

Performance Of Wusn In Environmental And Security Monitoring System

Venkadesh.R*, DR.K.Rajan**, R.Balaji***

*(Vice-Principal, Vel Tech Engineering College Chennai-62, India.)

** (Principal, Vel Tech Engineering college, Chennai-62.)

*** (Velammal Engineering College- Tifaccore Department, Chennai-62)

ABSTRACT

This paper introduces the concept of a Wireless Underground Sensor Network (WUSN). WUSNs can be used to monitor a variety of conditions, such as soil properties for agricultural applications and toxic substances for environmental monitoring. Unlike existing methods of monitoring underground conditions, which rely on buried sensors connected via wire to the surface, WUSN devices are deployed completely belowground and do not require any wired connections. Each device contains all necessary sensors, memory, a processor, a radio, an antenna, and a power source. This makes their deployment much simpler than existing underground sensing solutions. Wireless communication within a dense substance such as soil or rock is, however, significantly more challenging than through air. This factor, combined with the necessity to conserve energy due to the difficulty of unearthing and recharging WUSN devices, requires that communication protocols be redesigned to be as efficient as possible. This paper provides an extensive overview of applications and design challenges for WUSNs, challenges for the underground communication channel including methods for predicting path losses in an underground link, and challenges at each layer of the communication protocol stack.

Keywords: Wireless sensor networks; Underground sensing, Environmental Monitoring, Border patrol and security monitoring, Underground wireless channel.

1. Introduction

Sensor networks are currently a very active area of research. The richness of existing and potential applications from commercial agriculture and geology to security and navigation has stimulated significant attention to their capabilities for monitoring various underground conditions. In particular, agriculture uses underground sensors to monitor soil conditions such as water and mineral content [1].

Sensors are also successfully used to monitor the integrity of belowground infrastructures such as

plumbing [3,2], and landslide and earthquake monitoring are accomplished using buried seismometers [11]. The current technology for underground sensing consists of deploying a buried sensor and wiring it to a data-logger on the surface which stores sensor readings for later retrieval. Dataloggers, may be equipped with a device for wired or single-hop wireless backhaul to a centralized sink, but often data is manually retrieved by physically visiting the datalogger [3]. All of these existing solutions require sensor devices to be deployed at the surface and wired to a buried sensor [20]. 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:

1.1 Concealment – Current underground sensing systems require dataloggers or motes deployed at the surface with wiring leading to underground sensors [4,20] 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.

1.2 Ease of deployment – Expansion of the coverage area of existing underground sensing systems requires deployment of additional

dataloggers and underground wiring. Even if terrestrial WSN technology is used for underground monitoring as in [20], 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.

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

1.4 Reliability – A datalogger 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 datalogger 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 datalogger 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.

1.5 Coverage density – Sensors in existing underground applications are typically deployed close to their controlling datalogger to minimize the distance between them. Coverage density can therefore be uneven – high in the vicinity of the datalogger, but low elsewhere in the environment. WUSNs allow sensors to be deployed independent of the location of a datalogger. 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. APPLICATIONS

We classify current and potential underground applications into four categories: environmental monitoring, infrastructure monitoring, location determination, and border patrol and security monitoring.

2.1. Environmental monitoring

As described above, a type of sensor is being used in agriculture to monitor underground soil conditions, such as water and mineral content, and to provide data for appropriate irrigation and fertilization. A wireless underground system, however, can provide a significant refinement to the current approach for more targeted and efficient soil care. For example, since installation of WUSNs is easier than existing wired solutions, sensors can be more densely deployed to provide local detailed data. Rather than irrigating an entire field in response to broad sensor data, individual sprinklers could be activated based on local sensors. In a greenhouse setting, sensors could even be deployed within the pot of each individual plant.

The concealment offered by a WUSN also makes it a more attractive and broadly viable solution than the current terrestrial agricultural WSNs. Visible and physically prominent equipment such as surface WSN devices or dataloggers would most likely be unacceptable for applications such as lawn and garden or sports field monitoring. WUSNs are particularly applicable to sports field monitoring, where they can be used to monitor soil conditions at golf courses (see Fig. 1), soccer fields, baseball fields, and grass tennis courts. For all of these sports, poor turf conditions generally create an unfavorable playing experience, so soil maintenance is especially important to ensure healthy grass. An additional practical feature of underground sensors is that they are protected from equipment such as tractors and lawnmowers.

Monitoring the presence and concentration of various toxic substances is another important application. This is especially important for soil near rivers and aquifers, where chemical runoff could contaminate drinking water supplies. In these cases, it may be desirable to utilize a hybrid network of underground and underwater sensors. In addition to monitoring soil properties, WUSNs can be used for landslide prediction by monitoring soil movement [22]. Current methods of predicting landslides are costly and time-consuming to deploy, preventing their use in the poorer regions that stand to benefit the most from such technology. Like terrestrial WSN devices, WUSN devices should be inexpensive, and deployment is as simple as burying each device. WUSN technology will allow for a much denser deployment of sensors so that landslides can be better predicted and residents of affected areas can be warned sufficiently early to evacuate. Another

possible application is monitoring air quality in underground coal mines. Buildup of methane and carbon monoxide is a dangerous problem that can lead to explosions or signify a fire in the mine, and the presence of these gasses must be continually monitored [7].

This application would necessitate a hybrid architecture of underground open-air sensors and underground embedded sensors deployed between the surface of the ground and the roof of the mine tunnel. This would allow data from sensors in the mine to be quickly routed to surface stations vertically, rather than through the long distances of the mine tunnels. Another mining application would include an audio sensor (i.e., a powerful, high-sensitivity and low-power microphone suitable to underground environments) attached to the distributed underground sensor nodes to assist in location and rescue of trapped miners. WUSN devices with microphones would also be useful for other applications, such as studying the noises of underground animals in their natural habitats. Although not specifically underground, a WSN is utilized to monitor the movement of a glacier in [13].

Devices were deployed within the glacier, providing a rare example of a WSN deployed within a dense material. A WSN has also been used to monitor volcanic eruptions [24], an application which could benefit from WUSN technology. Earthquake monitoring and prediction can also be facilitated by WUSN technology. Unlike landslide prediction, where soil movement near the surface is of interest, useful data for earthquakes comes from multiple depths below the surface. The multi-depth nature of WUSNs will allow data to be routed back to an aboveground sink through a multi-depth topology.

2.2. Infrastructure monitoring

A large amount of underground infrastructure exists, such as pipes, electrical wiring, and liquid storage tanks. WUSNs can be used to monitor all of these. For example, fuel stations store fuel in underground tanks, which must be carefully monitored to ensure that no leaks are present and to continually determine the amount of fuel in the tank. Homes in locations without a sewer usually have an underground septic tank, which must be monitored to prevent overflow. WUSNs will also be useful in monitoring underground plumbing, where sensors can be deployed along the path of pipes so that leaks can be quickly localized and repaired. Sensors may also be useful in monitoring the structural health of any underground components of a building, bridge, or dam [16]. Wireless devices could be embedded within key structural components to monitor stress, strain, and other parameters [5]. Additionally,

WUSNs can be useful for military applications where an underground infrastructure exists, such as minefield monitoring. Existing work has examined wireless communication among surface anti-tank mines, enabling them to form a “self-healing” minefield [7]. A WUSN would enhance this technology by allowing mines to communicate even when deployed underground where they are concealed.

2.3. Location determination of objects

Stationary underground sensor devices that are aware of their location can be used as a beacon for location-based services. One can imagine devices deployed beneath the surface of a road that communicate with a car as it drives over.

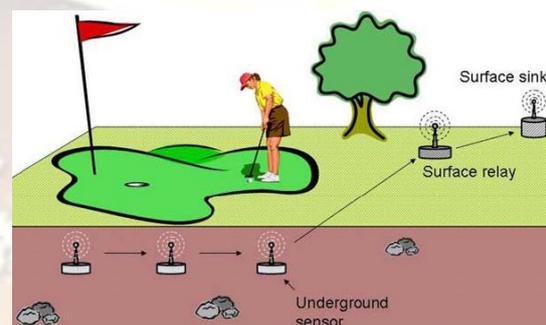


Fig. 1. A WUSN deployed for monitoring a golf course.

Underground sensors can be used to monitor soil salinity, water content, and temperature. Surface relays and sinks, which can be placed away from playing areas, are used to forward WUSN sensor data to a central receiving point (in this case, the golf course maintenance building).

A possible service would be to alert the driver to an upcoming stop sign or traffic signal. The car would receive the information about the upcoming signal and relay this to the driver. Location information could also serve as a navigational aid for autonomous systems, e.g., an autonomous fertilizer unit, which navigates around the area to be fertilized based on underground location beacons and soil condition data from underground sensors. WUSN technology can also be used to locate people in the event of a building collapse. Devices could be deployed throughout a building and programmed with their physical location. Building occupants would then carry a device on their person. In the event of a collapse, the occupant's device could be localized to a specific section of the building by communicating with the stationary devices. This could provide rescuers with a general area to search for survivors. Although this application is not strictly underground, the dense nature of the rubble from a building collapse poses challenges to wireless communication similar to soil.

2.4. Border patrol and security monitoring

WUSNs can be used to monitor the aboveground presence and movement of people or objects. Similar to location determination, deployed devices must be stationary and aware of their location. Unlike location determination, however, where objects announce their presence via direct communication with the embedded device, presence monitoring requires the use of sensors, such as pressure, acoustic, or magnetic, to determine the presence of a person or object. This application is useful for home and commercial security, where sensors could be deployed underground around the perimeter of a building in order to detect intruders. Since their presence is hidden, intruders would be less likely to know about and thus take action to disable the security system. On a larger scale, WUSNs can be very useful for border patrol. Wireless pressure sensors deployed at a shallow depth along the length of a border could be used to alert authorities to illegal crossings. Each sensor would be programmed with location information as it is deployed, allowing the exact location of an illegal crossing to be easily determined and giving a general area in which to deploy authorities for a search. Rural areas are the ones needing the most security, and WUSN technology would allow a monitoring system to be easily deployed in these areas without any necessary infrastructure since they are self-powered.

3. 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.

3.1. 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.

Additionally, terrestrial WSN devices can be equipped with a solar cell [12,22] to supplement or even replace a traditional power source, which is obviously not an option for WUSN devices. Scavenging opportunities for WUSN devices, such as converting seismic vibrations or thermal gradients to energy [22,18,13], do exist, but it remains to be explored whether these methods can provide sufficient energy to operate a device in the absence of a traditional power supply. In [15], the state of the art in more unconventional techniques for energy scavenging is surveyed. 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.

3.2. 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 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.

3.2.1 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.

3.2.2 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.

3.2.3 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 as illustrated in Fig. 2. 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.

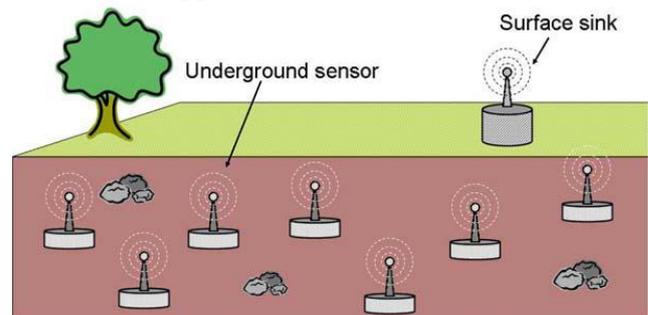


Fig. 2. Underground topology.

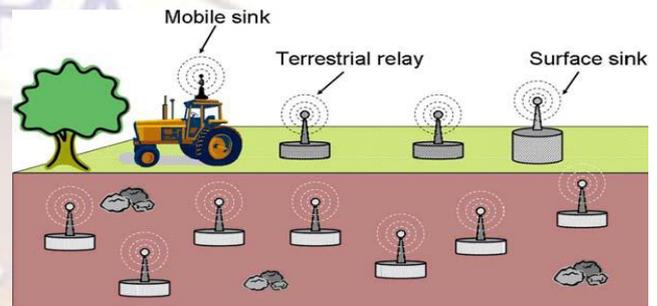


Fig. 3. Hybrid topology.

Hybrid Topology: This is composed of a mixture of underground and aboveground sensor devices as shown in Fig. 3. 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].

3.3. Antenna design

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

3.3.1 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.

3.3.2 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 [19]. 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.

3.3.3 Directionality – Future research must address whether an omni-directional 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 implies that with a vertically oriented antenna, communication with devices above and below would be impaired [19]. 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.

4. 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 [6,18,23] 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.

4.1. 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.

4.1.1 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, as shown in Fig. 4. This figure includes both losses due to material absorption, as predicted by the model in [25], as well as free-space losses, given by the standard formula $(\frac{4\pi d}{\lambda})^2$.

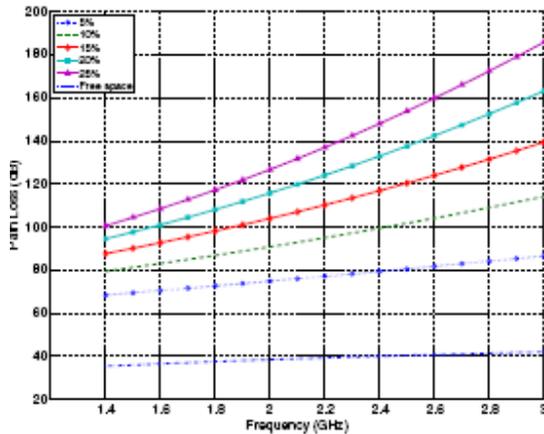


Fig.4. Path loss due to material absorption and spherical wavefront spreading over a distance of 1 m for a 50% sand, 35% silt, and 15% clay soil sample with various volumetric moisture contents. A curve demonstrating losses due only to wavefront spreading in free space is provided as reference. A bulk density of 1.3 g/cm³ and a specific density of 2.66 g/cm³ are assumed for the soil. Material absorption rates are predicted by the model from [24].

Even frequencies in the MHz range may experience attenuation on the order of over 100 dB per meter depending on soil conditions. Path losses are highly dependent on the soil type and water content. Soils are generally classified according to the size of their particles. In declining order of size they are: sand, silt and clay, or a mixture thereof [6]. 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.

4.1.2 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.

4.1.3 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.

4.1.4 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.

4.1.5 Noise – Even the underground channel is not immune to noise. Sources of underground noise include power lines, lightning, and electric motors [21]. Additionally, atmospheric noise is present in the underground [14,21]. 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.

4.2. 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 ϵ_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.

4.2.1 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 [23]. 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 [18]. For example, losses at 900 MHz and 40% volumetric water content are reported in [18] as 20 and 55 dB per meter for sandy and clay soils, respectively.

4.2.2 Particle size – Soils are classified by the diameter of their particles, and are generally described as some variation of sand, silt, or clay. A good overview of this topic, along with a diagram used to classify soils based on the percentage of each of the three major components, is given in [6]. Sandy soils produce the least amount of loss, and clay soils the most [18]. In addition, different soil

particle types respond differently to changes in water content.

4.2.3 Density – Increasing soil density increases path loss. The denser a soil, the greater the signal attenuation.

4.2.4 Temperature – Increasing the temperature of soil changes its dielectric properties and will increase signal attenuation [6]. Additionally, changes in temperature will affect the dielectric properties of any water present in the soil. These properties are summarized in Table 1.

Table 1
 Soil Properties and their effect on signal attenuation

Parameter	Change	Effect on signal attenuation
Water content	↑	↑
Temperature	↑	↑
Soil bulk density	↑	↑
% Sand	↑	↓
% Clay	↑	↑

4.3. Soil dielectric prediction models

As discussed previously, knowledge of the complex dielectric constant ϵ_r of the soil or rock through which a wave is propagating allows us to predict the attenuation due to material absorption using wellknown electromagnetics 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 ϵ_r 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 [20].

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 [20]. 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. A more extensive treatment of soil dielectric models is available in [20]. Here, we discuss a volumetric model from [24], which allows us to vary key soil properties such as water content,

density, and particle size, and provides a good indication of how these various parameters affect the rate of signal attenuation by the soil. The model in [24] was constructed by taking measurements over a range of frequencies and for a variety of different soils and soil water contents. 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.

4.4. Example underground link budget

Although challenging, such communication is in fact possible. To demonstrate this it is useful to work through a simple link budget equation [17].

$$P_r = P_t + G_t + G_r - 20 \log \left(\frac{4\pi d}{\lambda} \right) - L_m \quad (1)$$

In this equation, P_r represents signal power at the receiver in dBm, G_t is the gain of the transmitter antenna in dB, G_r is the gain of the receiver antenna in dB, $20 \log \left(\frac{4\pi d}{\lambda} \right)$ represents free space path loss due to spherical wavefront spreading, and L_m represents signal attenuation in dB due to absorption by soil and water.

To demonstrate the possibility of underground wireless communication via EM waves, we utilize a frequency of 315 MHz (chosen due to the availability of commercial terrestrial WSN motes at this frequency), a transmitter power of 1 W, and an antenna gain of 2 dB at both the transmitter and receiver (typical for a k2 dipole antenna [19]). A typical receiver sensitivity is -100 dBm. Assuming then that P_r must be at least -100 dBm at the receiver to have a viable communication link, this value, combined with the assumed antenna gains and transmitter power, is utilized in (1). The only unknown remaining is L_m , which allows us to determine the maximum signal loss due to material absorption in this situation (a 315 MHz carrier frequency with a 1 W transmitter). Using these values, L_m can be solved for to determine the permissible signal loss per meter due to material absorption. At a distance of 5 m, for example, (1) demonstrates that material losses can be up to 25.6 dB/m while maintaining a power at the receiver of at least -100 dBm. At a distance of 2 m, material losses can be up to about 68 dB/m. Actual values of L_m for various soil conditions were presented. These theoretical values of permissible losses due to material absorption compare well with actual losses that will be experienced, which were presented earlier. Although communication over distances typical of terrestrial WSNs is infeasible, this analysis demonstrates that shorter range links are possible. The range over which communication will be possible is highly dependent on soil conditions however.

4.5. Alternative physical layer technologies

It is clear that the underground is not an optimal environment for wireless communication using EM waves. High attenuation caused by soil particles and water in the ground make communication over practical distances difficult. Although we have chosen to focus this section on EM communication due to the large amount of available information on EM wave propagation underground, other, possibly more suitable, physical layer options exist for WUSNs which are less explored. One possible alternative to EM waves for underground communication is Magnetic Induction (MI). Using MI for the physical layer of a WUSN could have several benefits. One of these is that dense media such as soil and water cause little variation in the rate of attenuation of magnetic fields from that of air, since the magnetic permeabilities of each of these materials is similar [18].

Although generally unfavorable for open-air communication since magnetic field strength falls off as $1/R^3$, where R is the distance from the transmitter, compared to $1/R$ or $1/R^2$ for EM waves, the reduction in signal loss caused by propagation through soil compensates for this in the underground. Another interesting property of MI is that since the magnetic field is generated in the near-field, it is non-propagating [18]. This means that multi-path fading is not an issue for MI communication. Additionally, since communication is achieved by coupling in the non-propagating near-field, a transmitting device will be able to detect the presence of any active receivers via the induced load on the coil. This property may provide valuable information for protocols, acting as a type of acknowledgement that the transmission was sensed by some remote device.

Additionally, MI communication solves the issue of antenna design for underground sensors since transmission and reception is accomplished with the use of a small coil of wire. The strength of the magnetic field produced by a given coil is proportional to the number of turns of wire, the cross-sectional area of the coil, and the magnetic permeability of any material placed in the core of the coil. The use of wire coils for MI transmission and reception represents a substantial benefit over the use of antennas for propagating EM waves. The low frequencies necessary for the propagation of EM waves mean that large antennas are necessary for reasonable efficiency, which obviously conflicts with the necessity that underground sensors remain small. Another alternative to EM waves is seismic waves. Communication via seismic waves has been successfully demonstrated in both soil and rock at ranges of up to 1 km [10]. Seismic waves have many drawbacks, however. Frequencies even lower than those needed for EM communication are necessary

for their propagation over any useful distance. The system in [10] utilizes an 80 Hz carrier, and has only 3–5 Hz of bandwidth. Additionally, higher frequencies of seismic waves may produce audible coupling to the air, and generating seismic waves requires a large amount of energy.

4.6. Existing work

There was much interest in single-hop underground communication links numerous years ago, which subsequently died out due to the infeasibility of the long-distance links that were the focus of the research [9,19]. For example, a system is proposed in [19], where trapped miners can communicate through fallen rock using electrodes buried in the ground a distance of 91 m or more apart. The receiver uses a similar setup. The system uses frequencies from 1 to 10 kHz. In a more recent work, digitized audio has been successfully received at ranges of up to 150 m through solid rock using a carrier at 4 kHz and QAM-16 modulation [21]. This system achieves a data rate of 2 kbps. The feasibility of using terrestrial WSN nodes for underground communication has been tested in [19]. MicaZ nodes from Crossbow using a frequency of 2.4 GHz and transmit power of 1 mW were buried at various depths, and communication was attempted with both surface devices and other underground devices. It was determined that communication with surface devices is possible over very short ranges (a few meters), but communication with other underground devices using such a high frequency is not. There is also existing work which examines the use of MI for communication, although experiments are carried out underwater rather than in the underground. The use of FSK modulation with MI for digital communication with several underwater devices is demonstrated in [18], at ranges of up to several hundred meters. Specifically, a data rate of 153 bps is achieved at a distance of 250 m and a frequency of 1530 Hz. Carrier frequencies in the 100 kHz range should be suitable for low-loss propagation in the underground [8]. Although high-power transmitters and large coils were used for these experiments, the necessary power and coil size for the shorter-range communication links characteristic of a WUSN are feasible.

5. COMMUNICATION ARCHITECTURE

This section addresses the protocol stack of WUSNs, the 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.

6. CONCLUSION

The concept of WUSNs in which sensor devices are deployed completely below the 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.

REFERENCES

- [1] Advanced Aeration Systems, Inc. Rz-aer tech sheet. Available from: <<http://www.advancedaer.com/>>
- [2] J. Burrell, T. Brooke, R. Beckwith, Vineyard computing: sensor networks in agricultural production, *IEEE Pervasive Computing* 3 (1) (2004) 38–45.
- [3] Campbell Scientific, Inc. Available from: <<http://www.campbellsci.com/>>.
- [4] R. Cardell-Oliver, K. Smettem, M. Kranz, K. Mayer, Areactive soil moisture sensor network: design and field evaluation, *International Journal of Distributed Sensor Networks* 1 (2) (2005) 149–162.
- [5] S. Cheekiralla, *Development of a wireless sensor unit for tunnel monitoring*, Master's thesis, Massachusetts Institute of Technology, 2004.
- [6] D. Daniels, *Surface-Penetrating Radar*, *IEEE*, August 1996.
- [7] T. Dubaniewicz, J. Chilton, H. Dobroski, Fiber optics for atmospheric mine monitoring, in: *Industry Applications Society Annual Meeting, 1991., Conference Record of the 1991 IEEE*, 1991, pp. 1243–1249.
- [8] C. Evans-Pughe, Close encounters of the magnetic kind [near field communications], *IEEE Review* 51 (5) (2005) 38–42.
- [9] G. Howe, On the transmission of electromagnetic waves through and around the earth, *The Electrician* 72 (1926) 484–486.
- [10] K. Ikrath, W. Schneider, Communications via seismic waves employing 80-Hz resonant seismic transducers, *IEEE Transactions on Communications* 16 (3) (1968) 439–444.
- [11] K. Imanishi, W. Ellsworth, S.G. Prejean, Earthquake source parameters determined by the safod pilot hole seismic array, *Geophysical Research Letters* 31 (L12S09) (2004).
- [12] X. Jiang, J. Polastre, D. Culler, Perpetual environmentally powered sensor networks, in: *Fourth International Symposium on Information Processing in Sensor Networks, 2005*, pp. 463–468.
- [13] K. Martinez, R. Ong, J. Hart, Glacsweb: a sensor network for hostile environments, in: *IEEE SECON* 2004, pp. 81–87.
- [14] E. Neuenschwander, D. Metcalf, A study of electrical earth noise, *Geophysics* 7 (1) (1942) 69–77.
- [15] J. Paradiso, T. Starner, Energy scavenging for mobile and wireless electronics, *IEEE Pervasive Computing* 4 (1) (2005) 18–27.
- [16] C. Park, Q. Xie, P. Chou, M. Shinozuka, Duranode: wireless networked sensor for structural health monitoring, in: *IEEE Sensors* 2005, pp. 277–280.
- [17] T. Pratt, C. Bostian, J. Allnutt, *Satellite Communications*, second ed., Wiley, 2003.
- [18] S. Roundy, P. Wright, J. Rabaey, A study of low level vibrations as a power source for wireless sensor nodes, *Computer Communications* 26 (11) (2003) 1131–1144.
- [18] J. Sojodehei, P. Wrathall, D. Dinn, Magneto-inductive (MI) communications, in:

OCEANS, 2001. MTS/IEEE Conference and Exhibition, vol. 1, 2001, pp. 513–519.

- [19] E. Stuntebeck, D. Pompili, T. Melodia, Underground wireless sensor networks using commodity terrestrial motes. Tech. rep., *Georgia Institute of Technology*, April 2006.
- [20] R.L. Van Dam, B. Borchers, J.M. Hendrickx, Methods for prediction of soil dielectric properties: a review, in: Proceedings of SPIE – *The International Society for Optical Engineering*, vol. 5794, 2005, pp. 188–197.
- [21] J. Vasquez, V. Rodriguez, D. Reagor, Underground wireless communications using high-temperature superconducting receivers, *IEEE Transactions on Applied Superconductivity* 14 (1) (2004) 46–53.
- [22] T. Voigt, H. Ritter, J. Schiller, Utilizing solar power in wireless sensor networks, in: *IEEE Local Computer Networks*, 2003, pp. 416–422.
- [23] T.P. Weldon, A.Y. Rathore, Wave propagation model and simulations for landmine detection. Tech. rep., *University of North Carolina – Charlotte*, Department of Electrical and Computer Engineering, 1999.
- [24] G. Werner-Allen, K. Lorincz, M. Welsh, O. Marcillo, J. Johnson, M. Ruiz, J. Lees, Deploying a wireless sensor network on an active volcano, *IEEE Internet Computing* 10(2) (2006) 18–25.



Venkadesh.R completed his B.E. Computer Science and Engineering from University of Madras in 1999 and M.Tech Electronics and Communication Engineering from Pondicherry

University in 2004. He has 10 years of teaching experience in engineering colleges. He has published 2 international journals, 4 international conferences attended workshops and Faculty Development programmes. Interested area is Communication and Networking. At present he is working as Vice-Principal and Assistant Professor, Department of Electronics and Communication Engineering, Vel Tech Engineering college, Chennai-62, India



K.Rajan completed his B.E. Electrical and Electronics and M.E. Applied Electronics at P.S.G. College of Technology, Coimbatore. He has completed his Ph.D. from J.N.T.U. Anantapur, AP

in high frequency power system for industrial and commercial zones. He has 19 years of industrial experience in R&D, production and 9 years of teaching experience in engineering colleges. He has published 6 international and national journals. He also presented papers in 14 international and national conferences. Interested area is power electronics and power system. At present he is working as Principal in Vel Tech Engineering College. – RS Trust..



R.Balaji passed out his B.E. Electronics and communication Engineering from VelTech Engineering College, Anna University in 2009 and he is completed M.E Embedded

technologies from Velammal Engineering College-Tifaccore Department, Anna University in 2012. He has worked as Junior Research Scholar in Vel Tech Dr.RR & SR Technical University for 1 year. He has participated in workshop and research programmes. Interested area is Communication Engineering.