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Key Communication Techniques for Underground Sensor Networks

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Abstract

Wireless Underground Sensor Networks (WUSNs) are the networks of wireless sensors that operate in the underground soil medium. In this monograph, to realize reliable and efficient WUSNs, two enabling techniques are developed to address the challenges brought by the underground soil medium, including the EM wave-based WUSNs and the MI-based WUSNs. For EM wave-based WUSNs, the heterogeneous network architecture and dynamic connectivity are investigated based on a comprehensive channel model in soil medium. Then a spatio-temporal correlation-based data collection scheme is developed to reduce the sensor density while keeping high monitoring accuracy. For MI-based WUSNs, the MI channel is first analytically characterized. Then based on the MI channel model, the MI waveguide technique is developed in order to enlarge the underground

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transmission range. After that, the optimal deployment algorithms for MI waveguides in WUSNs are analyzed to construct the WUSNs with high reliability and low costs. Finally, the mathematical models are developed to evaluate the channel and network capacities of MI-based WUSNs. This monograph provides principles and guidelines for WUSN designs.

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1

Introduction

Wireless Underground Sensor Networks (WUSNs) [1] are the networks of wireless sensor nodes operating below the ground surface. As a natural extension to the well-established wireless sensor networks (WSNs) [2] paradigm, WUSNs are envisioned to provide real-time monitoring capabilities in the underground soil environments. In WUSNs, the networks of wireless nodes are buried underground and communicate through soil. A wide variety of novel and important applications can be enabled by WUSNs [1, 63, 64], such as intelligent agriculture, underground pipeline monitoring, border patrol, mine disaster prevention and rescue, among others. Compared with existing underground monitoring strategies, WUSNs have the advantages in timeliness of data, ease of deployment and data collection, concealment, reliability, and coverage density [1].

1.1 Design Challenges

Despite the potential advantages of WUSNs, the underground soil environment is a hostile place for wireless communications and requires existing networking solutions and communication protocols for terrestrial WSNs be reexamined. The objective of this monograph is to

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analyze the unique characteristics of the WUSNs in the underground soil environments and to find out the solutions to realize the reliable and efficient communication in WUSNs. The key difference between the WUSNs and the terrestrial WSNs is the communication medium. To realize wireless communications in such medium, there are mainly three possible signal propagation techniques [1]: (1) the electromagnetic (EM) wave-based technique, (2) the magnetic induction (MI)-based technique, and the (3) the seismic wave-based technique.

- Well established in the terrestrial WSNs, the **EM wave-based technique** still works in underground soil medium. However, since the propagation medium is no longer air but soil, rock and water, the unique channel characteristics of EM waves in soil environments needs to be modeled [3]. The communication and networking solutions under the impacts of the unique soil channel characteristics also need to be investigated.
- Besides the EM waves, the **MI-based technique** can also be used for wireless communications in soil medium since it is not affected by the dense soil medium with high material absorptions [59]. However, the signal strength of the MI-based signal attenuate very fast as the transmission distance increases. The effective solutions to enlarge the MI transmission range need to be developed. The corresponding higher layers of the protocol stack also need to be designed.
- Although the seismic wave-based technique is identified as an effective communication solution for blind subterranean mammal [41], it is not suitable for the WUSNs due to two reasons: (1) The operating frequency of the seismic wave-based system is very low, which results in extremely narrow bandwidth and low data rate. Such low data rate cannot meet the requirement of most digital communication systems. For example, the system in [28] utilizes an 80 Hz carrier, and has only 3–5 Hz of bandwidth. (2) The transducer requires a large amount of energy to generate the seismic waves that can carry the digital signals [1]. Since it is

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almost impossible to change the batteries of the underground sensor nodes after the deployment, the system lifetime of the seismic wave-based system is unacceptable short in underground soil environments.

1.2 EM Wave-based WUSNs vs Magnetic Induction-based WUSNs

According to the above discussion, both the EM wave-based technique and MI-based technique have the potential to realize the wireless communications in underground soil medium. Therefore, based on these two signal propagation techniques, we develop two enabling techniques to overcome the unique challenges brought by the soil transmission medium, including the EM wave-based WUSNs and the MI-based WUSNs.

The two types of WUSNs have unique advantages in different underground applications: if the underground sensor nodes are buried in a shallow depth (such as border patrol), the EM solution can be used since the underground-to-aboveground channels that have large communication range can be utilized. If the underground sensor nodes are deployed in deep underground environments (such as pipeline monitoring) or no aboveground devices are allowed, the MI solution has advantages in the pure underground-to-underground channel.

1.2.1 EM Wave-based WUSNs

In soil medium, the well established wireless communication techniques using EM waves do not work well [3]. First, EM waves experience high levels of attenuation due to the absorption by soil, rock, and water in the soil medium. Since the underground sensor devices have limited radio power due to the energy constraint, the transmission range between two sensor nodes is extremely small (no more than 4 m). Second, the path loss of the EM waves in soil medium is highly dependent on numerous soil properties such as water content, soil makeup (sand, silt, or clay), and density. Those soil properties can change dramatically with time (e.g., soil water content increases after a rainfall) and location (e.g., soil properties change dramatically over

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short distances). Consequently, the transmission range of the underground sensors also varies dramatically in different times and positions.

Besides the communication channel between underground sensors, the channels between underground (UG) sensor nodes and aboveground (AG) data sinks also needs to be analyzed. Hence, three types of channels exist in WUSNs in soil medium, including: underground-to-underground (UG–UG) channel, underground-to-aboveground (UG–AG) channel, and aboveground-to-underground (AG–UG) channel. For the UG–AG channel, the transmission range is much longer than the UG–UG channel [9, 49, 50, 68]. This is because a large portion of the radiation energy can penetrate the air–ground interface from the soil to the air, and the path loss in the air is much smaller than that in the soil. For the AG–UG channel, the transmission range is much smaller than the UG–AG channel since most of the radiation energy is reflected back when penetrating the air–ground interface from the air to the soil. Similar to the UG–UG channel, the transmission ranges of the UG–AG and AG–UG channels are also dramatically influenced by many environmental conditions and system configurations, including soil water content, soil composition, UG sensor burial depth, AG sink antenna height, and signal operating frequency [1, 3, 35, 49, 50].

The complex characteristics of the UG–UG, UG–AG, and AG–UG channels create unique challenges in the design of WUSNs in soil medium. First, in the envisioned applications of WUSNs in soil medium, the underground sensor nodes are expected to transmit sensing data to one or multiple aboveground data sinks via single or multi-hop paths. Hence, the connectivity in WUSNs is essential for the system functionalities. Because of the complex channel characteristics, the connectivity analysis in the WUSNs is much more complicated than in the terrestrial wireless sensor networks and ad hoc networks. Moreover, the number of underground sensors is expected to be as small as possible due to the high deployment/maintenance cost. However, an extremely high density of underground sensors is required to maintain the full connectivity of WUSNs due to the harsh underground channel conditions. This conflict constitutes one of the greatest challenges to deploy the WUSNs.

In this research, we first quantitatively model the channel characteristics of the three types of channels of WUSNs in soil medium. Based

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on the channel model, we propose a heterogeneous network architecture and analyze the dynamic connectivity of such network that captures the influence of multiple system and environmental parameters. Moreover, we introduce aboveground mobile sinks to WUSNs and developed a spatio-temporal correlation-based data collection scheme, which significantly reduces the sensor density while keeping high monitoring accuracy. Finally, we propose a theoretical method to determine the optimal sensor density under the proposed scheme, which provides principles and guidelines for the design and deployment of WUSNs.

1.2.2 MI-based WUSNs

As discussed previously, the EM wave-based techniques encounter two major problems in soil medium: the high path loss and the dynamic channel condition. If the sensors of WUSNs are buried in the shallow depth, sensor can communicate with the aboveground data sinks directly using EM waves since the UG–AG channel has relatively large communication range. However, many WUSN applications, such as underground structure monitoring, require the sensors buried deep underground, where only UG–UG channel is available.

MI is a promising alternative physical layer technique for WUSNs in deep burial depth. Since the magnetic permeabilities of the underground medium such as soil and water are similar to that of the air, the attenuation rate of magnetic fields in underground soil medium is very close to the rate in terrestrial environments [1]. This fact guarantees that the MI channel conditions remain constant for a certain path in different times. However, MI is generally unfavorable for terrestrial wireless communication, since the magnetic field strength falls off much faster than the EM waves in terrestrial environments. In soil medium, although it is known that the soil absorption causes high signal attenuation in the EM waves systems but does not affect the MI systems, it needs to be analyzed whether the total path loss of the MI system is lower than that of the EM waves system or not.

In this research, we conduct detailed analysis on the path loss and the bandwidth of the MI system in underground soil medium. Based on the channel analysis, we develop the MI waveguide technique in order

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to reduce the high path loss of the traditional EM wave system and the ordinary MI system. By utilizing the passive relay coils, the MI waveguide system dramatically increases the transmission range of underground sensors in soil medium. Moreover, we analyze the deployment strategies of MI waveguides in WUSNs. We develop optimal deployment algorithms to use the MI relay coils to connect the underground sensors. The proposed algorithm provides strategies to deploy MI-based WUSNs with high reliability and low costs. Finally, we theoretically investigated the channel capacity, network capacity, and the reliability of the new developed MI-based networks. Compared to the traditional wireless networks, both the channel and network capacities of MI-based WUSNs have significant different characteristics due to the completely different signal propagation techniques and network geometric structure. Moreover, the usage of multiple resonant MI relay coils in MI-based WUSNs brings more reliability concerns. The analysis results provide principles and guidelines for the MI-based WUSN design.

1.3 Organization

This monograph is organized as follows. In Section 2, an overview of potential applications for WUSNs is provided. In Section 3, the EM wave-based WUSNs are developed. In particular, the models of the three types of channels, i.e., UG–UG channel, UG–AG channel, and AG–UG channel, are first developed. Then based on the channel model, the network architecture and the dynamic connectivity in EM wave-based WUSNs in soil are investigated. At the end of this section, a spatio-temporal correlation-based data collection scheme is developed for WUSNs in soil medium. In Section 4, the MI-based WUSNs in soil medium are introduced. Specifically, the MI channel model for WUSNs in soil medium is first provided. Then, the MI waveguides are developed to significantly enlarge the UG–UG communication range. After that, the optimal deployment algorithms for MI waveguide are presented. At the end of this section, mathematical models are developed to evaluate the channel capacity, network capacity, and the reliability of MI-based WUSNs. Finally, Section 5 summarizes the research contributions and identifies several future research directions.

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