\theta_{rt})}; \quad r = r_i + r_t \quad (19)$$

Where Γ (19) denotes the amplitude angle of the reflection coefficient at the reflection point P . It depends on the refractive index of soil, the incident and the refracted angles (n , θ_{ri} and θ_{rt} respectively). ϕ is the phase angle of the reflection coefficient according to P . $\delta(r) = d - r$ is the difference of the direct and the reflected paths taken by the EM wave during the transmission. In [46], authors investigated that path loss models presented in 14 and 17 becomes invalid if the burial depth is less than 50cm. In such cases, a proportion of the EM wave travels from soil to air and then propagates along the surface and comes back to the receiver (Figure 10). These waves are known as lateral waves [79]. In this approach, the received power P_r for the lateral wave is given by (20).

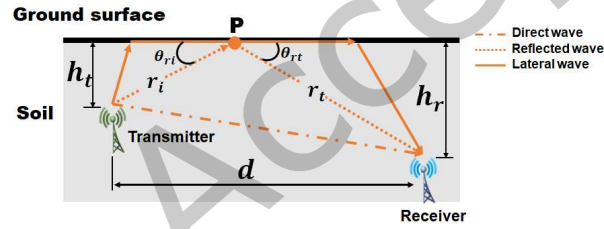


Fig. 10. Overview of direct, reflected and lateral waves.

$$P_r = P_t + 20 \log(\lambda_s) - 40 \log(d) - 8,69(h_t + h_r)\alpha + 20 \log(T) - 30 \quad (20)$$

Where P_t is the transmit power, λ_s is the wavelength in soil, d is the linear distance between the transmitter and the receiver nodes. h_t and h_r are the burial depths of the transmitter and the receiver nodes, respectively. T is the refraction coefficient of the soil, and its numerical value is computed according to (21).

$$T = \frac{2 \cos(\theta_{ri})}{n \cos(\theta_{ri}) + \cos(\theta_{rt})} \quad (21)$$

6.1.3 NC Modified Friis: Chaamwe et al. [35] proposed a semi-empirical model merging the Conventional Modified Friis approach and that of CRIM-Fresnel. The model combined the reflection due to wave attenuation proposed in CRIM-Fresnel (7) and the Modified Friis model (14). Moreover, the authors consider the signal attenuation due to wave refraction by adding the attenuating factor K (22) of the angular defocussing.

$$K(dB) = 20 \log \left(\sqrt{\frac{\epsilon_1 \cos(\theta_1)}{\epsilon_2 \cos(\theta_2)}} \right) \quad (22)$$

θ_1 and θ_2 are the incoming and outgoing wave angle respectively, ϵ_1 and ϵ_2 denote the wave dielectric constant of the source and the destination environment respectively. The total path loss proposed in [35] is resumed in (23). The value of the attenuation due to material absorption (α) and the value of the phase shifting constant (β) are given in (16)

$$L_{tot}(dB) = 6.4 + 20\log\left(d\beta K\sqrt{\frac{2R}{1+R}}\right) + 8.68\alpha d \quad (23)$$

The authors claim that their path loss model integrates better characteristics responsible for the signal attenuation than the Conventional Modified Friis and the CRIM-Fresnel models. Meanwhile, the path loss model presented in [35] also needs a laboratory analysis of a soil sample like the Conventional Modified Friis and the CRIM-Fresnel models. This analysis aims at finding the values of DC (ϵ') and the LF (ϵ'') of the soil also based on the Peplinski derivations like the Conventional Modified Friis. In practice, EM wave attenuation due to refraction occurs when the signal travels near the ground surface and is often neglected for topsoil region communications. Furthermore, the incidence and the refracted angles (θ_1 and θ_2 respectively) of the wave may change according to the position of each node and require additional settings to get their numerical values.

6.1.4 TDR Modified Friis: A different approach has been proposed by the authors of [140]. They use a Time Domain Reflectometer (TDR) to find *in situ* the values of the CDC. The resulting path loss model is able to predict in real time the loss of EM waves in the soil. The outputs of the a TDR measurement gives the values of the CDC (real and imaginary parts of the CDC) that are used as inputs in the Conventional Modified Friis (14).

In order to evaluate the TDR Modified Friis, the authors compared their approach to Conventional Modified Friis and to real measurements on the 03 configurations. The results reveal that the value of the root means squared error in the TDR Modified Friis is smaller than the CRIM-Fresnel and the Conventional Modified Friis. Thus, the proposed model is assumed to be more accurate than the existing path loss models. However, the use of a TDR equipment remains costly, and its deployment within a network is a costly problem. Furthermore, analysing a soil sample is challenging, especially for large and non-uniform deployment fields.

6.2 Mixing Path Loss Models

6.2.1 ZS Free Space Modified Friis based model: Most of the mixing path losses in WUC add to the free space path loss, the loss due to underground communication. Sun et al. [163] propose a path loss model for UG2AG and AG2UG communications. To achieve it, the authors add to Free Space to the Conventional Modified Friis model, the loss due to Soil-Air and Air-Soil refraction for UG2AG and AG2UG communications, respectively. The resulting path losses are given in (24). Where θ is the incidence angle of the wave, ϵ' is the dielectric constant, L_{ug} and L_{ag} are the Conventional Modified Friis (14) and the free space [53] path losses respectively.

$$L_{UG2AG} = L_{ug} + L_{ag} + 10\log\left(\frac{(\sqrt{\epsilon'} + 1)^2}{4\sqrt{\epsilon'}}\right), L_{AG2UG} = L_{ug} + L_{ag} + 10\log\left(\frac{(\cos\theta\sqrt{\epsilon'} - \sin^2\theta)^2}{4\cos\theta\sqrt{\epsilon'} - \sin^2\theta}\right) \quad (24)$$

The loss due to reflection of the EM wave that can occur in different depths are not considered by Sun et al. [163]. Moreover, the added refraction loss seems to avoid the effect of the loss factor ϵ'' of the wave and in practice, the incidence angle cannot be easily obtained especially in real time application.

6.2.2 XD Free Space Modified Friis based model: Another mixing model for the prediction of signal loss in UG2AG/AG2UG communications is proposed by Dong et al. [47]. Their approach is quite similar to the one proposed by Sun et al. [163]. However, for UG2AG, the authors neglect the loss due to EM wave refraction. Indeed, the signal travels perpendicularly from a higher density medium (soil) to a lower density one (air). Furthermore,

for AG2UG communication, the loss due to refraction L_r depends on the refractive index of the soil n (25). In order to give an approximate value, Dong et al. assume that the signal incidence angle is zero degrees, thus, the maximum power path taken by the signal. ϵ' and ϵ'' are the dielectric constant and the loss factor, respectively. The resulting path losses for UG2AG and AG2UG communications are resumed in (26).

$$L_r = 20 \log \left(\frac{n+1}{4} \right); \quad n = \sqrt{\frac{\sqrt{(\epsilon')^2 + (\epsilon'')^2} + \epsilon'}{2}} \quad (25)$$

$$L_{UG2AG} = L_{ug} + L_{ag}; \quad L_{AUG2UG} = L_{ug} + L_{ag} + L_r \quad (26)$$

6.3 Complete Path Loss Model

Wohwe et al. [183] proposed the Wireless Underground Sensor Network Path Loss Model named WUSN-PLM (27). It is derived into two forms $WUSN_{PLM_{\#1}}$ (28) and $WUSN_{PLM_{\#2}}$ (29) for topsoil and subsoil regions respectively. Knowing that, the reflection phenomenon occurs when an EM is closed of the ground surface (topsoil), the reflection effects are considered [35]. The resulting path loss is given by (28). However, in subsoil regions, the reflection effects are neglected, thus, the corresponding loss is reported by (29).

$$WUSN_{PLM}(dB) = L_{d1}(dB) + L_{ug}(dB) + L_{d2}(dB) \quad (27)$$

$$WUSN_{PLM_{\#1}}(dB) = -288.8 + 20 \log \left(d_{ag1} \cdot d_{ag2} \cdot d_{ug} \cdot \beta \cdot f^2 \cdot \sqrt{\frac{2R}{1+R}} \right) + 8.69\alpha \cdot d_{ug} \quad (28)$$

$$WUSN_{PLM_{\#2}}(dB) = -288.8 + 20 \log (d_{ag1} \cdot d_{ag2} \cdot d_{ug} \cdot \beta \cdot f^2) + 8.69\alpha \cdot d_{ug} \quad (29)$$

The constants α and β are respectively the real and the imaginary part of the complex propagation constant and are based on the prediction of ϵ' and ϵ'' performed by the Mineralogy-Based Soil Dielectric Model (MBSDM) [108, 182].

The distance travelled by the EM wave in free space (above the ground region) are d_{ag1} and d_{ag2} ; the distance travelled by the wave under the ground is d_{ug} . When the transmitter and the receiver are entirely underground (UG2UG), d_{ag1} and d_{ag2} are the distance travelled by the signal inside the waterproof box (For same boxes, $d_{ag1} = d_{ag2}$). However, the signal attenuation in free space can be neglected for a smaller distance (less than 1m) between the transmitter and the receiver [25]. The underground distance between the transmitter and the receiver nodes is d_{ug} . Since the wave reflection phenomenon is observed at the topsoil region (*top_depth*), we consider the loss due to reflection. The resulting path loss is resumed by $WUSN_{PLM_{\#1}}$ (28). However, for subsoil regions (*sub_depth*), the losses due to reflection are neglected, and the overall path loss becomes $WUSN_{PLM_{\#2}}$ (29).

For UG2AG communications, d_{ag1} is the distance travelled by the wave in the transmitter box, d'_{ug} denotes the buried depth and d_{ag2} is the travelled distance in free space by the EM wave. The underground distance d_{ug} crossed by the wave is related to the burial depth d'_{ug} and the critical angle θ . Furthermore, when the soil is dry, the critical angle $\theta \approx 15^\circ$ and for moist soil, it is roughly equal to 30° like it is shown in [25]. Thus, if the transmitter is located at the *top_depth*, the overall path loss is expressed according to (28). Whereas, if the transmitter is located at the *sub_depth* the path loss is expressed through (29).

During AG2UG communications, the signal loss is slightly similar to UG2AG. However, additional attenuation caused by refraction (30) is considered [47]. Furthermore, if the receiver node is located at *top_depth* and *sub_depth*, the corresponding path loss becomes $WUSN'_{PLM_{\#1}}$ (31) and $WUSN'_{PLM_{\#2}}$ (32) respectively.

$$WUSN'_{PLM}(dB) = WUSN_{PLM}(dB) + 20 \log \left(\frac{n+1}{4} \right) \quad (30)$$

$$WUSN'_{PLM_{\#1}}(dB) = -288.8 + 20 \log \left(d_{ag_1} \cdot d_{ag_2} \cdot d_{ug} \cdot \beta \cdot f^2 \cdot \sqrt{\frac{2R}{1+R}} \cdot \frac{(n+1)}{4} \right) + 8.69\alpha \cdot d_{ug} \quad (31)$$

$$WUSN'_{PLM_{\#2}}(dB) = -288.8 + 20 \log \left(d_{ag_1} \cdot d_{ag_2} \cdot d_{ug} \cdot \beta \cdot f^2 \cdot \frac{(n+1)}{4} \right) + 8.69\alpha \cdot d_{ug} \quad (32)$$

Table 7. Comparison of the path loss approaches.

Models	Communications	CDC	Inputs parameters	Attenuations
Conventional Modified Friis [91]	UG2UG	Peplinski	m_v , bulk density, particle size, wave frequency, clay and sand proportions.	-
CRIM-Fresnel [25]	UG2UG	CRIM	m_v , bulk density, particle size, wave frequency, clay and sand proportions.	Reflection
NC Modified Friis [35]	UG2UG	Peplinski	m_v , bulk density, particle size, wave frequency, clay and sand proportions.	Reflection + Refraction
TDR Modified Friis [140]	UG2UG	TDR device	m_v , bulk density, particle size, wave frequency, clay and sand proportions.	-
ZS model [163]	UG2AG/AG2UG	Peplinski	m_v , bulk density, particle size, wave frequency, clay and sand proportions.	Reflection
XD model [47]	UG2AG/AG2UG	Peplinski	m_v , bulk density, particle size, wave frequency, clay and sand proportions.	Reflection
WUSN-PLM [183]	UG2UG UG2AG/AG2UG	MBSDM	m_v , wave frequency, sand proportion.	Reflection + Refraction

The path loss models are summarised in Table 7 in terms of the communication types, the CDC prediction approach, and the input parameters. According to the literature, only Peplinski or CRIM derivations are used for the CDC evaluation. However, both approaches are similar in considering the same inputs (volumetric water content, bulk density, particle size, wave frequency, clay, and sand proportions) since they are based on the Debye relaxation spectrum of free water. Contrary to the Conventional Modified Friis, the CRIM-Fresnel and the NC Modified Friis consider additional losses due to wave reflection and wave refraction in soil. Like existing underground path loss models, the mixing path loss models are based on Peplinski equations for the CDC prediction; thus, the same input parameters are required for the path loss prediction. However, the mixing models only consider addition loss due to the reflection phenomena of the wave and neglect the attenuation due to refraction in soil.

7 ENERGY HARVESTING

Energy Harvesting for WUSN is not trivial and some popular methods for conventional WSNs, like solar, cannot be used. In general, there are four popular techniques of energy harvesting for WUSNs: (i) Wireless Power Transfer; (ii) Thermal Energy Harvesting; (iii) Piezoelectric Energy Harvesting; and (iv) Micro Fuel cell energy harvesting.

7.1 Wireless Power Transfer

Electromagnetic energy is usually captured from the ambient RF sources, generated by high electromagnetic fields, like TV broadcast stations, radar stations, Wi-Fi routers, Bluetooth, global system for mobile communications (GSM), and other communication networks [83, 124, 176]. RF energy harvesting devices can convert electromagnetic energy into a usable direct current voltage to power low-power consumer electronics like sensor nodes. Several researchers show how RF can be used for Wireless Information Transfer (WIT) and Wireless Power Transfer (WPT) [39, 191]. The systems that perform both information and power transfer are known as Simultaneously Wireless Information and Power Transmission (SWIPT) systems [196]. There is a trade-off between information rate and delivered energy, commonly referred to as rate-energy (R-E) trade-off [24]. Grover *et al.* [58] have characterized the R-E region for point-to-point discrete channels by taking into account the white Gaussian noise model to emulate the effect of many random processes that occur.

The working principle of devices based on WPT is proposed by [101]. Two hardware architectures are presented depending on whether the energy harvesting circuit and the communication module share the same antenna. In a separated system (Figure 11b), the energy harvester has a dedicated antenna and therefore can be considered as the power supply. In that case, it automatically saves energy and powers the wireless communication module. In a co-located system (Figure 11a), the energy harvester and the communication module share the same antenna. It is possible to switch between the two modes. One significant advantage of such systems is their reduced size.



Fig. 11. Architecture of a communication module for wireless power transfer. (a) Co-located system: the energy harvester and the transceiver share the same antenna. (b) Separated system with two antennas.

According to [99], the harvested power from different RF sources is between $450\mu\text{W}$ to $7\mu\text{W}$ at a frequency of around 900MHz and a distance of 5m to 40m. Clerckx *et al.* explored in [38] several methods for transferring energy wirelessly during data transmission. The authors of [124], have investigated the potential of these methods for above-ground applications and present several challenges such as the wireless power transfer efficiency in soil and mobile power source over the ground for their usage in an underground environment. The simplest method under this kind of energy harvesting is RF radiation. The received power neglects the environmental losses, and the antenna gains are obtained from the Friis equation [53]. Apart from the amount of energy to be transferred during wireless communication, the frequency range and the hardware restrictions must be considered. The use of higher frequency of EM waves such as ultraviolet rays (8×10^{14} to 3×10^{16} Hz), X-rays (3×10^{16} to 3×10^{19} Hz), and gamma rays ($> 10^{19}$ Hz), can break DNA molecules. Thus, for safety purposes, the non-ionizing band between 30kHz and 300GHz is used for telecommunications and can therefore be applied for SWIPT systems [115].

7.2 Thermal Energy Harvesting

In general, heat energy coming from temperature variation in the environment can be scavenged into electricity via fundamental thermal conversion techniques based on the Seebeck and the Peltier effects [100, 130, 166]. Thermoelectric energy harvesting and pyroelectric energy harvesting, relying on the temperature changing over distance and time, respectively, are the two most commonly used thermal energy harvesting techniques [54].

7.2.1 Thermoelectric Energy Harvesting: The thermoelectricity or Peltier-Seebeck effect results from direct heat conversion into electricity or conversely through Seebeck and Peltier effects. In other words, when two metals are placed in electric contact, electrons flow out of the one in which the electrons are less bound and into the other [27]. Thermoelectric energy harvesting is a conventional technique for converting wasted thermal energy into electrical power employing thermoelectric generators (TEGs) [4]. A TEG collects electricity from a temperature difference with the help of P-type and N-type semiconductor materials. Thus, when there is a difference in temperature across either side of the TEG, charge carriers in doped semiconductors will migrate from the hot side to the cold side [193]. TEGs are typically made up of hundreds of P-type (positive) and N-type (negative) semiconductors. These latter are connected in series through electrical links and in parallel thermally between two ceramic layers [100]. The resulting voltage difference between the two plates is proportional to the difference in temperature between the two plates.

Also known as thermopower, thermoelectric power, or thermoelectric sensitivity [63], S is the Seebeck coefficient of the ceramic plates. It represents the voltage generated per degree of temperature difference of a material, as induced by the Seebeck effect. All materials are sensitive to the effects of thermoelectricity and their corresponding Seebeck coefficients are in $[100 - 1000\mu V/^{\circ}K]$. For example, iron has a thermopower of around $19\mu V/^{\circ}C$ at $0^{\circ}C$ [43, 80].

Elefsiniotis et al. [48] proposed a thermoelectric harvester for a sensor designed for aircraft applications. Regardless of the low temperature, the minimum harvested energy is more than 39.74J. Furthermore, TEGs have been used on BMW cars for generating electricity from waste heat to improve overall engine efficiency [40]. Pullwitt et al. investigated in [127] the potential of TEGs by analyzing the feasibility of their use at different soil temperatures. The authors considered a sensor node equipped with nine temperature sensors at different depths (2cm to 45cm) buried underground. The most optimal temperature difference is found between the ground level sensor and one buried at 21.5cm. By using a Peltier element, authors showed that more than 1Wh can be generated during the summer season.

7.2.2 Pyroelectric energy harvesting: Pyroelectricity can be defined as the property of a polar crystal material to produce electricity when subjected to a change of thermal energy. Thus, depending on the temperature change, the crystals become polarized positively or negatively [126]. Some research showed that pyroelectricity is exhibited only in crystallized non-conducting substances having at least one axis of symmetry that is polar (that is, having no center of symmetry, the different crystal faces occurring on opposite ends) [29]. Thus, contrary to thermoelectricity, the pyroelectric effects are observed only with a certain type of crystals or pyroelectric materials. Pyroelectric materials can generate energy due to temperature fluctuations due to the net dipole moment. This temperature change of the material will alter the quantity of the charges and creates an electric current [80].

The pyroelectric coefficient p is defined as the change in the spontaneous polarization vector with temperature and it can be expressed as a function of the surface charge density D introduced in the material and the variation of temperature ΔT [41]. By considering a homogeneous pyroelectric material characterized with a constant pyroelectric coefficient, the pyroelectric current i can be expressed in terms of the pyroelectric charge density D (33).

$$i = \frac{D}{dt} = pA \frac{\Delta T}{dt}, p = \frac{D}{\Delta T} \quad (33)$$

Where A denotes the surface area of the pyroelectric material, and the ratio $\frac{\Delta T}{dt}$ is the rate of temperature change.

Yang et al. [188] developed a Pyroelectricity that uses Zirconate Titanate film on the P-type and N-type components of the nanogenerator. Thus, the resulting pyroelectric generator is known as PZT. In [189], authors showed the potential of a developed pyroelectric nanogenerator. The proposed nanogenerator was able to

generate around $0.215mW/cm^3$. Another recent research [198] investigates pyroelectric harvesting by combining pyroelectric material with ferroelectric material. They showed that a hybrid material could be used to generate pyroelectricity at low temperatures ($< 100^\circ C$).

Despite the interest in pyroelectric harvesting, the need for a particular material and a tuning polarization makes this technology very challenging for WSN or WUSN.

7.3 Piezoelectric Energy Harvesting

Commonly known as the piezoelectric effect, piezoelectricity is a phenomenon converting mechanical into electrical energy due to the inherent polarization characteristics of certain crystals. Piezoelectric ceramics and polymers are two common piezoelectric materials [78]. A piezoelectric material creates an electrical potential gradient when subjected to mechanical stress and produces an electric field proportional to the applied stress. The main characteristic of piezoelectric material is to transform a vibration mechanism into an alternating current wave [180]. However, the opposite is also true. Thus, if an external voltage is placed across the material, it produces mechanical stress (34).

$$\delta = \frac{\sigma}{Y} + dE; \quad D = \epsilon E + d\sigma \quad (34)$$

where δ is the mechanical strain and σ is the mechanical stress. Y (in Pa) is the modulus of elasticity (Young module), and a table of modulus of elasticity for different types of soil is given by Kahrobaee et al. [76]. D the electrical displacement, E the electric field and ϵ the dielectric constant.



Fig. 12. Overview of a piezoelectric harvester. (a) An unimorph piezoelectric harvester with one piezoelectric layer. (b) A bimorph piezoelectric harvester with two piezoelectric layers and one electrode.

The architecture of an unimorph and a bimorph piezoelectric harvester is given in Figure 12. In each case, the piezoelectric and electrode layers can vibrate on the z -axis. Jayarathne et al. [71] have designed a device for vibration energy harvesting based on Arduino Nano. The main idea was to harvest the energy from the vibration of a vehicle by using the PZT as piezoelectric material. The average voltage output was 3.65V in the experiment against a theoretical voltage of 5.99V. A vibration energy harvesting system for WUSN has been proposed in [76]. The authors analyzed the piezoelectric energy resulting from the vibration penetration through the soil caused by a centre pivot irrigation system. The vibration frequency was 0.24Hz, and the authors claimed that it is lower than the practical range of commercial vibration energy harvesters. Moreover, the theoretical harvestable power of 17mW is not achieved during the experiments. Thus, piezoelectricity harvesting can be possible in WUSN with a higher value of acceleration, therefore, a higher vibration from the surface.

7.4 Microbial Fuel Cells–Based Energy Harvester

A microbial fuel cell (MFC), or biological fuel cell, is a bio-electrochemical device that drives the power of respiring microbes to convert organic substrates directly into electrical energy. In other words, the MFC is a fuel cell, which transforms chemical energy into electricity using oxidation-reduction reactions [14, 170]. The microbial fuel

cell (MFC) technology offers sustainable solutions for energy harvesting. However, the generation of practically usable power from MFCs remains a major challenge for several applications but can be suitable for low-power devices such as sensors. Pietrelli *et al.* investigated in [125] an energy-efficient harvester based on a Terrestrial MFC (TMFC) for WSN to power the microcontroller and the transceiver. Thus, the converter must transform the 0.6V input to 3.3V output voltage to meet the node's needs. When a plant is considered as MFCs (PMFC), the metabolism of micro-organisms is used as a catalyst and generates electrical energy. Thus, its main advantage is that it can generate energy from organic matter in the soil as fuel [15]. Because of the photosynthesis phenomena, the plants introduce a continuous supply of nutrients. The electro-generation will allow the movement of organic compounds to the anode compartment and the cathodic reduction of oxygen to create a closed electrical circuit. Additionally, it is possible to assess the health of the plants by measuring the electrogenic potential of the colony of bacteria. So a PMFC can be used as a biosensor that measures the plant's health and powers a low-power electronic device. However, the main parameter that can influence the production of energy while using PMFC is the plant's health status. The production of micro-organisms of the plant roots will not be regular if the plant is infected by parasites [31]. Figure 13 presents the functioning of a PMFC.

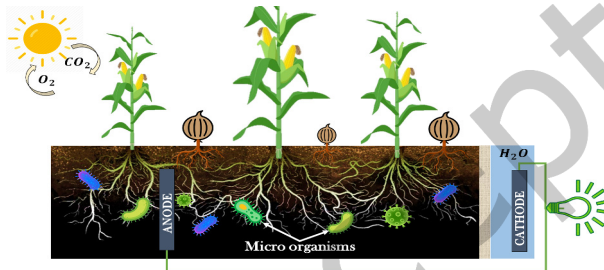


Fig. 13. Overview of the functioning of a PMFC harvester.

An alternative of using PMFC in a WSN is presented by Niwa *et al.* [113]. They investigated the sediment microbial fuel cell (SMFC) technology to replace conventional batteries used by sensor nodes. However, their experiments reveal that the SMFC provides ultra-low voltage and ultra-low current. Meehan *et al.* present in [106] an MFC-based system that can harvest energy in the water and, after that, powers a hydrophone deployed in the water. Their experiments can reach $1mW$ maximum power at $2.4mA$ MFC current. However, this power is insufficient for the proper functioning of an electronic device such as a hydrophone.

Another practical experiments of MFC harvesting in [160] show that $29mW/m^2$ to $49mW/m^2$ can be generated. The authors have concluded that the cathode catalyst, electrode material, and distance between electrodes and electrolytes influence the achievable electrical output power. Furthermore, a $67mW/m^2$ maximum power has been observed in PMFC. MFC and PMFC harvesting techniques are up-and-coming for power generation in battery-based applications that require low power and where battery replacement is not practical, such as WUSN.

8 CURRENT CHALLENGES AND DISCUSSIONS IN WUSN

WUSNs are an exciting and promising research area due to the nature of the underground environment in which sensor nodes are deployed. The use of underground channels led researchers to also rethink terrestrial WSN paradigms. However, the design of a WUSN faces several challenges such as power conservation, topology design, antenna design, and environmental extremes [10].

8.1 Hardware constraints

8.1.1 Power constraint. Depending on the intended application, WUSN devices should have a lifetime of at least several years to make their deployment cost-efficient. This challenge is complicated by the high wave attenuation

in soil, which requires that WUSN devices have radios with greater transmission power than terrestrial WSN devices. As a result, power conservation is a primary concern in the design of WUSNs. Like terrestrial WSNs, the lifetime of WUSNs is limited by each device's self-contained power source. However, access to WUSN devices will be much more complex than access to terrestrial WSN devices in most deployments, making retrieving a device to recharge or replace its power supply less feasible. While recharging devices deployed close to the surface may be possible with induction techniques, recharging buried devices will be difficult, if not impossible. Deploying new devices to replace failed ones is similarly tricky [72, 174]. Furthermore, contrary to terrestrial WSN in which solar cells can be used to power the sensor [72, 174], in the case of WUSN, it is challenging to apply this kind of traditional solar energy supply. However, as discussed in Section 7, several recent research considers new solutions for energy supply in WUSN. From these solutions, we can cite wireless power transfer, microbial fuel cells, thermal and piezoelectricity harvesting techniques [119, 139]. However, they still need to be explored and improved to provide sufficient energy to operate an underground sensor node without a traditional power supply. Therefore, power conservation remains the primary objective of the power constraint in WUSNs. Nowadays, energy conservation can be achieved by using both energy-efficient hardware (or components) and light and simple programs (mostly based on the sleep/wake-up approach).

8.1.2 Computing and memory limitations. Similar to classical WSN, in WUSN, the microcontroller and the memory are limited in terms of the clock speed (in tens KHz or MHz) and the storage size (in hundreds KB), respectively. The main objective of these limitations are the reduction of energy consumption and the overall price of a sensor node (each component). As a result, they may struggle to perform complex calculations or process large amounts of data. Thus, in general, the tasks of a node in a WUSN or WSN are reduced in collecting (with or not basic computations) physical data and transmitting them through the communication module to a distant receiver. Commonly, an external memory can be added to the sensor node to save permanently data within the main board of the sensor node (through an external non-volatile memory) or an external slot card [51]. Since the various tasks of an underground node are similar to those of a terrestrial node, both can use microcontrollers and memories with the same features.

8.1.3 Communication ranges. The communication range in WUSN depends on the radio transceiver used. Contrary to traditional WSN which can have a communication radius of up to 10 km, in WUSN, the communication distance is reduced by a few meters according to the wireless communication technology used. This reduction of the communication range is mainly caused by the attenuation of the radio wave (widely used) in the soil. To have a better range of communication, wireless technologies with low frequency are more adapted (see Section 5.2) than 2.4GHz-based protocols. Thus, the use of low-frequency helps in increasing the communication range of a sensor node, moreover, as we saw in Section 5.2, traditional transceivers based on EM waves can be replaced by new types of transceiver that use ACW, MPT, MI to enhance the communication range in WUSN. Nevertheless, due to the dynamic changes in the soil properties, the communication ranges are also altered, but depending on the technology used and the requirements of the application, these changes can be minimized.

8.1.4 Antenna design. The selection of a suitable antenna for WUSN devices is another challenging problem. In particular, the challenges related to the antenna design in WUSN are:

Variable requirements: Different devices may serve different communication purposes and require antennas with differing characteristics. For example, devices deployed in the topsoil may need special consideration due to the reflection of EM radiation experienced at the soil–air interface. Additionally, they will likely act as relays. Buried devices acting as vertical relays may require antennas in horizontal and vertical directions.

Size: Frequencies in the MHz or lower ranges will likely be necessary to achieve reasonable propagation distances of several meters. It is well known that the lower the frequency used, the larger antenna must be to efficiently transmit and receive at that frequency [42]. For example, at a frequency of 100MHz, a quarter

wavelength antenna would measure 0.75m. It is a challenge for WUSN to keep the sensor devices as small as possible.

Directionality: Communication with a single omnidirectional antenna will likely be challenging since WUSN can consist of devices at varying depths, and common omnidirectional antennas experience nulls in their radiation patterns at each end. This implies that with a vertically oriented antenna, communication with devices above and below would be impaired [42]. This issue may be solved by equipping a device with antennas oriented both vertically and horizontally.

8.2 Node deployments and network cost

The deployment of sensor nodes within the sensor fields can be deterministic or random (self-organizing). In deterministic deployment, the positions of the nodes and the different paths are pre-determined through the deployment area [153]. Meanwhile, in the case of random (or self-organized) deployment, the position of each node is not known in advance. Thus, the process of setting up routes is greatly influenced by energy consumption and is achieved by sensor nodes themselves. Even if a particular application uses a deterministic deployment, nodes should self-organize themselves after failures of some nodes to enhance the network's fault tolerance. In most of the WUSNs, the location of nodes is determined before their deployment itself. Thus, buried nodes collect data in a predefined location. However, due to node failures, another self-organizing behaviour of nodes could maintain the sensed data routing up to the BS [11, 13, 184]. When designing a WUSN, the cost of the whole network is an essential factor to take into consideration. Since the deployment area can become huge, the number of sensors within the field will significantly increase, thus the overall deployment cost. To reduce the deployment cost in WUSN, each sensor should be less expensive as possible and the minimum number of sensor nodes required should be determined before the real deployment [9, 26, 42].

8.3 Topology design

The design of an appropriate topology for WUSNs is of critical importance to network reliability and power conservation. WUSN topologies will likely be carefully planned, since only concrete areas are of sensing interest. A careful balance must be reached among these considerations to produce an optimal topology. Here, we provide concerns and suggestions associated with each of these considerations.

Intended application: Some applications may require very dense deployments of sensors over a small physical area, while others may be interested in sensing phenomena over a larger area but with less density. Security applications, for example, will require the dense deployment of underground pressure sensors, while soil monitoring applications may need fewer devices since differences in soil properties over tiny distances may not be of interest.

Minimization of the power usage: Intelligent topology design can help to conserve power in WUSNs. Since attenuation is proportional to the distance between a transmitter and receiver, power usage can be minimized by designing a topology with a large number of short-distance hops rather than a smaller number of long-distance hops.

Cost oriented: Unlike terrestrial sensor devices, the cost is involved in the excavation necessary to deploy WUSNs. The deeper a sensor device is, the more excavation is required to deploy it, and the greater the cost of deploying that device. Additional costs will be incurred when the power supply of each device has been exhausted, and the device must be unearthed to replace or recharge it. Thus, when the cost is a factor, deeper deployment of devices should be avoided if possible, and the number of devices should be minimized.

With the above considerations in mind, two possible topologies for WUSNs should address most underground sensing applications. One possibility is to place the devices at the surface, while the other is to place them underground (Figure 14).

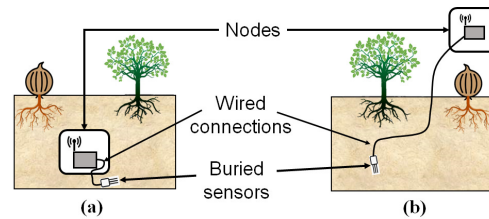


Fig. 14. Location of sensor nodes in a WUSN. (a) Node components and the sensor are fully buried under the ground. (b) Only the sensor is fixed under the ground. A wire cable is used to connect the sensor to the node located above the ground.

8.3.1 Located at the ground surface. There are several applications based on sensor networks for real-time monitoring of the soil, such as agriculture. Here, most of the electronic components (microcontroller, power supply, wireless transceiver, etc.) are located above the ground except the sensor itself [149]. This kind of *pseudo* WUSNs cannot be considered entirely as WUSNs because the wireless communications do not take place through the soil (Figure 14b). Indeed, knowing that the transceivers are located above the ground, all wireless communications occur over the air. However, even if the wireless communication is through the air (with lower attenuation than in the ground), a wired connection between the node and the sensor can be broken. Thus, in applications such as precision agriculture in which the soil is often ploughed to prepare a new seed, human or truck activities can break the wired connection with the sensor, making the node useless [60]. Furthermore, in such a hybrid sensor network, the nodes consist of terrestrial-based hardware devices such as WSN430, M3, A8, Zolertia Firefly, TelosB, micaZ, mica2, Iris, etc. [3, 16].

8.3.2 Fully buried under the ground. In this case, the nodes and their various components are completely buried under the ground, placed in a protective box to protect the electronic components from humidity (Figure 14a). In addition, high temperatures will also destroy the electronic components depending on the type of soil and the type of box used. Several WUSN research studies favor the use of plastic enclosures [183]. For better performance and higher energy efficiency, most of the nodes are designed and built specifically for a particular application [195, 197]. Thus, the use of commodity terrestrial nodes without any improvement is not suitable for WUSN applications [159].

8.4 Environmental extremes

The underground environment is far from ideal for electronic devices. Water, extreme temperatures, animals, insects, and excavation equipment all represent threats to a WUSN device, and it must be provided with adequate protection. Microcontrollers, transceivers, power supplies, and other components must be resilient to these factors. Additionally, the physical size of the WUSN device should be kept small, as the expense and time required for excavation increase for larger devices. Bearing in mind that the new techniques for powering sensor nodes are not yet fully exploitable (Section 7), the appropriate components of the nodes must be chosen carefully to be appropriate for the temperatures of the deployment environment while balancing environmental considerations with physical size and capacity concerns. Devices will also be subjected to pressure from people or objects moving overhead or, for deeply deployed devices, the inherent pressure of the soil above.

8.5 Socio-ecological impact

Regardless of the positive impact of WUSN/IoUT and the research orientation in improving the rate between performance and energy consumption, the heterogeneity of the existing systems lead to their proliferation. This proliferation is leading to new environmental problems linked to electronic waste. Thus, this social and ecological problem may be responsible for the increase in the CO₂ emission. Future WUSN/IoUT must be more eco-friendly

and consider the recycling process before deployment. Another interesting direction for these systems is to enable interoperability between existing systems, with the idea that an existing underground sensor network can be reused or merged with another system to enable new applications. As in any system where users share a common resource, the interoperability of the WUSN will raise the issue of privacy protection, has only a few practicable solutions but many shortcomings.

9 CONCLUSIONS

Contrary to classical WSN, Wireless Underground Sensor Networks or Internet of Underground Things are exposed to several additional challenges. In this survey, we conducted a comprehensive review of WUSN, organized and written as a tutorial. We examine both theoretical and practical aspects. Due to the diversity of existing WUSN systems, we first grouped them into applications and testbeds and provided a new classification of application scenarios. The resulting taxonomy allows us to group all WUSN applications into three clusters: i) Environmental and agricultural monitoring; ii) Underground structural monitoring; and iii) Infrastructure monitoring and intrusion tracking. For each application cluster and existing testbed, we compared the related systems according to several relevant parameters.

Furthermore, the five wireless technologies widely used on WUSN applications and testbeds are identified and described in detail. Based on their characteristics, we provided a comparison of the wireless technologies in terms of 9 parameters. We can conclude that electromagnetic waves are the most widely used for WUSN compared with other technologies (magnetic induction, acoustic wave, mud pulse telemetry, and visible light communication). Moreover, according to the comparison provided, we observed that wireless technology is highly related to the type of application. For example, EM is more suitable for WUSN applications for environmental and agricultural monitoring due to the limited buried depth of the sensor nodes (usually less than 50cm). However, for applications like downhole monitoring, MPT is widely used because of its low latency and its high communication range.

Since allowing reliable communication in WUSN remains a relevant issue, we also studied recent research on predicting signal path loss in the soil. We mainly focused on path loss models for EM due to their broader usage. We compared three different families of path loss models, covering UG2UG, UG2AG/AG2UG and all three types of communications. From this comparison, we concluded that the latter is more general while better performing.

The energy supply remains a key challenge for WUSN, as usual energy harvesting techniques such as solar panels are not useful underground. We presented some further options: i) wireless power transfer; ii) thermal energy; iii) piezoelectricity; and iv) microbial fuel cell harvesting. However, despite promising results, these harvesting techniques are not currently capable of feeding a sensor network efficiently and need to be improved. Finally, we discussed the current challenges of WUSN. We identified important problems not yet solved in order to inspire and guide future research. With this survey and tutorial, we aim to foster the further development of WUSN and their individual challenges. We strongly believe that WUSN have a great potential to address various societal and business challenges, such as precision agriculture or environmental monitoring. WUSN offer some unique properties, such as device concealment and thus protection against damage or theft, low costs, and a unique sensing environment.

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