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Wireless Underground Sensor Networks

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Abstract

With the development of sensing networks and Internet of things, wireless sensor networks have been applied to different fields of our society. With the perceived sensing demands for soil, mining lanes, etc., wireless underground sensor networks (WUSNs) have developed rapidly recently. Compared to typical terrestrial wireless sensor networks, WUSNs have unique applications and features due to their wireless transmission characteristics and layout environments, especially WUSNs in soil. In this paper, we discuss the wireless propagation characteristics and engineering implementation methods of WUSNs in tunnels/tubes/pipelines/lanes and WUSNs in soil. The prospects for the future development of WUSN are discussed as well.

Keywords: wireless underground sensor network; sensors and actuators; wireless propagation; multipath; transmission loss

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1. Introduction

Wireless sensor networks (WSN) are distributed sensing networks. Wireless sensor networks wirelessly aggregate information collected by sensors distributed across an area to monitor and control specific conditions within the area [1-3]. WSN technology is closely related to Internet of things technology. It can be said that WSN is a technical backbone of Internet of things, and its application range is very wide in today's society. The development of WSN benefited from the rapid development of micro-electro-mechanism systems (MEMS), systems on chip (SoC), wireless communication, and low-power embedded technology. Wireless sensor networks have the following advantages. First, their sensing ability is high, and they can realize dense spatial sampling and close-range monitoring that cannot be realized by a single sensor. Secondly, they have excellent work flexibility, and no human intervention is required after being deployed. Wireless sensor networks also have the advantage of high reliability. The existence of a large number of redundant nodes makes the system more fault-tolerant, avoids single-node failure problems, and reduces the requirements for individual nodes. In addition, it is cost-effective, it can reduce the cost of wired transmission, and the cost of a single node is also low. Now, WSN technology has been widely used in industrial control, smart homes, consumer electronics, security, military security, logistics, intelligent precision agriculture, environmental awareness, and health monitoring [4-5].

Expanding the application field and optimizing the service model are important development directions for wireless sensor networks. In recent years, wireless underground sensor networks (WUSNs) have received increasing attention [6]. Designing the network and sensor node is an important factor for efficient topology and energy constraints. Wireless communication channels play a pivotal role in WUSNs applications. Different factors such as propagation loss, reflection, refraction, diffraction, and frequency affect the transmission parameters. There are two types of WUSN for different application scenarios. The first is WUSN, which is placed in the tunnel/tube/pipeline/lane, and the other is WUSN, which is laid in the soil. Pipelines, lanes, etc. are usually located underground for mining, petroleum, and municipal engineering. If

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wireless sensor networks are applied to these fields, they must be optimized [7-9]. However, in these occasions, most of the communication channels and the electromagnetic field energy distribution between the nodes can be in the air within the tunnel/tube/pipeline/lane. The design of this type of WUSN can be referred to the design for terrestrial wireless sensor networks. In some cases, mature technologies such as ZigBee and WiFi can be used. In other application fields, such as agriculture, safety supervision, and mining, it is of great significance for the distributed monitoring of soil parameters. In the typical applications for planting parameter monitoring, landslide warning, and working surface management, the wireless sensing nodes need to be buried in the soil. Nodes must meet the long-term distributed perception of soil parameters [10-11]. However, due to the particularity of the soil medium, it is difficult for existing wireless networking methods such as ZigBee, WiFi, GPRS, and 3G/4G to meet the requirements of establishing a distributed wireless sensing system in the soil medium in terms of transmission distance, multipath effect, and node energy consumption demand [12-13]. The wired transmission method is often subject to cost and erection, and it is difficult to adopt it in a similar application environment [14-15].

2. WUSN for Tunnel/Tube/Pipeline/Lane Monitoring

2.1. EM Wave Propagation in Tunnels/Tubes/Pipelines/Lanes

The transmission of signals has two important factors from an engineering point of view: propagation model and network design. It is an important factor for establishing any kind of network with efficient propagation of signals and uses the optimum design of nodes in it. The WUSN signal energy in the tunnel/tube/pipeline/lane environment is transmitted in a confined space during transmission. The transmission path is narrow and tortuous. The final received signal is multi-path, reflected, scattered, and diffracted by the inner wall and the device. Thus, the signal has been significantly distorted and attenuated. The noise of people moving in the tunnel/tube/pipeline/lane and the complicated noise of the engineering equipment all cause noise interference of the WUSN wireless channel. Therefore, it is necessary to analyze the specificity of WUSN wireless channels from the three aspects of multipath effect, Doppler shift, and noise interference of wireless communication, and consider the influence of various factors on the channel. The inner surface of tunnels/tubes/pipelines/lanes is rough, and the received signal is composed of many refracted waves and scattered waves with different fading, delays, and phase shifts. The wideband channel statistical model can utilize the classical time-invariant impulse response channel. The model indicates that the channel is invariant in one symbol period, the multipath fades from the time domain perspective, and the time that the channel transmits to the receiving antenna depends on the length of the transmission path, while the number of paths in the multipath channel is large and the distance is different. Thus, the received signal envelope is blurred or expanded, which appears as a symbol divergence, resulting in a delay spread. From the perspective of airspace, multipath fading is divided into small-scale fading and large-scale fading.

In WUSN communication, single-antenna systems are mostly used, and wireless signal transmission is mainly affected by frequency selective fading and time-selective fading. The large-scale fading of the communication distance of communication equipment in the mine is not obvious, so there is small-scale fading in tunnel wireless transmission. The wireless communication system test has confirmed that the Nakagami channel model has a good fit to the measured data and has theoretically become a representative wireless channel model. In order to fit the communication statistics of multiple fading in the WUSN in tunnel/tube/pipeline/lane channels, the Nakagami model can be used to fit the signal amplitude fading characteristics of the tunnel/tube/pipeline/lane wireless channel. Using the Nakagami model under different conditions is modeled to further simplify the complexity of theoretical modeling. If a relative displacement occurs between the receiver and the transmitter of the WUSN, the frequency of the received signal is shifted, that is, the Doppler effect occurs. In the WUSN environment, if the number of electromechanical devices is large, the power is high and the startup is frequent, and the generated electrical noise spectrum is wide and the level is high. This kind of spectrum wide and high level noise can be regarded as pulse interference. This kind of strong, white-looking noise covers the entire signal bandwidth, which brings great difficulties to signal transmission and restoration. Although the pulse signal noise is spectrally uniform, it is found from the time domain analysis that strong impulse noise only has a large effect on some frequency signals. The strength of pulse interference is mainly determined by the pulse distribution probability and pulse power.

The Nakagami channel model has a good fit to the measured data, so it has become a kind of wireless channel model with broad representative meaning in theory and has important application value. If there is corresponding test equipment, the Nakagami model shown above can be used to establish a fit model in the tunnel/tube/pipeline/lane and provide a more realistic reference for the node layout. However, if you want to establish a theoretical analytical model, you can return to the theoretical starting point and obtain the following analysis. Signals play an important role in any kind of wireless propagation. Basically, the propagation model of electromagnetic waves (EMW) consists of three kinds, i.e., the empirical model, the site-specific model, and the theoretical model [16]. These basic kinds of propagation further give inheritance to wireless propagation models such as the free space propagation model, the two-way ground model, and the log-normal model [17]. The first propagation, the free space model, deals with line of sight between transmitter and receiver communication. No impediment exists in transmitter and receiver communication for this propagation model. The second propagation model, the two-way ground model, is obtained from the application of the free space model. In this model, reflected and direct rays are assumed in communication with greater distance than height. The third model, the log-normal model, is empirical and analytical with a path loss factor. Results vary from the derived ones, and it is applicable in hostile environments such as underground pits [18] by Patri. Furthermore, the loss of power can be categorized as shadow fading or multipath fading. For shadow fading, the log-normal model with the relation of Gaussian distribution variable shows the fading phenomena of the strength of received signals. The improved model is known as the log-normal shadowing model, and it is suitable for wireless sensor networks. For multipath fading, received signals pass via two or more paths, which causes two interferences such as constructive and destructive. This phenomenon produces phase shifting and the addition of some noises in the signal. In a dynamic environment, the strength of received signals varies randomly because of environmental changes and the movement of objects. Figure 1 shows the typical configuration WUSN in a tunnel/tube/pipeline/lane.

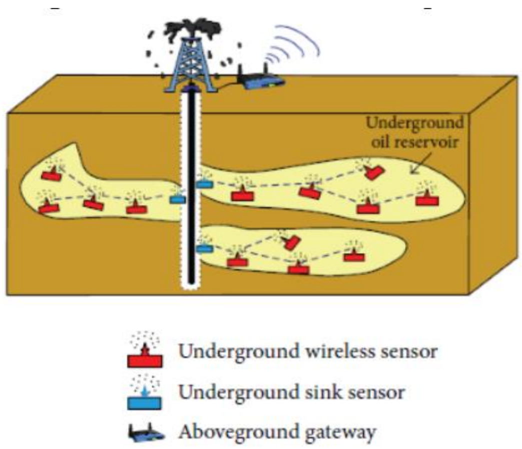

Figure 1. WUSN in tunnel/tube/pipeline/lane [Akkas, 2017]

2.2. WUSN Design in Tunnels/Tubes/Pipelines/Lanes

Signal transmission in WUSNs for tunnels/tubes/pipelines/lanes is different compared to that in terrestrial networks [19-20]. Since the wireless electromagnetic energy is mainly concentrated in the air of confined space, for the engineering design of the WUSN in a tunnel/tube/pipeline/lane field, some classical designs and concepts for the terrestrial wireless sensor networks can be borrowed. Firstly, in the network topology design, we can use the clustering concept that terrestrial wireless sensor networks are often implied, and group nodes are spatially distributed closely into the same cluster. The periodic election or presetting is introduced to obtain the data aggregation node (the cluster header). In addition, if commercial protocols are adopted, network protocols based on a multi-hop structure such as ZigBee may be considered. The transmission of wireless signals in the tunnel/tube/pipeline/lane environment is often accompanied with multipath effects. Therefore, it is possible to introduce intelligent antenna technology based on the network topology to increase the transmission ability of wireless energy to specific areas. Since the transmission characteristics of different wireless signal bands are different, if there is a high requirement for space division multiplexing, the 2.4 GHz band may be considered. If the signal penetration is to be mainly increased, a common ISM band such as 433 MHz may be selected. In addition, in order to increase the anti-noise characteristics of the signal, it is usually necessary to select a spread spectrum method to obtain an improvement in the signal-to-noise ratio at the receiving end. The hardware structure of the node is usually designed around a low-cost microcontroller chip with rich functions such as STM32. However, the design of nodes such as MICA and TelosB can be directly used in this field. There is no need to pursue rich functions in the design of the hardware structure. Simple and effective design not only reduces costs and improves efficiency, but also lowers the chance of failure and is expected to save power. The signal attenuation effect is higher compared to that in air or free space. In a WUSN, the tubes or pipelines consist of a large number of sensor nodes located at different regions with the sink node. Usually, the sink node for oil or gas is located at the wellbore or gas station for data collection. Sensors communicate through electromagnetic waves and data sent through it. The environment is complex with water, oil/gas, and composition of soil particles. In order to meet the application requirements of WUSN in the tunnel/tube/pipeline/lane environment, many innovative designs have been proposed.

For example, the research of Anupama et al. [21] was based on a tube/pipeline with over 100 motes of sensors network. They presented a step-wise research methodology for the system with its applications to the monitoring of pipeline systems. In [22], Yu et al. suggested a novation information collection algorithm for tubes/pipelines with sensor networks and concluded that the algorithm improves the network performance by consuming less energy and extends the network life time with less delays of communication. In [23], Bhavyarani et al. discussed the communication and monitoring of sensor networks for pipelines in desert areas. They investigated over a 1350 km distance area by installing sensor network equipment to scan the tube/pipeline with low band width. Solar panels were the source of energy for the system, and it was stored in batteries. In [24], Mustafa et al. conducted research on an underground tube for the extraction of oil. They studied the bit error rate of different soil samples or mixtures in an underground environment with a terahertz band. Akkas [25] discussed underground coal mines and concluded that the usage of MICA2 motes in underground coal mines work efficiently up to 5-25m. Distance, soil composition, and frequency also matter with suitable bands. In [26], Akkas and Sokullu discussed channel analysis in underground environments. They used a 300-700 MHz band for the soil medium. According to their channel analysis, the 433 MHz frequency range is better for underground environments (underwater channels for pipelines/tubes). They achieved efficient results for sensor nodes with MICA2 and MICA2DOT motes. Their designed models are shown in Figure 2 (left side for MICA2 and right side for MICA2DOT). They concluded that the frequency range between 300-700 MHz bands is efficient for underground environments to improve channel propagation.

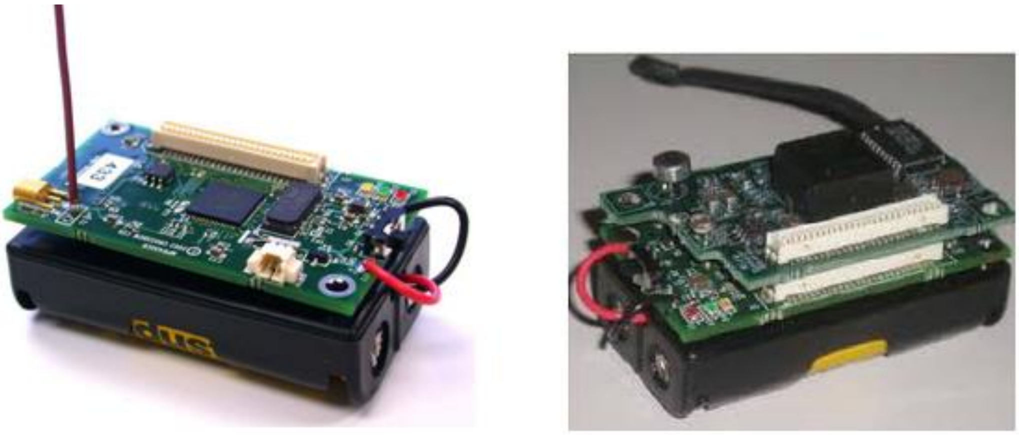

Figure 2. MICA2 mote by Akkas (left) and MICA2DOT mote by Akkas and Sokullu (right)

In Table 1, we compare different kinds of motes, such as MicaZ, MICA2, MICA2DOT, and Imote2, with different parameters, including their memory of MPU, data rates, sizes, frequency bands, and type of radio.

Table 1. Comparison of typical motes

Feature	MPU Memory	Data Rate (kbs)	Size (cm)	Freq. Band (MHz)	Radio
MicaZ	128+512 kB Flash, 4 kB SRAM	250	5.8x3.2x0.7	2400 - 2483	TI CC2420 (IEEE 802.15.4)
MICA2	128+512 kB Flash, 4kB SRAM, 4 kB EEPROM	38.4	5.8x3.2x0.7	868 - 916 (spectral - agile)	TI CC1000
MICA2DOT	128+512 kB Flash, 4kB SRAM, 4 kB EEPROM	38.4	2.5x0.6	868 - 916, 433 or 315 (spectral - agile)	TI CC1000
Imote2	32MB Flash, 256kB SRAM, 32 MB SDRAM	250	3.6x4.8x0.9	2400 - 2483	TI CC2420 (IEEE 802.15.4)

3. Wireless Underground Sensor Network (WUSN) in Soil

3.1. Propagation in Soil

Unlike the WUSN used in tunnel/tube/pipeline/lane scenarios, the WUSN in soil faces greater challenges. A WUSN in soil is a network formed by wireless underground sensor nodes that propagate data through the soil to collect, process, and transmit data in the monitored area [27]. Wireless underground sensor networks have significant advantages over traditional wireless sensor networks. The WUSN nodes are buried in the underground soil and do not affect the traffic and operations on the ground. The monitoring parameters in soil can be achieved directly by WUSNs in soil. In this occasion, the sensor node with the wireless transceiver module is completely buried in the underground soil (sometimes, except for the sink node), and the data is transmitted wirelessly. The biggest difference between WUSN and the above-ground WSN is the electromagnetic wave propagation medium. The electromagnetic waves of the nodes communicate through the soil medium, and the transmission characteristics depend on the soil medium itself, including the soil structure composition, soil moisture content, and other things (for example, multipath and reflection due to roots in soil). The architecture of typical communication between WUSN nodes is shown in Figure 3.

Propagation of signals under the soil is difficult compared to that above ground. Underground communication is dependent on different conditions. Compared with propagation in tunnel/tube/pipeline/lane scenarios, soil has a greater attenuation and absorption of electromagnetic wave propagation. In addition, when the sensor nodes communicate, the ground acts as an interface between two different media (air and soil), which also reflects, refracts, and radiates electromagnetic waves. Fading occurs when the signal propagates through soil, and as a result, refraction and reflection with irregular obstacles such as roots, stones, or rocks make propagation waves scattered. Therefore, the transmission of electromagnetic waves in WUSNs in soil media is fundamentally different from traditional terrestrial wireless sensor networks and WUSNs used in tunnel/tube/pipeline/lane scenarios. According to this, the sensor nodes, protocols, algorithms, and transmission paths and models for WUSNs in soil will be different from those of the above-ground WSNs. WUSNs have two communication methods: underground-aboveground communication and underground-underground communication (UA path and UU path). The underground channel is dynamic. It depends on changes in soil properties, especially changes in soil moisture. The multipath effect, reflection of air and soil interfaces, radiation of underground objects, node burial depth, etc. also have a great impact on wireless underground EM wave propagation.

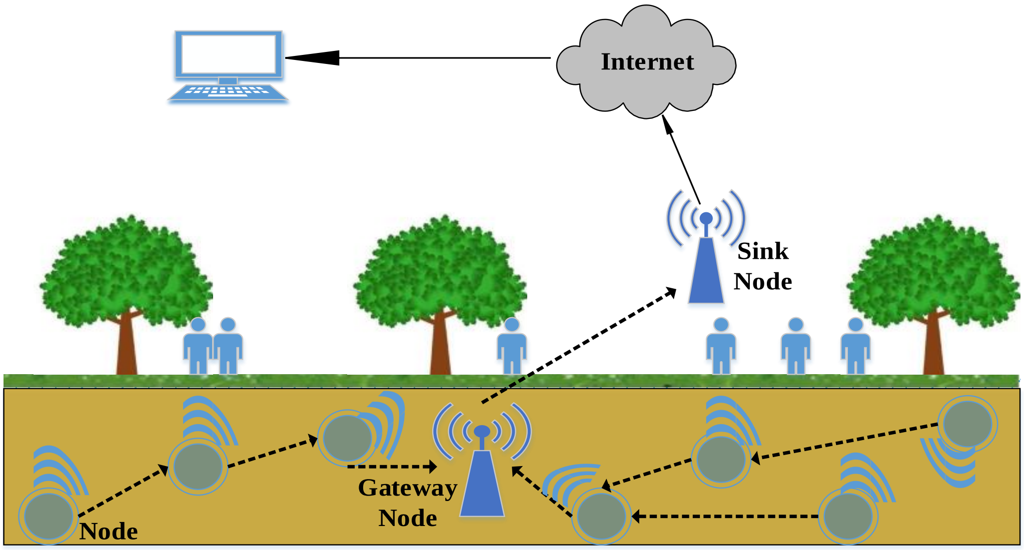

Figure 3. Architecture of typical communication between WUSN nodes

Regarding WUSNs in soil, many researchers have conducted excellent theoretical research work. The concept of WUSN in soil was proposed by Akyildiz [28] in 2006. It is important to study the effects of electromagnetic radiation before deploying any sensor nodes in the soil [29]. In [30], Warrier explained that scattering, refraction, and reflection play an important role in WUSN for the communication of electromagnetic waves. Yigit et al. [31] discussed packet size in WUSNs. Packet size is an important factor for the reliability and performance of a network. They studied different styles of packet sizes, such as fixed or dynamic packet sizes of different formats. The advancement of technologies and new research discoveries highlight many other parameters that are equally important for in-soil propagation, such as the burial depth and volumetric water contents (VWC). Yu [32] discussed the burial depth factor in WUSNs with the relation of volumetric water contents (VWC) and the use of three different frequencies. The burial depth is related to the reflection of rays from underground to air or free space at the surface. VWC is directly proportional to the path loss of signals in WUSNs. According to the experiments, different frequencies such as 433 MHz, 868 MHz, and 915 MHz were used for in-soil propagation, and the optimum propagation was obtained for the zone of 400 MHz frequency band with less path loss. The soil propagation is dependent on other factors such as the transmitting power, gain of antennas of the transmitter and receiver, topology, and protocol techniques. The variation of different features of soil and their effect on signal attenuation are shown in Table 2.

Table 2. Soil features and their effect on signal attenuation

Feature	Variation	Effect on Signal Attenuation
Bulk density of soil	High	High
Water content	High	High
Sand %	High	Low
Clay%	High	High
Temperature	High	High

3.2. Node Design

In the design of nodes, it is necessary not only to meet the needs of in-soil propagation measurements, but also to consider the corresponding engineering and commercial needs. Many researchers adopt the star network extension structure, which has the lowest latency and minimum energy consumption compared with other topologies. The node is composed of a microcontroller (MCU) part, a communication part, an extended sensor interface part, a digital communication interface part and a system power supply part. Different researchers use different communication technologies for node designing.

Stuntebeck et al. [33] used MICAZ motes for their research work with the *Zigbee* module. They deployed different distances such as an indoor range of 20-30 m and an outdoor range of 75-100 m. The sink node was connected to the Crossbow MIB510 programming board, which allowed communication via a serial connection to the laptop. Li [34] described deployment in coil mines with a structure-aware self-adaptive (SASA) protocol. The detection of system errors was observed in experiments involving packet loss, bandwidth of network, and latency. In these experiments, 27 MICA2 motes were deployed in the coal mines for the communication of messages. Wan et al. [35] conducted research on the *LoRa* module AS62-DTU20 in WUSNs, which is based on SX1278. Power conservation and the cost of nodes are equally important for the network. They concluded that the node design provides better test results compared with Zigbee and narrow band (NB) in WUSN. Tiusanen [36] presented his excellent design named Soil Scout. Soil Scouts have a streamlined structure and high performance. They are palm-size wireless underground sensor nodes for the monitoring of agriculture soil parameters and are shown on the left in Figure 4. When installed in heavy clay soil, they can overcome 236 m communication distances and 110 dB calculated path losses. Their power-saving design allows their working life to exceed one year. In addition, our project team is also developing a soil temperature WUSN based on LoRa, the chipboard design of which is shown on the right in Figure 4. The results of this research will be published in subsequent research papers in the near future. Zemmour et al. [37] conducted experiments with the Agilent 8722ES vector network analyzer. They used the ultra wideband (UWB) method, which showed the effects of buried antennas and soil moisture on burial depth. In these tests, the PlusON antenna was used with the underground UWB antenna.

Figure 4. Soil Scout by Tiusanen (left) and our soil temperature WUSN design with LoRa (right)

4. WUSN in the Future

In recent years, many unique approaches have appeared for WUSNs. Nevertheless, much research work is required in this field. It is clear that WUSN is a good replacement for wired networks in underground environments. WUSNs are cost-effective, which indicates their huge popularity. Future WUSNs could provide a vital role in many applications with the advancement of expertise. For the propagation in underground environments such as tubes and in soil, fast computation and trustworthy nodes make WUSNs a replacement for wired networks. Efficient protocols are key for good communication among the nodes. Researchers have presented many good protocols, which are available according to the desired need. Using WUSNs and the mutual communication and networking clustering between sensor nodes, a sensor network system suitable for soil and tube/pipeline applications can be established and applied to engineering applications in related fields. As WUSN is still a new area of research, there are not many solutions available in many practical fields for real-world applications.

Wireless sensor node energy is often the most important factor determining the performance of wireless sensor networks. Since WUSNs are often placed underground, only some WUSN nodes are used for mines lane and tunnels. Utility power can be used, and batteries can be easily replaced. In other environments, however, it is often difficult to perform battery replacement after node deployment. Especially for some WUSNs arranged in the soil environment, battery replacement is not carried out during the whole life cycle after deployment. Therefore, the WUSN node requires meticulous energy design compared to the ordinary WSN node. Existing WUSNs are mostly powered by carbon batteries, alkaline batteries, lead acid batteries, or polymer lithium batteries. However, these schemes have shortcomings in terms of energy density and environmental robustness. In the future development of WUSN, it is conceivable to use a chemical battery with water reaction for its function. In other words, the chemical battery in the node can interact with the water molecules in the surrounding environment to generate energy for the nodes to work. This method is especially suitable for the case where nodes are placed in soils with large water content. In addition, with the development of wireless charging technology, wireless charging methods can also be used to supplement energy for nodes [38-39].

The node design of a WUSN is also an important aspect that determines its performance. Traditional solutions usually use a design around the MCU. The integration, cost, and flexibility are limited in this way. The programmable system-on-chip that has emerged in recent years is expected to solve this problem. For example, Cypress's PSoC series chips can meet the needs of WUSN (PsoC3 PsoC4, PsoC5, and PsoC6). PsoC enables flexible, customizable, and highly integrated digital-analog hybrid embedded systems on a "silicon". With its highly integrated CPU, memory, digital subsystem, analog subsystem, digital/analog bus, universal digital block (UDB), and other system resources, it can effectively adapt to different functions of WUSN application functions. The biggest advantage of adopting PsoC to meet the diverse WUSN requirements lies in the application flexibility brought by its high degree of functional scalability [40]. Different interface and functional requirements for sensors can be combined with PsoC's internal system resources and user UDB design to achieve a highly functional and flexible design on a common hardware platform. In other words, multiple requirement design is adapted by one hardware scheme. For the design, the user can combine the native IP core and UDB module and can quickly build a user IP core and development API for specific applications and form independent intellectual property rights in a short time. This transforms the traditional business model based on the hardware platform into an IP core. It is a new and profitable business model of the service. In addition, PsoC integrates a variety of energy management features for low-power applications, making it ideal for energy-sensitive WUSN node designs. The demand for WUSN through PsoC has the advantages of wide adaptability, good versatility, rapid development, low cost, good reliability, and independent intellectual property rights [41-42].

The lack of mainstream communication protocols in the WUSN field also constrains the applications of WUSN. Although protocols such as ZigBee and WiFi can be applied to some fields of the WUSN in tunnel/tube/pipeline/lane scenarios, they do not achieve good transmission effects in soil. The traditional wireless communication protocol with a frequency band at 433 MHz is not used on a large scale, so it is slightly lacking in terms of cost and development cycle. The development of low-power wide area network (LPWAN) technology in recent years is expected to provide new technical support for WUSN. These LPWAN technologies use new signal modulation schemes (such as chirp spread spectrum (CSS)) to achieve greater penetration and transmission distance [43-44]. The network topology is simple, and the layout is easy. Its strong penetration also helps unify traditional WSN nodes with WUSN nodes, nodes in the tunnel/tube/pipeline/lane, and nodes in the soil into the same network. Its cost and power consumption are basically the same as those of the traditional ZigBee. Among these LPWAN technologies, LoRa and NB-IoT have the brightest application prospects in the WUSN field. LoRa locates unlicensed bands below 1 GHz, so there is no extra charge for application. NB-IoT uses licensed bands below 1 GHz, which are based on mobile data base stations. LoRa uses a free, unlicensed band and is an asynchronous communication protocol that is the best choice for battery power and low cost. The LoRa and LoRa protocols have unique features in handling interference, network overlap, scalability, and more. In particular, LoRa uses a free unlicensed band and is an asynchronous communication protocol. It is the best choice for low power WUSN applications. However, if the WUSN has a demand for quality of service (QoS), then NB-IoT can be considered [45-46]. The NB-IoT nodes must be networked periodically, which consumes extra battery power; therefore, NB-IoT may be a better choice for WUSN applications that require frequent communication, short latency, or large amounts of data. For lower cost, higher battery life, and no ongoing traffic costs, LoRa is better than NB-IoT for the WUSN application scenario where communication is not frequent [47-48].

5. Conclusions

The presence of WUSNs is intended to be beneficial for modern and smart usage by introducing new scopes. In this work, we touch upon a comprehensive review of wireless underground sensor networks (WUSNs). The rate of packet loss increases when the distance between transceivers increases. With the advancement of new technologies, there exists a large scope in this area of sensor networks, especially the low cost and ease of operation. WUSNs deal with different new kinds of technologies. It is very essential to choose the best protocol for WUSNs because of their complexity in soil and loss parameters. The future of WUSNs is bright with the presence of LPWAN technologies, which overcome the global problem. Still, new solutions are required to achieve soil propagation with advanced nodes and sensors. The irregularity of soil behavior with channel propagation can be adjusted through optimal algorithms and better error control schemes.

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