

# Wireless Signal Propagation Using Magnetic Induction in Underground Sensor Network

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**Abstract---**The wireless underground sensor networks (WUSNs) and the terrestrial wireless sensor networks differ in the aspect of signal propagation medium. The underground sensor network is a challenging environment for wireless communications since the propagation medium consists of soil, rock and water. The former signal propagation techniques use the EM wave suffers from high path loss, dynamic channel condition and large antenna size. To overcome these disadvantages we go for a MI (Magnetic Induction) technique. Based on the channel analysis, the MI waveguide technique is used to reduce the high path loss. The MI transmission technique requires low operating frequencies and lesser power than the ordinary RF frequencies. But the lower operating frequencies requires high antenna size used to transmit and receive signals at 300 MHz .Based on the analysis we increase the transmission range to a larger extent than the existing range with the help of low antenna size. In this paper, we first provide a detailed analysis on the path loss and the bandwidth of the MI communication channel in underground environments. Then based on the analysis, we develop the MI waveguide technique for WUSNs, which can significantly reduce the path loss, enlarge the transmission range and achieve practical bandwidth for MI communication in underground environments. In particular, the MI transmitter and receiver are modeled as the primary coil and secondary coil of a transformer. Multiple factors are considered in the analysis, including the soil properties, coil size, the number of turns in the coil loop, coil resistance, operating frequency. The analysis shows that the ordinary MI systems have larger transmission range but lower bandwidth than the EM wave systems. However, neither the ordinary MI system nor the EM wave system is able to provide enough communication range for practical WUSNs applications. Motivated by this fact, we develop the MI waveguide technique to enlarge the communication range. In this case, some small coils are deployed between the transmitter and the receiver as relay points, which form a discontinuous waveguide. It shows that the MI transmission is not affected by soil type, composition, compaction, or moisture content, and requires less power and lower operating frequencies than RF transmission. However,the theoretical/experimental results show that the communication range is no more than 30 inches (0.76 m). Moreover, the bandwidth of the MI system is not considered in the paper.

## I. INTRODUCTION

SENSOR networks are currently a very active area of research. Sensors are also successfully used to monitor the integrity of belowground infrastructures such as plumbing, and landslide and earthquake monitoring are accomplished using buried seismometers. While the usefulness of these applications of sensor network technology is clear, there remain shortcomings that can impede new and more varied uses. These shortcomings include: visibility (versus concealment), ease of deployment, timeliness of the data, reliability, and potential for coverage density. This paper departs from current technology and introduces the concept of Wireless Underground Sensor Networks (WUSNs), where the majority of sensor devices, including their means of transmitting and receiving, are deployed completely below the ground. WUSNs can address the cited shortcomings of current existing underground sensor networks in the following ways:

**Concealment** – Current underground sensing systems require data loggers or motes deployed at the surface with wiring leading to underground sensors [3,9] in order to avoid the challenge of wireless communication in the underground. The aboveground Components of the sensing system are vulnerable to agricultural and landscaping equipment such as lawnmowers and tractors, which can cause damage to devices. Visible devices may also be unacceptable for performance or aesthetic reasons when monitoring sports fields or gardens. WUSNs, on the other hand, place all equipment required for sensing and transmitting underground, where it is out of sight, protected from damage by surface equipment and secure from theft or vandalism.

**Ease of deployment** – Expansion of the coverage area of existing underground sensing systems requires deployment of additional data loggers and underground wiring. Even if terrestrial WSN technology is used for underground monitoring as in [9], underground wiring must still be deployed to connect a sensor to a surface device. Additional sensors in a WUSN can be deployed simply by placing them in the desired location and ensuring that they are within communication range of another device.

**Timeliness of data** – Data loggers often store sensor readings for later retrieval. WUSNs are able to wirelessly forward sensor readings to a central sink in real time.

**Reliability** – A data logger may have tens of sensors connected to it and represents a single point of failure for all of them. Since the sensors of a single data logger may be spread over a large physical area, a failure of a datalogger could be catastrophic to a sensing application. WUSNs, however, give each sensor the ability to independently forward readings, eliminating the need for a data logger as well as the wire that must be buried between a datalogger and a sensor. Additionally, WUSNs are self-healing. Device failures can be automatically routed around, and the network operator can be alerted to device failure in real time.

**Coverage density** – Sensors in existing underground applications are typically deployed close to their controlling data logger to minimize the distance between them. Coverage density can therefore be uneven – high in the vicinity of the data logger, but low elsewhere in the environment. WUSNs allow sensors to be deployed independent of the location of a data logger. While the benefits of WUSNs should be clear from the above, there are a number of research challenges that must be addressed to make them feasible. WUSNs may appear to be similar to their terrestrial counterparts, but the underground environment is a hostile place for wireless communication and requires that existing architectures for terrestrial WSNs, including hardware and communication protocols, be reexamined. The remainder of the paper is organized as follows. In Section 2 we provide an overview of potential applications for WUSNs. Section 3 describes several factors that are important to consider in the design of WUSNs and proposes possible network topologies. In Section 4, we present an overview of the underground channel and the associated challenges. Section 5 examines the communication architecture of WUSNs and explains the challenges existing at each layer of the protocol stack. We conclude the paper in Section 6.

## 2. WUSN DESIGN CHALLENGES

WUSNs are an exciting research area because of the unique nature of the underground environment. From a severely impaired underground channel to practical considerations such as the size of a device's antenna, the underground forces us to rethink terrestrial WSN paradigms. In this section, we describe four considerations for WUSN design necessitated by this unique environment: power conservation, topology design, antenna design, and environmental extremes.

### A. Power conservation

Depending on the intended application, WUSN devices should have a lifetime of at least several years in order to make their deployment cost-efficient. This challenge is complicated by the lossy underground channel, 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 the self-contained power source of each device. Unfortunately, access to WUSN devices will be much more difficult than access to terrestrial WSN devices in most deployments, making retrieval of a device to recharge or replace its power supply less feasible. While recharging of devices deployed close to the surface may be possible with induction techniques, recharging deeper devices will be difficult, if not impossible. Deployment of new devices to replace failed ones is similarly difficult. The authors describe technologies to generate energy from background radio signals, thermoelectric conversion, and vibrational excitation. Power conservation, therefore, should be a primary objective in the design of WUSNs. While it is possible to increase the lifetime of a device by providing it with a larger stored power source, this is not necessarily desirable since it will increase the cost and size of sensor devices. Conservation can be achieved by utilizing power-efficient hardware and communication protocols.

### B. Topology design

The design of an appropriate topology for WUSNs is of critical importance to network reliability and powerconservation. WUSN topologies will likely be significantly different from their terrestrial counterparts. For example, the location of a WUSN device will usually be carefully planned given the effort involved in the excavation necessary for deployment. Also three-dimensional topologies will be common in WUSNs, with devices deployed at varying depths dictated by the sensing application. The application of WUSNs will play an important role in dictating their topology, however, power usage minimization and deployment cost should also be considered in the design. A careful balance must be reached among these considerations to produce an optimal topology. Here, we provide concerns associated with each of these considerations as well as suggest new WUSN topologies.

**Intended application** – Sensor devices must be located close to the phenomenon they are deployed to sense, which dictates the depth at which they are deployed. Some applications may require very dense deployments of sensors over a small physical area, while others may be interested in sensing phenomenon over a larger physical area but with less density. Security applications, for example, will require a dense deployment of underground pressure sensors, while soil monitoring applications may need fewer devices since differences in soil properties over very small distances may not be of interest.

**Power usage minimization** – 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** – Unlike terrestrial sensor devices, where deployment simply requires physically distributing devices, significant labor, and thus cost, is involved in the excavation necessary to

deploy WUSNs. The deeper a sensor device is, the more excavation 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 cost is a factor, deeper deployment of devices should be avoided if possible, and the number of devices should be minimized. Minimizing the deployment conflicts with the dense deployment strategy suggested by power considerations, and an appropriate trade-off must be established. With the above considerations in mind, we suggest two possible topologies for WUSNs which should serve to address most underground sensing applications. These are the underground topology and the hybrid topology.

*Underground topology:* This consists of all sensor devices deployed underground, except for the sink, which may be deployed underground or aboveground. Similar to terrestrial WSNs, the sink in a WUSN is the node at which all data from the sensor network is received. Underground topologies can be single-depth, i.e., all sensor devices are at the same depth, or multi-depth, i.e., the sensor devices are at varying depths. Both communication protocols and sensor device hardware for multi-depth networks require special consideration to ensure that data may be efficiently routed to a surface sink. The depth at which devices are deployed will depend upon the application of the network, e.g., pressure sensors must be placed close to the surface, while soil water sensors should be located deeper near the roots of the plants. This topology minimizes (or eliminates, in the case of an underground sink) the aboveground equipment, providing maximum concealment of the network. Devices deployed at a shallow depth may be able to make use of a ground-air-ground path for the channel, which should produce lower path losses than a ground-ground channel.

*Hybrid Topology:* Since wireless signals are able to propagate through the air with lower loss than through soil, the aboveground sensor devices require a lower power output to transmit over a given distance than the underground sensor devices. A hybrid topology allows data to be routed out of the underground in fewer hops, thus trading power intensive underground hops for less expensive hops in a terrestrial network. Additionally, terrestrial devices are more accessible in the event that their power supply requires replacement or recharging. Thus, given a choice, power expenditures should be made by aboveground devices rather than underground devices. The disadvantage of a hybrid topology is that the network is not fully concealed as with a strictly underground topology. A hybrid topology could also consist of underground sensors and a mobile terrestrial sink which moves around the surface of the underground network deployment area and collects data from the underground sensors or terrestrial relays. In the absence of terrestrial relays, deeper devices can route their data to the nearest shallow device (which is able to communicate with both underground and aboveground devices), which will store the

data until a mobile sink is within range. This topology should promote energy savings in the network by reducing the number of hops to reach a sink, since effectively every shallow device can act as a sink. The drawback of this topology is the latency introduced by storing data until a mobile collector is within the range. Mobile sinks have already been used successfully for an aboveground WSN used for agricultural monitoring [2].

### C. Antenna design

The selection of a suitable antenna for WUSN devices is another challenging problem. In particular, the challenges are:

*Variable requirements* – Different devices may serve different communication purposes, and therefore may require antennas with differing characteristics. For example, devices deployed within several centimeters of the surface, may need special consideration due to the reflection of EM radiation that will be experienced at the soil-air interface. Additionally, near-surface devices will likely act as relays between deeper devices and surface devices. Deeper devices acting as vertical relays to route data towards the surface may require antennas focused in both the horizontal and vertical directions.

*Size* – Frequencies in the MHz or lower ranges will likely be necessary to achieve practical propagation distances of several meters. It is well known that the lower the frequency used, the larger an antenna must be to efficiently transmit and receive at that frequency. At a frequency of 100 MHz for example, a quarter-wavelength antenna would measure 0.75 m. Clearly this is a challenge for WUSNs since we desire to keep sensor devices small.

*Directionality* – Future research must address whether an omnidirectional antenna or a group of independent directional antennas is most appropriate for a WUSN device. Communication with a single omni-directional antenna will likely be challenging since WUSN topologies can consist of devices at varying depths, and common omnidirectional antennas experience nulls in their radiation patterns at each end. This issue may be solved by equipping a device with antennas oriented for both horizontal and vertical communication. Antenna design considerations will also vary depending on the physical layer technology that is utilized. We have focused on EM waves here, however, as discussed in Section 4, it remains to be determined whether other technologies are better suited to this environment.

3.4. Environmental extremes The underground environment is far from an ideal location for electronic devices. Water, temperature extremes, animals, insects, and excavation equipment all represent threats to a WUSN device, and it must be provided with adequate protection. Processors, radios, 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. Battery technology 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. The same environmental factors that make the underground a challenging environment for hardware also create extreme underground wireless channel conditions, which are discussed in detail in Section 4.

#### IV. UNDERGROUND WIRELESS CHANNEL

The underground wireless channel is one of the main factors that make realizing WUSNs a challenge. Although digital communication in the underground appears to be unexplored, EM wave propagation through soil and rock has been studied extensively for ground-penetrating radar [8,12,13] in the past.

In this section, we describe properties of the underground EM channel, the effect of various soil properties on this channel, and methods for predicting path losses in an underground communication link. Additionally, we describe alternative physical layer technologies which may be a better fit for WUSNs, and existing work on underground wireless digital communication.

##### A. Underground channel properties

Although EM wave propagation has been studied, a comprehensive channel model for the underground does not yet exist. We have identified five main factors, however, which impact communication with EM waves in the underground: extreme path loss, reflection/refraction, multi-path fading, reduced propagation velocity, and noise. Extreme path loss – Path loss due to material absorption is a major concern when using EM waves for underground communication. Losses are determined by both the frequency of the wave and the properties of the soil or rock through which it propagates. Lower frequencies propagate underground over a given distance and soil condition with less attenuation than higher frequencies. Attenuation per meter due to material absorption only is provided. Even frequencies in the MHz range may experience attenuation on the order of over 100 dB per meter depending on soil conditions

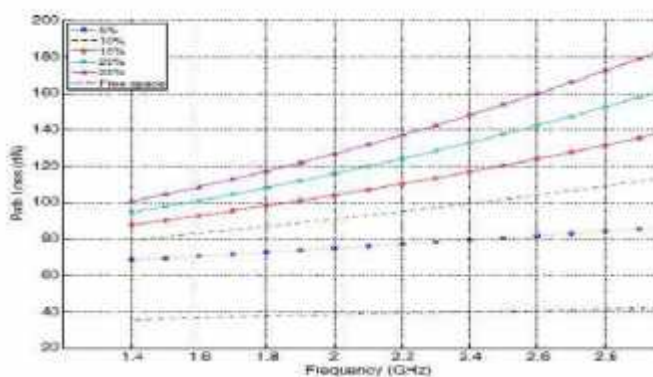


Fig-1: Path Loss Due To Material Absorption and Spherical Wavefront

Path losses are highly dependent on the soil type and water content. In the above figure, Path loss due to material absorption and spherical wavefront. spreading over a distance of 1 m for a 50% sand, 35% silt, and 15% clay soil sample with various volumetric moisture contents. A curve demonstrating losses due only to wavefront spreading in free space is provided as reference. A bulk density of 1.3 g/cm<sup>3</sup> and a specific density of 2.66 g/cm<sup>3</sup> are assumed for the soil. Soils are generally classified according to the size of their particles. Sandy soils are generally more favorable to EM wave propagation than clay soils. Moreover, any increase in soil water content will produce a significant increase in attenuation.

**Reflection/refraction** – WUSN devices deployed near the surface are able to communicate with both underground and surface devices, e.g., a surface sink, using a single radio. This implies that a communication link partially underground and partially in the air is necessary. When the propagating EM wave reaches the ground–air interface, it will be partially reflected back into the ground and partially transmitted into the air, as with any other type of medium transition. The reverse is true for transmissions from surface devices to underground devices.

**Multi-path fading** – The same mechanism described previously, whereby waves at medium transitions are partially transmitted and partially reflected, will also cause multi-path fading. This effect will likely be especially pronounced for sensors deployed near the surface, where the wave is close to the ground–air interface. Scattered rocks and plant roots underground, as well as varying soil properties, will act as scatterers and also produce fading. **Reduced propagation velocity** – EM waves propagating through a dielectric material such as soil and rock will experience a reduced propagation velocity compared to that of air. Since most soils have dielectric constants in the range of 1–80, a minimum propagation velocity of about 10% the speed of light is implied.

**Noise** – Even the underground channel is not immune to noise. Sources of underground noise include power lines, lightning, and electric motors. Additionally, atmospheric noise is present in the underground. Underground noise is generally limited to relatively low frequencies (below 1 kHz), however. The above properties of the underground channel are also highly dependent on the soil properties between the transmitter and receiver. Therefore, a thorough understanding of how various soil parameters affect the channel is necessary.

##### B. Effect of soil properties on the underground channel

The composition of a soil, including its water content, particle sizes, density, and temperature, all combine to form its complex dielectric constant  $\epsilon_r$ . This parameter directly affects the attenuation of any EM signal passing through the soil, and it is thus useful to be able to predict its value. We now discuss in detail the effects of these and other parameters on signal attenuation.

**Water content** – Soil water content is by far the most significant parameter to consider when predicting signal loss through a

given type of soil. Any increase in the water content of a soil will make the channel significantly more lossy. An increase of about 137 dB loss per meter as water content rises from dry to 13% volumetric, at a frequency of 1 GHz is reported in [13]. Although soil conditions are not reported for this work, the effect of a rise in water content is highly dependent on the type of soil, e.g., sandy soils show less attenuation as water content increases than do clay soils [8]. For example, losses at 900 MHz and 40% volumetric water content are reported in [8] as 20 and 55 dB per meter for sandy and clay soils, respectively. Attenuation caused by soil water content is also dependent on the frequency being used.

### C. Soil dielectric prediction models

As discussed previously, knowledge of the complex dielectric constant  $\epsilon_r$  of the soil or rock through which a wave is propagating allows us to predict the attenuation due to material absorption using well known electro magnetic relations. Although not a complete model of the underground channel, it can give a good indication of channel conditions since attenuation due to material absorption is the major concern in underground wireless communication with EM waves. Thus, a major challenge for predicting attenuation in an underground link is to compute the dielectric constant of the soil in which the WUSN devices are deployed. Fortunately, several models are available for accurately predicting for a homogenous soil sample. However, predicting path losses for an underground channel remains a challenge due to the inhomogeneous nature of ground. Soil makeup, density, and water content can all vary drastically over short distances. Soil dielectric prediction models generally fall into three categories: phenomenological, volumetric, and semi-empirical. Phenomenological models relate relaxation times with the frequency-dependent behavior of soil. Volumetric models predict the dielectric constant based on the soil makeup and the dielectric properties of each material. Semi-empirical models are based on observed relationships between various characteristics of the material and its dielectric properties. Slightly different versions of the model are used for 0.3–1.3 GHz and 1.4–18 GHz. Both take as parameters the frequency, volumetric water content, bulk density, specific density of solid soil particles, mass fractions of sand and clay, and temperature. In Fig. 1 signal loss per meter due to material absorption predicted by this model is shown. The figure is based on a soil mixture of 50% sand, 15% clay, and 35% silt over a range of frequencies and soil water contents. Clearly per meter signal attenuation increase with increasing frequency and water content. An increase in frequency, however, has a much larger effect at a higher water content. In The model predicts a greater increase in signal attenuation for soils with a clay consistency than for sandy soils. These figures reinforce the distinct challenge of underground wireless communication with EM waves characteristic of a WUSN are feasible.

## V. COMMUNICATION ARCHITECTURE

This section addresses the protocol stack of WUSNs. Classical layered protocol stack and its five layers, as well as the cross layered power management and task management planes. The unique challenges of the underground environment cannot, however, be addressed in terrestrial WSN protocols. Therefore, it is necessary to reexamine and modify each of the layers to assure that WUSNs operate as efficiently and reliably as possible. In addition, there are many opportunities in this environment for enhancing the efficiency of the protocol stack through cross-layered design. Although we promote a cross-layered design approach for WUSNs, it is nonetheless important to first understand the challenges at each layer of the traditional protocol stack. In this section we examine each layer of the protocol stack and outline the research challenges that must be addressed to make WUSNs feasible. We then discuss cross-layered design opportunities for WUSNs.

### A. Physical layer

Physical layer communication represents a significant challenge for WUSNs. EM waves propagating through soil and rock experience extreme losses as discussed in the previous section. Another challenge is the dynamic nature of the underground environment – loss rates are highly dependent on numerous soil properties, especially water content [8], which may vary over time. Wet soils cause extreme attenuation of EM waves, even to the point of making communication impossible at any distance [13]. Losses produced by an increase in soil water content, after a rainfall for example, can last for a significant amount of time. Given the challenging nature of EM wave propagation in the underground, designing an efficient antenna is very important. Embedding an antenna in a conductive medium such as soil can significantly affect its radiation and reception characteristics. As previously discussed, when propagating through soil and rock, lower frequencies of EM waves experience less attenuation than higher frequencies [12], so communication at practical distances of several meters will likely only be feasible when using these lower frequencies. Traditional EM antennas are much too large for a WUSN device at the low frequencies of interest. Given the power constraints of WUSN devices and the necessity of using low frequencies to reduce path losses as explained in the previous section, the selection of an appropriate modulation scheme in WUSNs is another challenge. Earlier works that have addressed underground wireless communication have focused solely on analog communication. A data rate of 2 kbps is achieved. Aside from this work, modulation schemes for underground communication continue to be an unexplored area. The use of a lower carrier frequency means that less bandwidth is available for data transmission, so WUSNs will be constrained to a lower data rate than terrestrial WSNs. Extreme channel losses will also affect the data rate in WUSNs. Open research issues at the physical layer are:

Additional analysis of electromagnetic, magnetic induction (MI), and seismic communication in the underground needs to be carried out to identify the most appropriate physical layer

technology. Some combination of these technologies may be optimal, particularly for shallow sensor devices which must communicate with both underground and surface devices.

A power-efficient modulation scheme suitable for the dynamic high-loss underground channel must be chosen. Research into varying the modulation scheme depending on underground channel conditions is needed. After a rainfall when the channel is severely impaired, for example, it may be better to trade higher data rates for a simpler modulation scheme. Modulation schemes requiring channel estimation by means of probe packets should be avoided due to the energy overhead involved in probe transmission.

The trade-off between reliability and capacity must be examined. Lower frequencies propagate with lower loss over a given distance underground, but also have less available bandwidth for data transmission reducing the channel capacity. An information theoretical study of the capacity of underground wireless communication channels is needed.

### B. Data link layer

Existing MAC protocols [7] intended for terrestrial WSNs will likely perform poorly in WUSNs. These protocols for terrestrial WSNs are typically either contention-based or TDMA-based, and focus on minimizing energy consumption by addressing four primary areas: idle listening, collisions, control packet overhead, and overhearing [7]. WUSNs require special consideration for MAC protocol development due to the characteristics of the underground wireless channel which we explained in detail in Section 4. Although energy conservation is the main focus of existing MAC protocols for terrestrial WSNs, energy savings are captured by reducing idle listening time [7]. In WUSNs, radios must transmit with a much higher output power than in the terrestrial WSNs in order to overcome path losses incurred in the ground. In order for underground sensors to have an acceptable lifetime, the number of transmissions must be minimized. Since collisions cause retransmissions, a WUSN MAC protocol should avoid collisions. Although this may be accomplished with a contention-based protocol using an RTS/CTS type scheme, this introduces unacceptable overhead in WUSNs. On the other hand, a TDMA-based scheme is able to eliminate collisions by reserving a timeslot for each device to transmit. However, in this case synchronization becomes a concern, and introduces its own overhead. Since WUSN devices will likely report sensor data infrequently, they can operate with a low duty cycle to save power. Unfortunately, a device's clock may drift a large amount during these periods of sleep and the network may lose its synchronization. Due to the lossy nature of the underground channel and energy constraints of sensor devices, signals will likely have relatively high bit error rates (BER) at the receiver. ARQ schemes are inappropriate for WUSNs due to the energy expenditures necessary for packet retransmissions and the overhead of acknowledgements. Channel coding using an FEC

scheme will be a better choice, however, this is an open research subject for WUSNs. Open research issues at the data link layer are:

Tradeoffs between the additional overhead of a TDMA-based protocol and the energy savings realized through collision elimination need to be explored to definitively determine whether a TDMA-based or contention-based MAC is most appropriate for WUSNs. A possible solution may be a hybrid MAC scheme, where depending upon network and underground wireless channel conditions, either a contention-based or a TDM Abased MAC may be optimal at a given time.

### C. Network layer

Ad-hoc network routing protocols generally fall into three categories: proactive, reactive, and geographical. Proactive routing protocols continuously maintain routes between all devices in the network, while reactive protocols perform route discovery only when a route is required. However, both of these classes of routing protocols have high signaling overhead. Additionally, predetermined routes, as in proactive routing, will likely not be useful as the network may lose synchronization over long sleep periods or a device may become unreachable due to increased soil water content. Geographical routing protocols establish routes using information about the physical location of the devices. In this manner, a route can be created that brings data physically closer to the destination with each hop. Geographical routing protocols may or may not be useful for WUSNs depending on the deployment. Most sensors will be deployed by digging or drilling a hole for each one, and thus, a detailed location information can be recorded at the time of deployment. In this scenario, geographical routing protocols may be useful. Alternatively, a WUSN may be deployed by randomly scattering sensor devices and then covering them with soil. This could be the case when constructing a road or laying the foundation of a building since the site is already excavated. In this scenario, location information for each device will not be known, and geographical protocols will be less useful. Current routing protocols for terrestrial WSNs [1] generally treat all devices equally with regard to selection for participation in a path from a source to a sink. Several consider the current energy level of a sensor when determining a path. The radio transmit power necessary to communicate between any two devices in a WUSN can vary greatly however, and it is important to consider in routing the data. In a hybrid underground-terrestrial sensor network, for example, it may be more power-efficient to route data to a terrestrial device, which could relay it through a series of terrestrial links rather than the high-cost underground links. For a WUSN deployed within and around an underground mine, it will be more power-efficient to route data through sensors in open-air mine tunnels than through those devices embedded in the soil and rock. Additionally, link costs will vary over time as soil conditions, such as water content, change. Network layer

protocols must be aware of the unique challenges of the underground in order to maximize the power efficiency and thus, the network lifetime. Open research issues at the network layer which must be addressed include:

The effect of the low duty cycle of WUSNs on routing protocols must be examined. The network topology can change drastically between sensing intervals and the network layer must efficiently handle this. Research into routing protocols suitable for time sensitive WUSN applications, such as presence monitoring for security with underground pressure sensors, is

#### *D. Transport layer*

A transport layer protocol is needed in WUSNs not only to achieve reliable collective transport of event features, but also to perform flow control and congestion control. While several transport layer protocols have been proposed for terrestrial WSNs, the high loss rates of the underground channel require this layer to be re-examined.

The primary objective is to save scarce sensor resources and increase network efficiency. A reliable transport protocol should guarantee that applications are able to correctly identify event features estimated by the sensor network. Congestion control is needed to prevent the network from being congested by excessive data with respect to the network capacity, while flow control is needed to avoid overwhelming network devices with limited memory by data transmissions. Due to the low data rates of WUSNs, congestion becomes an important problem, particularly near the sink. One method of avoiding this is to route data to terrestrial relays which are capable of a higher data rate. This could be accomplished at the network layer, and points to an interesting cross-layered solution to the congestion problem. Most existing TCP implementations are unsuited for WUSNs since the flow control functionality is based on a window-based mechanism and retransmissions. As stated before, we try to avoid/reduce the number of retransmissions in WUSNs in order to save energy. Rate-based transport protocols also seem unsuited for this challenging environment. In fact, although they do not adopt a window-based mechanism, they still rely on feedback control messages sent back by the destination to dynamically adapt the transmission rate, i.e., to decrease the transmission rate when packet loss is experienced or to increase it otherwise. The high delay and delay variance can thus cause instability in the feedback control. Furthermore, due to the very high unreliability of the underground channel, it is necessary to distinguish between packet losses due to the high bit error rate of the underground channel, from those caused by packets being dropped from the queues of sensor devices due to network congestion. When congestion is the cause of packet losses, the transmission rate should be decreased to avoid overwhelming the network, while in the case of losses due to poor channel quality, the transmission rate should not be decreased to preserve throughput efficiency. For these reasons, it may be necessary to devise completely new strategies to

achieve underground flow control and reliability. Open research issues at the transport layer which must be addressed include:

#### *E. Cross-layering*

The research challenges involving cross-layered protocol design are:

- *Utilizing sensor data for channel prediction* – As described earlier, the condition of the underground channel is highly dependent on any soil water content. Since monitoring of this variable will be a common use of WUSNs, a large percentage of sensor devices will be equipped with moisture sensors. This argues for a cross-layer approach between the application layer, where water content readings are being taken, and the lower layers, which could utilize this information for adjusting radio output power, appropriately choosing routes, and selection of an appropriate adaptive FEC scheme.

- *Utilizing channel data for soil property prediction* – The opposite of the above, whereby channel properties are predicted by sensor readings, can also be accomplished. Gradually increasing losses in the channel between two devices while other devices remain reachable may be interpreted to mean increasing water content. This could be used to sense soil conditions in the areas between devices where no sensors are deployed, and points to an interesting interaction between the application and network layers.

- *Physical-layer based routing* – Power savings can be achieved with the use of a cross-layer MAC and routing solution. Since soil conditions can vary widely over short distances, different power levels will be necessary to communicate with a given device's neighbors. In the interest of prolonging network lifetime, routes should generally try to utilize links where lower transmit powers are necessary. This information is gathered at the physical layer, but needs to be passed on to the network layer. Additionally, soil water content readings from surrounding devices can be processed to form a map of water content over the network's deployment terrain, allowing packets to be routed through dry areas where the soil produces less attenuation.

- *Opportunistic MAC scheduling* – Opportunistic scheduling at the MAC layer can be accomplished with the help of application-layer sensor data. For example, if a device detects continually increasing soil water content, it may try for a period to send packets at a higher power level to overcome the additional losses incurred, followed by a period of silence where it caches outbound packets, waiting for a decrease in soil water content in order to conserve power. Waiting for water content to decrease means a device will need fewer retransmissions and a lower transmit power.

- *Cross-layer between link and transport layers* – Transport layer functionalities can be tightly integrated with data link layer functionalities in a cross-layer integrated module. The purpose of such an integrated module is to make the information about the condition of the variable underground channel available also at the transport layer. In fact, the state of the

channel is usually known only at the physical and channel access sub-layers, while the design principle of layer separation makes this information transparent to the higher layers. This integration enables maximizing the efficiency of the transport functionalities, and the behavior of data link and transport layer protocols can be dynamically adapted to the variability of the underground environment.

## VI. CONCLUSION

We introduced the concept of WUSNs in which sensor devices are deployed completely below ground. There are existing applications of underground sensing, such as soil monitoring for agriculture. We demonstrated the benefits of WUSNs over current sensing solutions including: complete network concealment, ease of deployment, and improved timeliness of data. These benefits enable a new and wider range of underground sensing applications, from sports field and garden monitoring, where surface sensors could impede sports activity or are unsightly, to military applications such as border monitoring, where sensors should be hidden to avoid detection and deactivation. Underground is a particularly difficult environment for wireless communication which poses several research challenges for WUSNs. We demonstrated that the condition of the underground channel is dependent on the properties of the soil or rock in which devices are deployed, particularly the water content. Additionally, we showed that low frequencies are able to propagate with lower losses through the underground and that frequencies used by traditional terrestrial WSNs are infeasible for this environment. The use of low frequencies, however, severely restricts the bandwidth available for data transmission in WUSNs. This factor, combined with the high losses of the underground channel and the importance of conserving energy, necessitate reexamining existing terrestrial WSN communication protocols and developing new protocols which address these issues. We also presented major research challenges at each layer of the protocol stack for WUSNs and concluded the paper with suggestions for a cross-layer protocol solution.

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