Available online at www.sciencedirect.com
ScienceDirect
Ad Hoc Networks 4 (2006) 669–686
www.elsevier.com/locate/adhoc

Wireless underground sensor networks: Research challenges

Ian F. Akyildiz *, Erich P. Stuntebeck

Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, 75 5th St. NW, Atlanta, GA 30308, United States

Received 31 January 2006; received in revised form 20 April 2006; accepted 3 July 2006
Available online 12 July 2006

Abstract

This work 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 work 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

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 [32], and landslide and earthquake monitoring are accomplished using buried seismometers [13].

The current technology for underground sensing consists of deploying a buried sensor, such as that shown in Fig. 1, and wiring it to a data-logger on the surface which stores sensor readings for later

* Corresponding author. Tel.: +1 404 894 5141; fax: +1 404 894 7883.
E-mail addresses: ian@ece.gatech.edu (I.F. Akyildiz), eps@ece.gatech.edu (E.P. Stuntebeck).

1570-8705/$ - see front matter
doi:10.1016/j.adhoc.2006.04.003

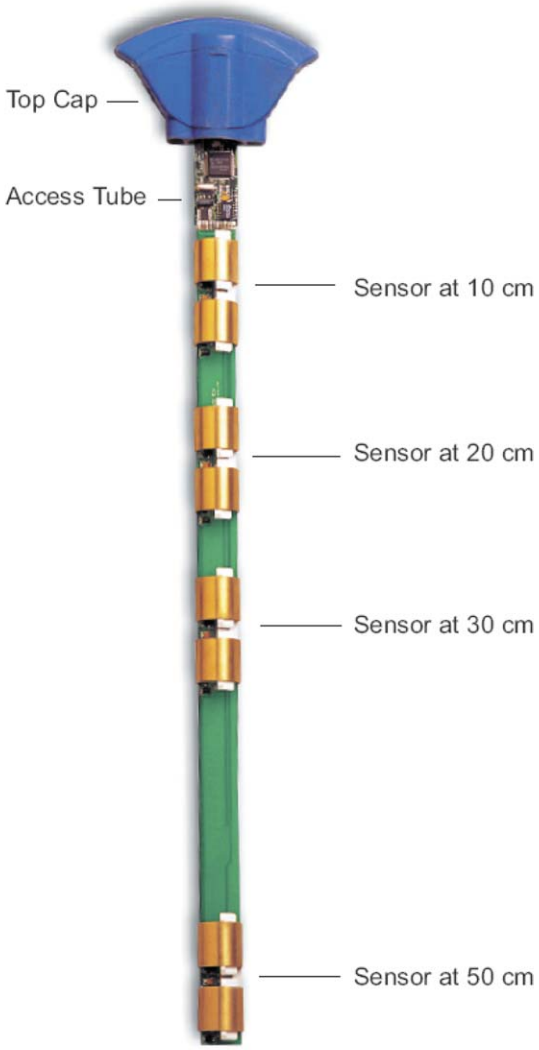

Fig. 1. An EasyAG II sensor from Campbell Scientific used for measuring soil volumetric water content and salinity at multiple depths [4].

retrieval. Dataloggers (see Fig. 2), 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 [4]. 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.

Fig. 2. A CR5000 datalogger from Campbell Scientific used for monitoring up to 40 sensors. Data is either manually retrieved from its onboard storage or transmitted to a central receiver [4].

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 dataloggers or motes deployed at the surface with wiring leading to underground sensors [5,20] 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.
- *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.

- *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.
- *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.
- *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. 3), 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* [28]. Current methods of predicting landslides are costly and time-consuming

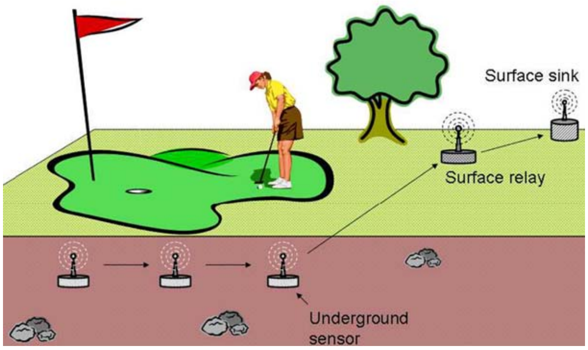

Fig. 3. A WUSN deployed for monitoring a golf course. Underground sensors can be used to monitor soil salinity, water content, and temperature. Surface relays and sinks, which can be placed away from playing areas, are used to forward WUSN sensor data to a central receiving point (in this case, the golf course maintenance building).

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 [9]. 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 [17]. 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 [38], 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-hop 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 [24]. Wireless devices could be embedded within key structural components to monitor stress, strain, and other parameters [6].

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. 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 [14,35] 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 [22,27,30], 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 [23], 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.

- *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 as illustrated in Fig. 4. 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

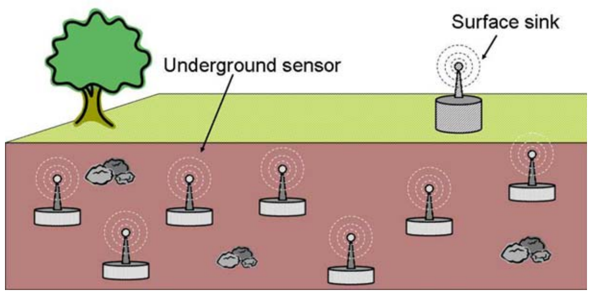

Fig. 4. Underground topology.

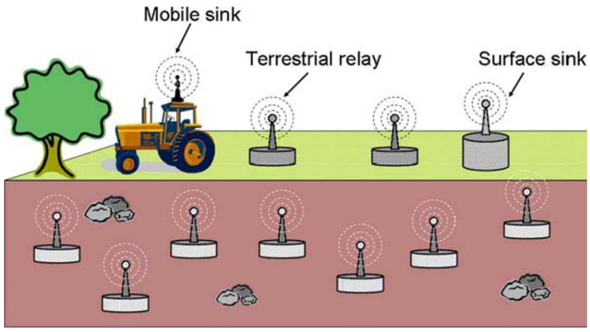

Fig. 5. Hybrid topology.

channel, which should produce lower path losses than a ground-ground channel.

Hybrid Topology: This is composed of a mixture of underground and aboveground sensor devices as shown in Fig. 5. 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 [3].

3.3. 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 [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.
- *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 [8,18,36,37] 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*.

- *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. 6. 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 $\left(\frac{4\pi d}{\lambda}\right)^2$. Attenuation per meter due to material absorption

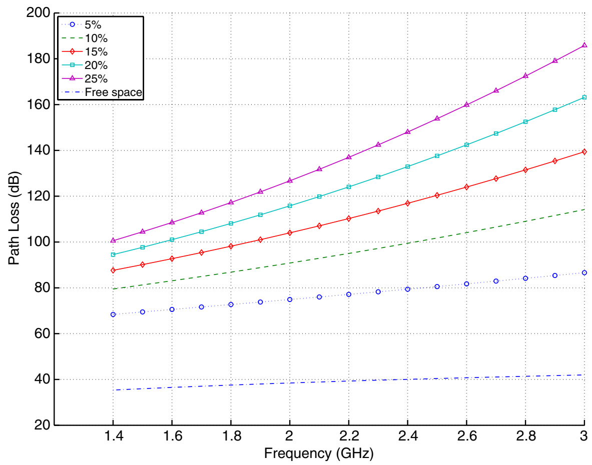

Fig. 6. Path loss due to material absorption and spherical wavefront spreading over a distance of 1 m for a 50% sand, 35% silt, and 15% clay soil sample with various volumetric moisture contents. A curve demonstrating losses due only to wavefront spreading in free space is provided as reference. A bulk density of 1.3 g/cm^3 and a specific density of 2.66 g/cm^3 are assumed for the soil. Material absorption rates are predicted by the model from [25].

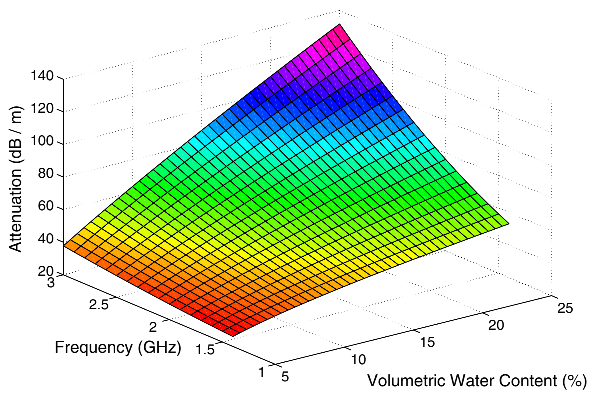

Fig. 7. Signal attenuation per meter due to material absorption predicted by the model from [25] for a soil mixture of 50% sand, 15% clay, and 35% silt.

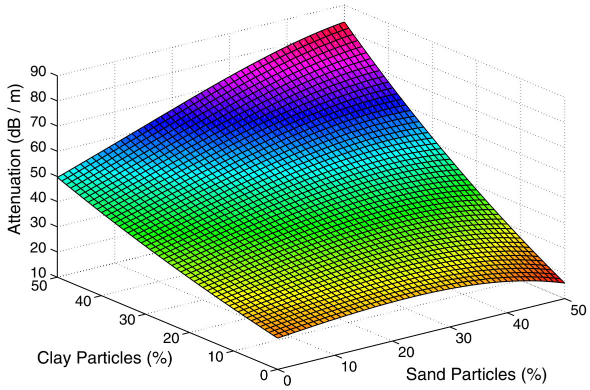

Fig. 8. Signal attenuation per meter due to material absorption predicted by the model from [25] for a 2.4 GHz signal in soil with 5% volumetric moisture content. Remainder from the sand/clay mixture is assumed to be silt.

only is provided in Figs. 7 and 8. 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 [8]. 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 [34]. Additionally, atmospheric noise is present in the underground [21,34]. 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.

- *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 [37]. 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. Attenuation caused by soil water content is also dependent on the frequency being used. Lower frequencies experience less attenuation at a given water content than higher frequencies, as demonstrated in Fig. 7.

- *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 [8]. 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.
- *Density* – Increasing soil density increases path loss. The denser a soil, the greater the signal attenuation.
- *Temperature* – Increasing the temperature of soil changes its dielectric properties and will increase signal attenuation [8]. Additionally, changes in temperature will affect the dielectric properties of any water present in the soil.

These properties are summarized in Table 1.

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 well-known 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 [33].

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 [33]. 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 [33]. Here, we discuss a volumetric model from [25], 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 [25] 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.

In Fig. 7 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 increases with increasing frequency and water content. An increase in frequency, however, has a much larger effect at a higher water content. In Fig. 8, we show the effect of varying the soil composition among sand, clay, and silt while holding the frequency and water content fixed. 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.

Table 1
Soil Properties and their effect on signal attenuation

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

4.4. 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 [26].

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

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 $\frac{\lambda}{2}$ 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 absorbtion 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 in Figs. 7 and 8.

These theoretical values of permissible losses due to material absorbtion compare well with actual losses that will be experienced, which were presented earlier (Figs. 7 and 8). 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 [29]. Although generally unfavorable for open-air communication since magnetic field strength falls off as $\frac{1}{R^3}$, where R is the distance from the transmitter, compared to $\frac{1}{R}$ or $\frac{1}{R^2}$ 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 [29]. 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 [12]. 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 [12] 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 the infeasibility of the long-distance links that were the focus of the research [11,39].

For example, a system is proposed in [39], 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 [34]. This system achieves a data rate of 2 kbps.

The feasibility of using terrestrial WSN motes for underground communication has been tested in [31]. MicaZ motes 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 [29], 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 [10]. 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. Fig. 9 illustrates 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. We then discuss cross-layered design opportunities for WUSNs.

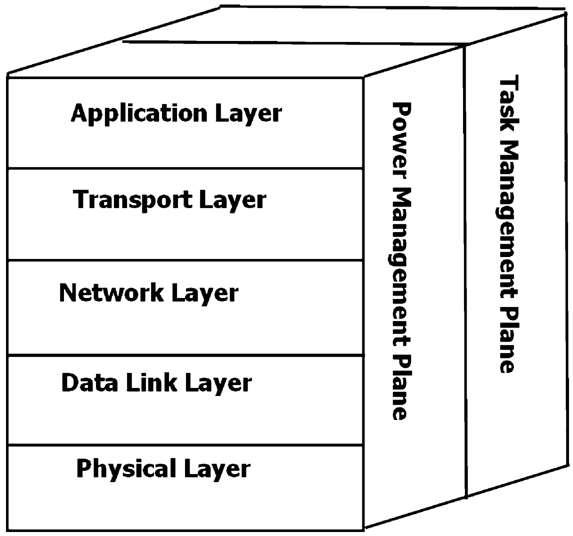

Fig. 9. WUSN protocol stack.

5.1. 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 [18], which may vary over time. Wet soils cause extreme attenuation of EM waves, even to the point of making communication impossible at any distance [37]. 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 [15]. As previously discussed, when propagating through soil and rock, lower frequencies of EM waves experience less attenuation than higher frequencies [36], 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. One exception is [34], which reports success using QPSK, QAM-16 and QAM-32 modulation schemes with a 4 kHz carrier and 10 W of transmit power. 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.

5.2. Data link layer

Existing MAC protocols [16] 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* [16]. 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 [16]. 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 loose 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 TDMA-based MAC may be optimal at a given time.
- Synchronization for very low duty cycles (on the order of minutes) needs to be explored.
- Adaptive FEC schemes need to be explored as a possible solution for the unique nature of the underground channel. When the channel is impaired by wet soil, for example, more powerful FEC schemes are necessary to overcome losses in the channel.
- Also the optimal packet size for WUSNs needs to be determined in particular by considering the underground channel effects in the calculations. Packet size will play an important role in both power conservation and quality of service. To maximize the power efficiency, it is desirable to minimize the amount of overhead transmitted in the form of packet headers. This would suggest a larger packet size but then the larger packet sizes will increase the overall latency of the network, as devices must wait longer for the channel to become available due to longer transmissions. An optimal tradeoff among these factors must be determined for WUSNs.

5.3. 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 [2] 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 necessary. Protocols for these applications must be able to establish a route between an event and a sink within a short interval following the event, while still coping with the challenges of the underground channel and remaining power efficient.
- The applicability of multi-path routing algorithms on WUSNs should also be examined. These algorithms can avoid the need for complete path switching in the event of a link failure, and research is needed to make them as energy-efficient as possible.

5.4. 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:

- New effective mechanisms tailored to the underground channel need to be developed in order to efficiently infer the cause of packet losses.
- New event transport reliability metric definitions need to be proposed, based on the event model and on the underground channel model.
- Optimal update policies for the sensor reporting rate are needed, to prevent congestion and maximize the network throughput efficiency as well as the transport reliability in bandwidth limited underground networks.
- An acceptable loss rate in WUSNs needs to be determined. This can translate directly to power savings for these severely power-constrained devices by reducing retransmissions. The acceptable loss rate is dependent on the application and the network topology, as well as on underground channel conditions.
- How best to handle the variable reporting periods of a WUSN needs to be determined. A WUSN will perform several tasks simultaneously, some of which may be more time sensitive than others. Soil water content measurements may only be reported every hour, but the presence of any toxic substance in the soil should be reported immediately. Thus, research is needed on providing differentiated levels of service at the transport layer for different types of sensor data.

5.5. 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.

6. 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.

Acknowledgements

The authors would like to thank Dr. Ozgur B. Akan, Dr. Eylem Ekici, Dr. Tommaso Melodia, Dr. Dario Pompili, and Mehmet C. Vuran for their valuable comments.

References

[1] Advanced Aeration Systems, Inc. Rz-aer tech sheet. Available from: <http://www.advancedaer.com/>.
[2] K. Akkaya, M. Younis, A survey on routing protocols for wireless sensor networks, Ad Hoc Networks (Elsevier) 3 (3) (2005) 325–349.
[3] J. Burrell, T. Brooke, R. Beckwith, Vineyard computing: sensor networks in agricultural production, IEEE Pervasive Computing 3 (1) (2004) 38–45.
[4] Campbell Scientific, Inc. Available from: <http://www.campbellsci.com/>.
[5] R. Cardell-Oliver, K. Smettem, M. Kranz, K. Mayer, A reactive soil moisture sensor network: design and field evaluation, International Journal of Distributed Sensor Networks 1 (2) (2005) 149–162.
[6] S. Cheekiralla, Development of a wireless sensor unit for tunnel monitoring, Master's thesis, Massachusetts Institute of Technology, 2004.
[7] G.E. Rolader, J. Rogers, J. Batteh, Self-healing minefield, in: Proceedings of the SPIE – The International Society for Optical Engineering, Battlespace Digitization and Network-Centric Systems IV, 13–15 April 2004, vol. 5441, no. 1, 2004, pp. 13–24.
[8] D. Daniels, Surface-Penetrating Radar, IEE, August 1996.
[9] 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.
[10] C. Evans-Pughe, Close encounters of the magnetic kind [near field communications], IEE Review 51 (5) (2005) 38–42.
[11] G. Howe, On the transmission of electromagnetic waves through and around the earth, The Electrician 72 (1926) 484–486.
[12] K. Ikrath, W. Schneider, Communications via seismic waves employing 80-Hz resonant seismic transducers, IEEE Transactions on Communications 16 (3) (1968) 439–444.
[13] K. Imanishi, W. Ellsworth, S.G. Prejean, Earthquake source parameters determined by the safod pilot hole seismic array, Geophysical Research Letters 31 (L12S09) (2004).
[14] 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.
[15] R.W.P. King, G.S. Smith, Antennas in Matter: Fundamentals, Theory, and Applications, MIT Press, 1981.
[16] K. Kredo, P. Mohapatra, Medium access control in wireless sensor networks, Computer Networks (Elsevier), in press.
[17] K. Martinez, R. Ong, J. Hart, Glacsweb: a sensor network for hostile environments, in: IEEE SECON 2004, 2004, pp. 81–87.
[18] T.W. Miller, B. Borchers, J.M. Hendrickx, S. Hong, L.W. Dekker, C.J. Ritsema, Effects of soil physical properties on GPR for landmine detection, in: Fifth International Symposium on Technology and the Mine Problem, 2002.
[19] T.A. Milligan, Modern Antenna Design, second ed., IEEE Press, 2005.
[20] R. Musaloiu, A. Terzis, K. Szlavecz, A. Szalay, J. Cogan, J. Gray, Life under your feet: a wireless soil ecology sensor network, in: EmNetS'06: Proceedings of the Third IEEE Conference on embedded networked sensors, 2006.
[21] E. Neuenschwander, D. Metcalf, A study of electrical earth noise, Geophysics 7 (1) (1942) 69–77.
[22] J. Pan, B. Xue, Y. Inoue, A self-powered sensor module using vibration-based energy generation for ubiquitous systems, in: 6th International Conference on ASIC, vol. 1, 2005, pp. 443–446.
[23] J. Paradiso, T. Starner, Energy scavenging for mobile and wireless electronics, IEEE Pervasive Computing 4 (1) (2005) 18–27.
[24] C. Park, Q. Xie, P. Chou, M. Shinozuka, Duranode: wireless networked sensor for structural health monitoring, in: IEEE Sensors 2005, 2005, pp. 277–280.
[25] N. Peplinski, F. Ulaby, M. Dobson, Dielectric properties of soils in the 0.3–1.3-GHz range, IEEE Transactions on Geoscience and Remote Sensing 33 (3) (1995) 803–807.
[26] T. Pratt, C. Bostian, J. Allnutt, Satellite Communications, second ed., Wiley, 2003.
[27] 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.
[28] A. Sheth, K. Tejaswi, P. Mehta, C. Parekh, R. Bansal, S. Merchant, T. Singh, U.B. Desai, C.A. Thekkath, K. Toyama, Senslide: a sensor network based landslide prediction system, in: SenSys'05: Proceedings of the 3rd international conference on embedded networked sensor systems, 2005, pp. 280–281.
[29] J. Sojdehei, P. Wrathall, D. Dinn, Magneto-inductive (MI) communications, in: OCEANS, 2001. MTS/IEEE Conference and Exhibition, vol. 1, 2001, pp. 513–519.
[30] M. Stordeur, I. Stark, Low power thermoelectric generator-self-sufficient energy supply for micro systems, in: International Conference on Thermoelectrics, 1997, pp. 575–577.
[31] E. Stuntebeck, D. Pompili, T. Melodia, Underground wireless sensor networks using commodity terrestrial motes. Tech. rep., Georgia Institute of Technology, April 2006.
[32] U.S. Water News. Street spies detect water leakage, December 1998. Available from: <http://www.uswaternews.com>.
[33] 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.

[34] J. Vasquez, V. Rodriguez, D. Reagor, Underground wireless communications using high-temperature superconducting receivers, IEEE Transactions on Applied Superconductivity 14 (1) (2004) 46–53.
[35] T. Voigt, H. Ritter, J. Schiller, Utilizing solar power in wireless sensor networks, in: IEEE Local Computer Networks, 2003, pp. 416–422.
[36] J. Wait, J. Fuller, On radio propagation through earth. Antennas and propagation, IEEE Transactions on Antennas and Propagation 19 (6) (1971) 796–798.
[37] 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.
[38] 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.
[39] H. Williams, Subterranean communication by electric waves, Journal of the British Institution of Radio Engineers 11 (1951) 101–111.

Ian F. Akyildiz received the B.S., M.S., and Ph.D. degrees in Computer Engineering from the University of Erlangen-Nuernberg, Germany, in 1978, 1981 and 1984, respectively. Currently, he is the Ken Byers Distinguished Chair Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, and Director of the Broadband and Wireless Networking Laboratory.

He has held visiting professorships at the Universidad Tecnica Federico Santa Maria, Chile, Universite Pierre et Marie Curie (Paris VI), Ecole Nationale Superieure Telecommunications in Paris, France, Universidad Politecnico de Cataluna in Barcelona, Spain, and Universidad Illes Baleares, Palma de Mallorca, Spain.

He is the Editor-in-Chief of *Computer Networks* as well as the founding Editor-in-Chief of *Ad Hoc Networks*. He is a past editor for *IEEE/ACM Transactions on Networking* (1996–2001), *Kluwer Journal of Cluster Computing* (1997–2001), *ACM-Springer Journal for Multimedia Systems* (1995–2002), *IEEE Transactions on Computers* (1992–1996), and *ACM-Springer Journal of Wireless Networks (WINET)* (1995–2005).

He received the "Don Federico Santa Maria Medal" for his services to the Universidad de Federico Santa Maria, in 1986. From 1989 to 1998, he served as a National Lecturer for ACM and received the ACM Outstanding Distinguished Lecturer Award in 1994. He received the 1997 IEEE Leonard G. Abraham Prize Award (IEEE Communications Society) for his paper entitled "Multimedia Group Synchronization Protocols for Integrated Services Architectures" published in the IEEE Journal of Selected Areas in Communications (JSAC) in January 1996. He received the 2002 IEEE Harry M. Goode Memorial Award (IEEE Computer Society) with the citation "for significant and pioneering contributions to advanced architectures and protocols for wireless and satellite networking". He received the 2003 IEEE Best Tutorial Award (IEEE Communication Society) for his paper entitled "A Survey on Sensor Networks," published in IEEE Communications Magazine, in August 2002. He also received the 2003 ACM Sigmobile Outstanding Contribution Award with the citation "for pioneering contributions in the area of mobility and resource management for wireless communication networks". He has been a Fellow of the Association for Computing Machinery (ACM) since 1996.

His current research interests include wireless sensor networks, wireless mesh networks, and dynamic spectrum access/xG/cognitive radio networks.

Erich P. Stuntebeck received the B.S. in Computer Engineering, Cum Laude, and the M.B.A. from the University of Notre Dame, Notre Dame, Indiana, in 2004. He then joined the Broadband and Wireless Networking Laboratory at the Georgia Institute of Technology, Atlanta, Georgia. He received the M.S. in Electrical and Computer Engineering in 2006, and is currently pursuing his Ph.D. and working as a research assistant. His research interests include wireless ad hoc and sensor networks as well as wireless mesh networks.