Channel Designing for underground Wireless Sensor Network (UWSN)

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Abstract: This task conceiting of underground activity of Wireless Sensor Network (UWSN). UWSNs can be made to supervise the different conditions, such as soil characteristics for forming 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.

Index Terms **- Magnetic Induction, Electromagnetic waves, Propagation Characteristics.**

I. Introduction

Wireless underground sensor networks (UWSNs) are networks of sensor nodes operating below the ground surface, which are envisioned to provide real-time monitoring capabilities in the complex underground environments consisting of soil, water, oil, and other components. In this paper, we investigate the possibilities and limitations of using UWSNs for increasing the efficiency of oil recovery processes. To realize this, millimeter scale sensor nodes with antennas at the same scale should be deployed in the confined oil reservoir fractures. This necessitates the sensor nodes to be operating in the terahertz (THz) range and the main challenge is establishing reliable underground communication despite the hostile environment which does not allow the direct use of most existing wireless solutions. The major problems are extremely high path loss, small communication range, and high dynamics of the electromagnetic (EM) waves when penetrating through soil, sand, and water and through the very specific crude oil medium. The objective of the paper is to address these issues in order to propose a novel communication channel model considering the propagation properties of terahertz EM waves in the complex underground environment of the oil reservoirs and to investigate the feasible transmission distances between nodes for different water-crude-oil-soil-CO2 compositions.

As defined in [1-5] UWSNs are networks of wireless sensor nodes operating below the ground surface. Compared to the current underground sensor networks which use wired communication methods for network deployment, UWSNs have advantages in timeliness of data, ease of deployment and data collection, concealment, reliability, and coverage density [1-5]. As a natural extension to the well-established wireless sensor networks (WSNs) [6] paradigm, WUSNs can be deployed to operate in underground tunnels and mines. In the future they are also envisioned to provide real-time monitoring capabilities in new challenging underground environments such as soil medium and oil reservoirs. In the tunnels and mines the WSNs are not fully buried underground—they operate below the surface of the earth but communicate through air ducts as medium. In the latter case, networks are fully located underground and communication takes place through the mixture of gas, water, and crude oil inside the oil reservoirs. These specific UWSNs are a promising and continuously expanding field that will enable a wide variety of novel applications, not possible with current underground monitoring techniques.

The system architecture of general UWSNs in soil medium is detailed in [5,6]. In this paper, we focus on UWSNs specifically tailored for operation in oil reservoirs. The wireless underground sensor network for oil recovery consists of a base station (data sink) located at the wellbore and a large number of wireless sensor nodes deployed uniformly in the fractures of the oil reservoir. The wireless sensor nodes are injected into the fracture with the fluid during the hydraulic fracturing process and remain in the fractures fixed to their walls. These fractures are usually quite long (~120 m) and very narrow (1~3.4 cm). The method proposed in this work for realizing the communication between the sensor nodes in these fractures is based on electromagnetic waves (EM) propagation which is completely different from other methods proposed so far [6-10]. The transmission environment in this case consists of a complex mixture of soil, water, and crude oil in various proportions and is very different from the traditional wireless propagation channel. As a result, the existing techniques for wireless propagation and communication fail to operate in a satisfactory manner in the fractures of the oil reservoir.

The major specifics of the WUSN operating in oil reservoirs can be summarized as follows.(i)The environment where the wireless sensor nodes are deployed is a 3D hydraulic fracture with a size of 100 m 3 m 1 cm (length height width). As the width of the fracture is less than 1 cm, the size of the sensor nodes should be in the millimeter magnitude. Furthermore, the millimeter scale sensor nodes necessitate antennas at the same scale which implies that the operating frequency has to be in the Gigahertz or Terahertz range [1-8].(ii)The fractures are filled with thick fluid consisting of water and crude oil. In such fluid transmission medium, an EM signal with frequency in the Gigahertz and Terahertz range will experience severe medium absorption, which leads to extremely high path loss and short transmission radius.(iii)The wireless sensor network as a whole will encounter severe energy problems. On one hand, the millimeter scale sensors only allow a very miniature battery with extremely limited energy supply. On the other hand the well-known solar and wind based energy harvesting schemes are not applicable underground.

The above-mentioned specifics of UWSN and the challenging problems they pose necessitate the development of new low-power signal propagation models and techniques for these networks.

Based on the determination of a transmission window in the Terahertz band optimal for the complex underground environment found in oil reservoirs the main contributions of this paper are as follows: proposition of a novel communication channel model considering the propagation properties of EM waves in the complex underground environment of the oil reservoirs; estimation of the feasible transmission distances between nodes and performance evaluation in terms of BER for different water-crude-oil-soil-CO2 composition.

Related work

Oil extracting

Oil recovery is a very complex process and since a lot of effort and resources are involved it is very important to have as much information as possible about the oil recovery reservoir/field at each stage of the process. Thus researchers have been looking for different innovative ways to address the question of extracting information about the state of the resources from the hostile underground oil environment.

Liu et al. [15] study the progress of carbon dioxide in oil reservoirs using ultrasound and show that their approach may lead to unique and powerful ways of monitoring the position of carbon dioxide, as well as visualizing the reality of the oil producing area. The work reports results from different experiments related to the investigation of acoustic waves properties in different media. Their studies include ultrasound reflection properties of stationary water-air, water-oil, air-oil, and oil-oil interfaces, as well as those of moving interfaces. Furthermore, experiments of ultrasound reflection properties in porous medium combined with air, water, and oil are described.

In [13] Xu et al. describe an oilfield associated gas recovery device designed to take into consideration the status of associated gas recovery process. The relation between gas temperature and pressure in the device during the heating process is analyzed and calculated through the ideal-gas equation. The gas recovery device described is theoretically proved to be feasible. The oilfield associated gas can be effectively recovered by the device which requires low investment and convenient field application.

In their project Mazzini et al. [8] study the feasibility of using a robotic manipulator for tactile mapping. A method is developed that requires only robot joint encoders and avoids the use of any force or tactile sensors, which are complex and unreliable in such a hostile environment.

Process of oil Recovery

Compared to the above-mentioned methods and techniques the use of UWSN for oil reservoir exploration is a very new and promising trend. However, due to the extremely high path loss, small communication range, and high dynamics of EM waves when penetrating the soil, water, and crude oil medium, most existing wireless solutions are inapplicable.

The oil recovery filed presents an underground environment which is much different from the ones studied in the works mentioned above. It contains besides soil, with different degrees of moisture, large amounts of crude oil as well as carbon dioxide (additionally injected in the fractures during the oil recovery process). The different medium components impose different attenuation and phase shifting effects on the EM waves especially when the Terahertz band is considered. The path loss fluctuates as the operating frequency changes due to the summation of EM waves with different phases. In order to achieve wireless transmission it is desirable to determine the frequency bands where the absorption loss experiences deep fades so that the path loss is minimized and the transmission range is maximized. As we are dealing with extremely high frequencies, even a very narrow channel (portion of the spectrum with deep fading in the values of the absorption) can bring more than enough bandwidth. However, since the EM waves are transmitted inside the fracture, the walls of the fracture limit the spread of the signal energy by reflecting the signal back into the fracture medium, which may also add additional fluctuations in the path loss values [5]. Furthermore, some molecules like carbon dioxide and hydrocarbons present in the considered medium are excited by EM waves at specific frequencies within the Terahertz band. An excited molecule internally vibrates; that is, its atoms show periodic motion while the molecule as a whole has constant translational and rotational motions. As a result of this vibration, part of the energy of the propagating wave is converted into kinetic energy or, from the communication perspective, is simply lost. EM waves at these specific frequencies within the Terahertz band encounter much higher attenuation in soil and liquid compared to air. This severely hampers the communication quality. Therefore, advanced models are necessary to accurately and completely characterize the underground channel in the Terahertz band and to lay out the foundations for efficient underground communication networks.

Channel designing for under ground

One of the major issues for realizing UWSNs is evaluating the performance of the wireless channel existing between the nodes. A number of factors—frequency, propagation loss, scattering, refraction, reflection, diffraction, and so forth—affect the wireless transmission making it difficult to predict the received signal. Wireless channel modeling in general is a challenging task and has been addressed by researchers from very different aspects depending on the specific application in mind—from cellular systems to connecting medical imaging devices in hospitals [12-16] and underground sensor networks. Channel modelling and simulation are an extremely important tool for analysis that reduces the cost of developing a complex system by limiting the amount of hardware required for evaluating its performance. These theoretical models have a second advantage in their ability to reproduce a channel for comparison between various communication strategies, resulting in an accurate measure of relative network performance as a whole. UWSNs are a very new concept and there are only very few studies that address the issues of the underground communication channel [5, 6,7]. The first works on studying the properties of the wireless underground channel [8,9] focus on the characterization of the "underground-underground," "underground-aboveground," and "aboveground-underground" electromagnetic waves channels, while capturing the effects of environment parameters such as soil composition and soil moisture, and system parameters such as the antenna gain, operating frequency, and the sensor burial depth. The propagation characteristics are investigated through simulation and results are provided for the path loss between two adjacent nodes.

Another recently published work [17] explores the possibility of utilizing the method of magnetic induction to provide wireless communication in underground oil reservoirs. The work addresses the system architecture and operational framework of a magnetic induction- (MI-) based wireless sensor network, where both the wireless energy transfer and the wireless communications in the reservoir are realized by the magnetic induction technique. It analytically examines the feasibility of this method and proves that it can provide communication up to around 1.5 m. Even though theoretically this is a promising approach, a feasible implementation seems possible in the next decades.

Conclusion

Working with underground sensors and using WUSNs in the THz band to provide detailed information during different phases of the oil recovery process are a very revolutionary topic and is not covered in any of the existing studies.

The objective of our work is to address the unique and important challenges for the implementation of wireless sensor networks in underground environments during oil recovery processes. To the best knowledge of the authors at the time of preparing this material there is no completed study regarding the modeling and thorough theoretical examination of the wireless communication process in WUSNs used in oil recovery process? We investigate the channel characteristics of the Terahertz EM waves in oil reservoir environments to determine an optimal frequency band that minimizes the total path loss and maximizes the transmission radius for an underground sensor network. Once the optimal operating frequency is determined, the link capacity and performance are evaluated based on the propagation channel model described in this work.

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