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## Design Approach for a Novel and Efficient Wireless Underground Communication System by using Electromagnetic Waves

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**ABSTRACT:** A Wireless Underground Communication Networks (WUCN's) consists of wireless device that operates below the ground surface. These devices are either (1) buried completely under dense soil, or (2) placed within a bounded open underground space, such as the underground mines and road/subway tunnels. The main difference between WUCN's and the terrestrial wireless communication networks is the communication medium. In this research paper, a signal propagation characteristic is described in these constrained areas. First, a channel model is described for electromagnetic (EM) waves in the soil medium. This model characterizes not only the propagation of EM waves, but also other effects such as the multipath, soil composition, water content and burial depth. Second, the magnetic induction (MI) techniques are analyzed for communication through soil. Based on the channel model, the MI waveguide technique for communication is developed in order to address the high attenuation challenges of MI waves through soil. Furthermore, a channel model, i.e. the multimode model, is provided in order to characterize the wireless channel for WUCN's in underground mines and road/subway tunnels. The multimode two cases for the underground communication, i.e., the tunnel channel and the room-and-pillar channel. Finally, the research challenges for the design communication protocols for WUCN's in both the underground environments are discussed based on the analysis of the signal propagation.

**KEYWORDS:** Wireless Underground Communication network, Electromagnetic Waves, Attenuation, Rayleigh Fading Channel Model, Bit Error Rate (BER), Signal to Noise Ratio (SNR), Modulation

### I. INTRODUCTION

Wireless Underground Communication Networks (WUCN's) constitute one of the promising application areas of the recently developed wireless networking techniques. The WUCN's consists of a wireless device that operates below the ground surface. These devices are either (1) buried completely under dense soil or (2) placed within a bounded open underground space such as the underground mines and road/subway tunnels. In the former case, the networks of wireless nodes are buried underground and communicate through soil. In this case, the WUCN's promise a wide variety of novel applications, including the intelligent irrigation, environmental monitoring, infrastructure monitoring, localization and border patrol. In the latter case, although the network is located underground, the communication takes place through the air, i.e., through the voids that exist underground. In this case, the WUCN's are necessary to improve the safety and productivity in underground mines, to realize the convenient communication for drivers and passengers in road/subway tunnels, and to avoid attacks by continuously monitoring these vulnerable areas. The main challenge for WUCN's is the realization of efficient and reliable underground wireless links to establish multiple hops and disseminate the data for seamless operation. The main difference between the WUCN's and the terrestrial wireless communication networks is the communication medium. For the WUCN's which are deployed in soil, the propagation medium is no longer air but soil, rocks and water. Although the well established terrestrial signal propagation techniques which are based on electromagnetic waves (EM) may still work in a soil medium, the channel model of EM waves in this environment needs to be developed. Besides EM waves, the alternate signal propagation techniques such

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as the magnetic induction (MI) can also be used for short-range communication in soil. For the WUCN's which are deployed in the underground mines and road/subway tunnels, the EM waves are the best choice for wireless signal propagation, since the radio signal are significantly different from those of the terrestrial wireless channels because of the restrictions which are caused by the lossy dielectric walls and the ceilings in the underground mines or road/subway tunnels.

## **II. LITERATURE SURVEY**

Since the wireless underground communication technology today has become a part of our daily life, the idea of wireless undersea communications underway may still seem far-fetched. However, the research has been active for over a decade on designing the works for wireless information transmission underwater. Human knowledge and understanding of the world's oceans, which constitute the major part of our planet, rests on our ability to collect the information from remote undersea locations. The characteristics of this channel are frequency-dependant propagation loss, severe multi-path and low speed of sound propagation. None of these characteristics are nearly as pronounced in land-based radio channels, the fact that makes the underwater wireless communication extremely difficult and necessitates dedicated system design. As mentioned earlier, the underground unlike the terrestrial network is a challenging environment for communication, the problems faced by electromagnetic waves lead to the use of magnetic induction as a means of communication underground.

### **ACOUSTIC WAVES**

Acoustic wireless communication is the most widely used technique in underwater wireless communication for its long distance communication ability[3][10][11]. However, it suffers from several major disadvantages, such as the transmission speed is greatly affected by the temperature gradients and air bubbles in the water, the performance is limited by the background noises as well as noises from some underwater equipment [12].

### **OPTICAL WIRELESS COMMUNICATION**

Optical wireless communication which has a favour in point-to-point communication over a range of a few kilometres in terrestrial communication is limited to a very short range because of the severe absorption and scattering in the underwater environment [13]. More seriously, the optical wireless communication may not perform signal transmission when soil or rock is hindered in its transmission path.

### **ELECTROMAGNETIC WAVES**

Traditionally, the wireless communication techniques by using electromagnetic (EM) waves encounter three major problems in the underground environments: the high path loss, the dynamic channel distortion and the large antenna size. First, the electromagnetic waves experience a high level of attenuation due to the soil, rock and water in the underground. Second, the path loss is highly dependent on numerous soil properties such as the water content, the soil make-up (sand, silt or clay) and density and can change dramatically with time and space. Consequently, the bit error rate (BER) of the communication system also varies dramatically in different times or positions. Third, a large size antenna is necessary for the efficient propagation of the EM waves. The path loss can be reduced if lower operating frequencies are used.

### **RADIO FREQUENCY WIRELESS COMMUNICATION**

Radio frequency wireless communication which uses electromagnetic waves in order to transmit a signal is the most popular wireless communication technique in the field of terrestrial communication. However, this conventional radio frequency does not work in the underwater environment due to high path loss, dynamic channel condition, large antenna size etc. [13][14]. Comparing with the other wireless underground communication methods i.e. acoustic, optical and RF, it permits long range communication as a promising alternative to acoustic communication. Although

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the coil size can be adjusted to the range of interest for MI waves and the relaying topology changes the performance significantly, the results given for 0.15 meters radius coil and grid topology form a practical and comparable MI communication channel permitting several kilometre range of communication within tens of kilobits per second similar to the acoustic channel but without high latency and propagation delay, multi-path fading, Doppler effects and large transceiver costs. Furthermore, for a short range although tens of kilobits per second data rate is very small compared with the optical communication. Moreover, it has high data rates compared with RF for the ranges extending from tens to hundreds of meters. The path loss of the MI waveguide system remains the lowest when high operating frequency is used. Hence, as compared with all other waves, the MI waves have a significant characteristic.

## MI WIRELESS COMMUNICATION

In the MI wireless communication, the signal transmission and reception are usually realized by two coils of wire [1], as shown in Figure 2. In this figure,  $a_t$  and  $a_r$  are the radii of the transmission and the reception coil respectively.  $N_t$  and  $N_r$  are the number of turns of the two coil respectively.  $R$  is the distance in the centres between these two coils and  $\alpha$  is the angle between the axes of these two coils. Suppose that the current in the transmission coil is a sinusoidal current

$$i(t) = I_m \sin(\omega t + \psi_0) \dots\dots\dots \text{Eqn. (1)}$$

Where  $I_m$  is the magnitude of the current,  $\psi_0$  is the initial phase,  $\omega$  is the angle frequency of this current and  $t$  represents the time. According to Ampere's right hand screw rule, a shift in the magnetic field will be generated around the transmission coil. This shift in the magnetic field will induce a shift in the electromotive force (EMF), or a shift in the current in the reception coil. In this way, the wireless communication has been accomplished.

## III. WIRELESS COMMUNICATION THROUGH SOIL USING ELECTROMAGNETIC WAVES

The EM waves encounter much higher attenuation in soil as compared to air. This severely hampers the communication quality. Moreover, the ground surface causes reflection as well as refraction, which requires a comprehensive investigation of the channel model. In addition, multi-path fading is another important factor in underground communication, since unpredictable obstacles in soil such as the rocks and the roots of trees make EM waves refracted and scattered. Therefore, advanced models are necessary to accurately and completely characterize the underground channel and to lay out the foundations for efficient underground communication.

### TWO-PATH RAYLEIGH FADING CHANNEL MODEL

For the derivation of the underground channel model, we first model the propagation characteristics in the soil. Then, the effects of reflections from the ground surface and the multi-path fading are captured. Finally, the bit error rate (BER) is derived as a function of communication parameters such as the operating frequency, modulation type, distance as well as the soil parameter such as the volumetric water content, sand and clay percentage and temperature.

### CHARACTERISTICS OF EM WAVES IN SOIL

Based on the developed channel model, the Bit Error Rate (BER) profile in the underground settings can be evaluated. The BER of a communication system depends mainly on three factors: the channel model (2) the Signal-to-Noise Ratio (SNR) and (3) the modulation method used by the system. Considering the channel model derived before, the signal-to-noise ratio (SNR) is given by the following formula:

$$\text{SNR} = P_t - L_f - P_n \dots\dots\dots \text{Eqn. (2)}$$

where  $P_t$  is the transmit power,  $L_f$  is the total path loss, and  $P_n$  is the noise energy. In the following part, we will discuss the effects of various factors on the BER in wireless channel of soil medium, including the modulation method, operating frequency, deployment depth; transmit power and volumetric water content.

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## MODULATION SCHEME

In order to provide an initial investigation in this area, various modulation schemes including the ASK, FSK and the PSK are investigated in order to illustrate their effects on the BER. The relationship between the maximum inter-mode distance of the single path channel model and the VWC is shown in Figure 1. The maximum inter-node distance is found subjected to a BER target of 10:3 for different modulation methods. In Figure 1, it can be seen that the PSK modulation method provides the largest range. Consequently, in our analysis, we consider the PSK modulation scheme. The study reported here includes propagation analysis and coverage as well as the available downlink (DL) throughput of OFDMA-based IEEE802.16m WiMAX system as a function of distance to the Base Station (BS) for a number of outdoor and indoor propagation scenarios. Moreover, Walls penetration loss is also considered. Adaptive modulation and Coding (AMC) schemes will be assumed in the present study for 5 MHz and 20 MHz channel bandwidth. The next generation of mobile WiMAX is IEEE 802.16m amends the IEEE 802.16e, j specification to provide an advanced air interface for operation in licensed bands. It is a recommended candidate for 4G. Unlike other wireless standards, WiMAX allows data transport over multiple broad frequency ranges. This lets the technology avoid frequencies that would interfere with other wireless applications.

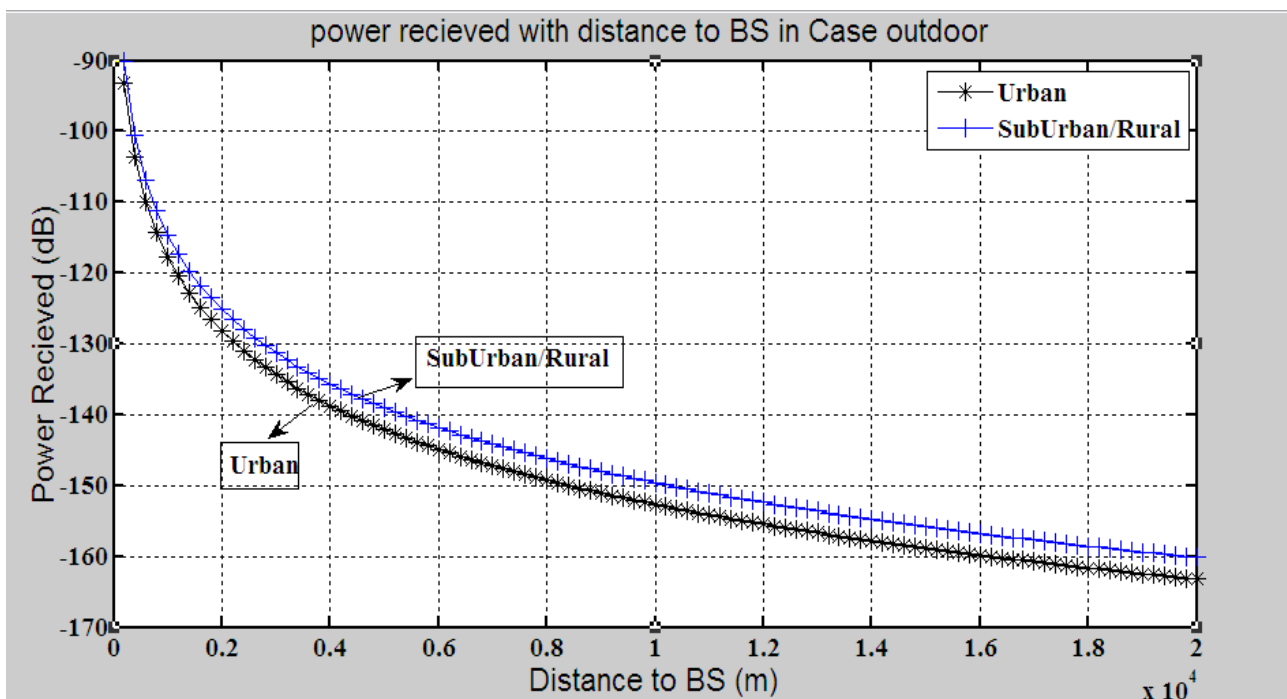


Figure 1 The Maximum Inter-Mode Communication Distance of One Path Channel Using Different Modulation Schemes

## OPERATING FREQUENCY AND THE DEPLOYMENT DEPTH

In Figure 2, the path loss is shown as a function of the burial depth,  $H$  for various values of the operating frequency,  $f$ . For a particular operating frequency, an optimum bury depth exists such that the path loss is minimized. This is particularly important in the topology design of WUCN's where the deployment should be tailored to the operating frequency of the wireless sensors. In Figure 2 (b), it can also be observed that the effect of reflection, and hence, the fluctuations in the path loss diminishes as the bury depth,  $H$  increase. More specifically, the underground channel exhibits a single-path characteristic when the bury depth is higher than 2 meters since the influence of reflection is negligible. On the other hand, for low depth deployment, a two path channel model should be considered. A wireless

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sensor network (WSN) consists of sensors used to monitor physical or environmental phenomena such as humidity, temperature, sound, vibration, pressure or motion and cooperatively pass the data through the network of sensors to a main location. As wireless network sensors become smaller in dimension and cheaper, researchers are deploying them in environments that are unconventional for electromagnetic signalling. One of those applications for wireless sensor network is underground wireless communication to monitor soil properties and then transmit the collected data to a node on the surface. Wireless underground sensor network has a lot of applications including: environmental monitoring, infrastructure monitoring, location determination and border patrol and security monitoring.

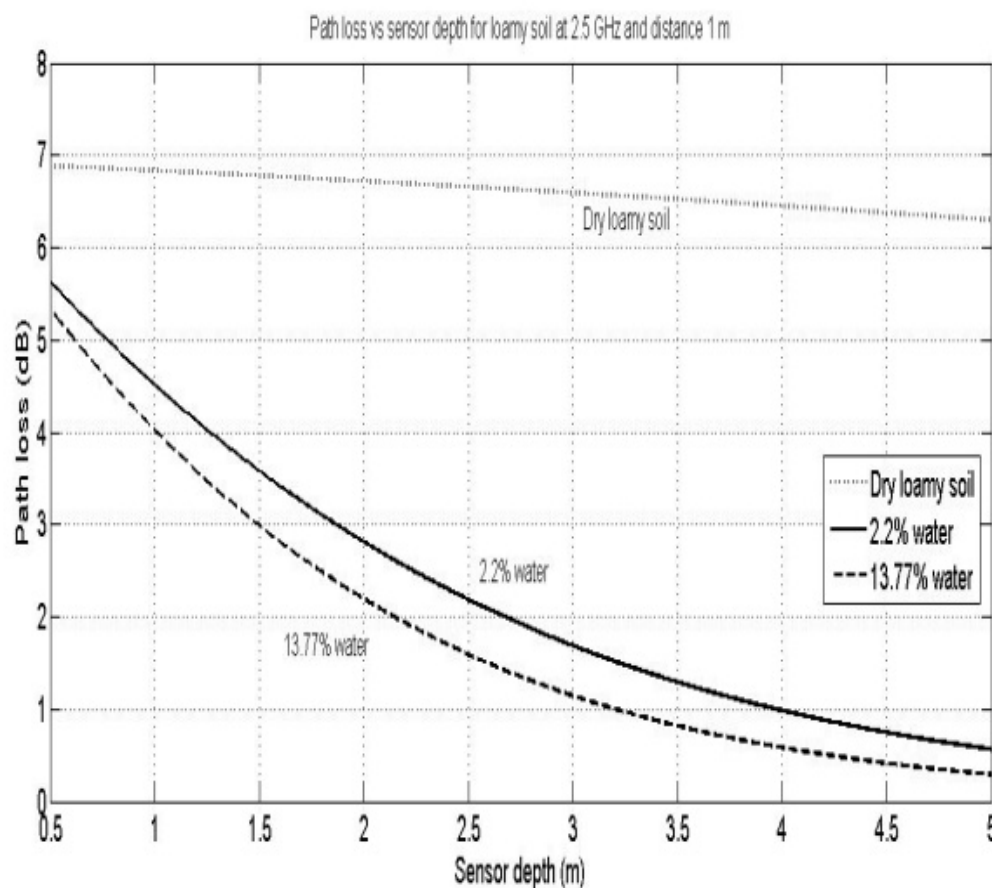


Figure 2 Path Loss versus Depth for Different Operating Frequencies with Two-Path Channel Model

## VOLUMETRIC WATER CONTENT VARIATION

The above analysis is performed assuming that the VWC is constant throughout the soil. However, field measurements reveal that the VWC also changes with the depth. Moreover, even at the same depth, communication can change by as much as 25% depending on the time of the year. In order to investigate the relation between the communication quality and the burial depth, the BER is evaluated based on the experimental data. We denote these data sets as Set 1 and Set 2, where the properties of each experiment are described as follows:

**Set 1:** The first data set consists of volumetric water content values which are measured at different depths in a black soil with 22.75% sand, 28.1% clay.

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**Set 2:** The second data set is from a sandy soil with 50% sand and 15% clay. Since sandy land soil keeps less water as compared to the black soil, this data set was included in order to illustrate the effect of soil content on the influence of variation of the VWC on the communication range.

Networks of sensors are envisaged to be major participants in future data-gathering systems for civilian and military applications, including medical and environmental monitoring and surveillance, home security, agriculture, and industry. Typically, a very large number of miniature sensing and communicating nodes are distributed *ad hoc* at the location of interest, where they establish a network and wirelessly communicate sensed data either to one another or to a base station using various network topologies. The optical modality is a potential solution for the links, due to the small and lightweight hardware and low power consumption, as well as other special features. Notably, the backscattering of light by molecules and aerosols in the atmosphere can function as a vehicle of communication in a way similar to the deployment of numerous tiny reflecting mirrors.

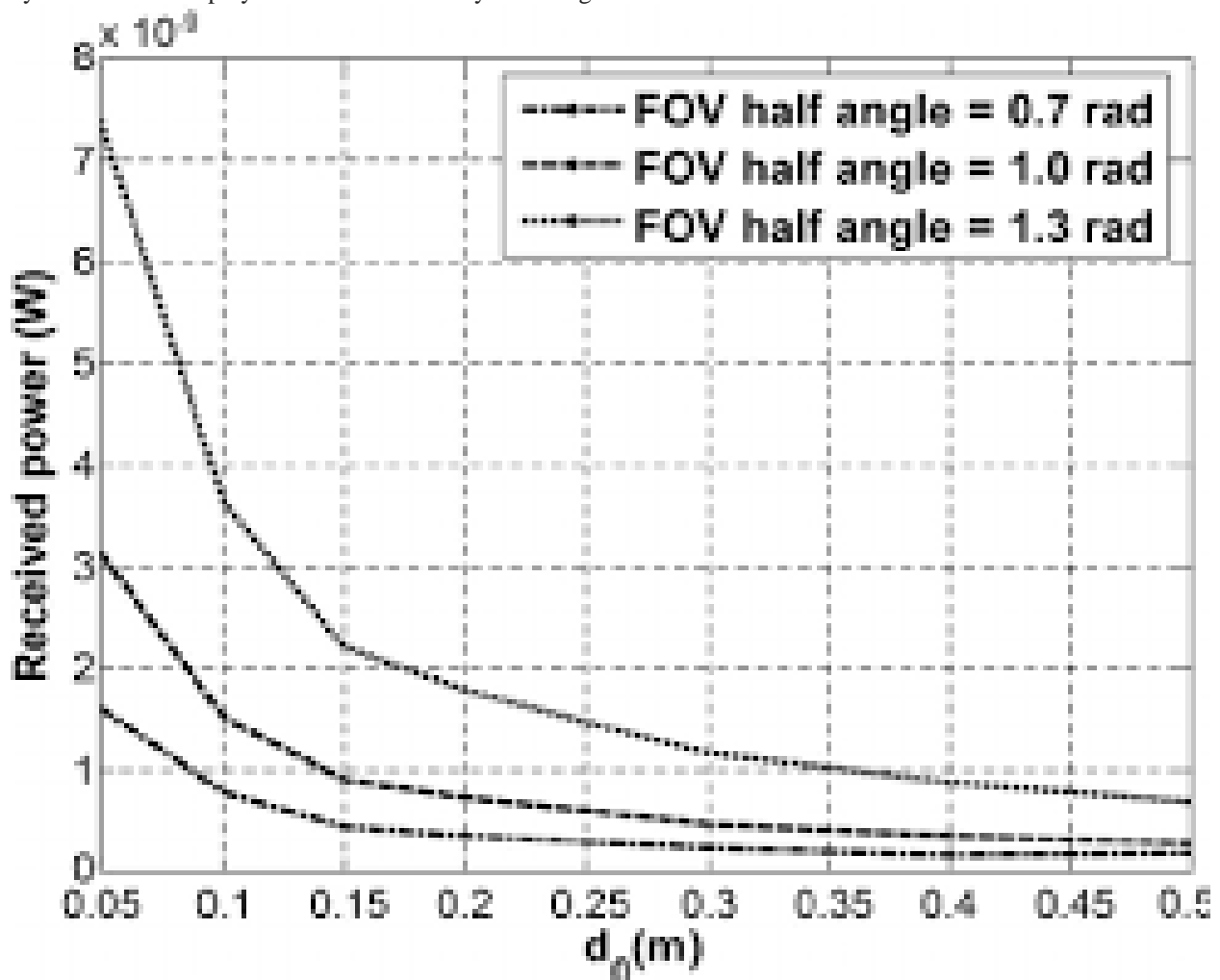


Figure 3 BER versus Inter-node Distance with Different Transmitting Power



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## IV. WIRELESS COMMUNICATION THROUGH SOIL USING MAGNETIC INDUCTION

As discussed in Section 2, the traditional signal propagation techniques by using EM waves encounter three major problems in the soil medium: high path loss, dynamic channel condition and large antenna size. First, EM waves experience high levels of attenuation due to absorption by soil, rock and water in the underground. Second, the path loss is highly dependent on numerous soils properties such as water content, soil make up (sand, silt or clay) and density and can change dramatically with time (e.g. increased soil water content after rainfall) and space (soil properties change dramatically over short distances). Consequently, the bit error rate (BER) of the communication system also varies dramatically in different times or positions. An unreliable channel brings design challenges for the underground devices and networks in order to achieve both the satisfying connectivity and channel efficiency. Third, the operating frequencies in MHz or lower ranges are necessary to achieve a practical transmission range. In order to efficiently transmit and receive the signals at that frequency, the antenna size is too large to be deployed in the soil. The Magnetic Induction (MI) is an alternative signal propagation technique for underground wireless communication, which addresses the dynamic channel condition and large antenna size challenges of the EM wave techniques. In particular, a dense medium such as soil and water causes little variation in the attenuation rate of magnetic fields from that of air, since the magnetic permeability of each of these materials are similar. Therefore, the MI channel conditions remain constant in a soil medium. Moreover, in the MI communication, the transmission and reception are accomplished with the use of a small coil of wire. Therefore, no lower limit of the coil size is required. However, the magnetic field strength falls off much faster than the EM waves. Consequently, MI is generally unfavourable for terrestrial wireless communication. In a soil medium, although the path loss of MI which is caused by the soil absorption is much less than the EM waves, the total path loss may still be higher.

### MI CHANNEL MODEL

In MI communication, the transmission and reception are accomplished with the use of a coil of wire, as shown in Figure 5 (a), where  $a$  and  $a_r$  are the radii of the transmission coil and receiving coil respectively;  $r$  is the distance between the transmitter and the receiver and  $90 - \alpha$  is the angle between the axes of the two coupled coils.

### MI WAVEGUIDE

Although the MI technique addresses the dynamic channel condition and large antenna size challenges of the EM wave techniques, its received power loss is much higher than in the EM wave case. For practical applications, this can be addressed by employing the relay points between the transmitter and the receiver. Contrary to the relay points which are used for the EM waves, the MI relay point is a simple coil without energy source or processing device. The sinusoidal current in the transmitter coil induces a sinusoidal current in the second relay point and so on and so forth. These relay coils form an MI waveguide in underground environments, which act as a waveguide that guides the so called MI waves. Wireless underground sensor networks (WUSNs) create many interesting possibilities for new topologies. By their nature, most WUSN deployments will be three-dimensional topologies since underground communication will take place at a variety of depths. Creative topology design in these networks can promote power savings in the underground, inaccessible, power-limited devices comprising a WUSN. A WUSN device deployed at a large physical distance from the sink must route its data toward the sink in a multi-hop fashion.

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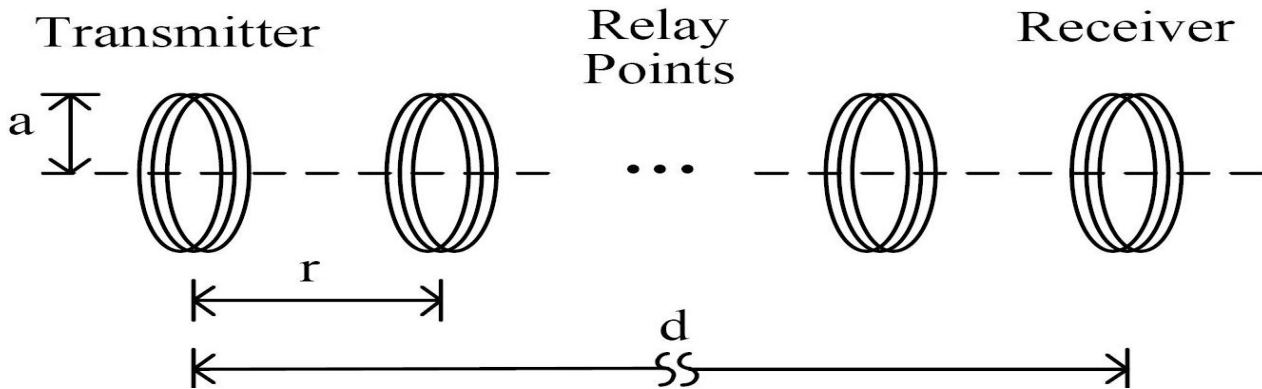


Figure 4 The Structure of the MI Transceiver and the MI Waveguide

## LOW OPERATING FREQUENCY AND LOW VOLUMETRIC WATER CONTENT

Figure 4 shows the path loss of the three techniques in db versus the transmission distance  $d$  by using a 300 MHz signal in the soil with a 5% VWC. It can be seen that in the very near region ( $d < 1$  meter), the path loss of the MI technique is smaller than that of the EM wave technique. However, as the transmission distance increases, the MI signal attenuates much faster than the EM wave signal. It may have up to 20 db higher path loss than the EM wave signal. As expected, the MI waveguide technique greatly reduces the signal path loss as compared to the other two techniques. It is shown that the path loss of the MI waveguide system is less than 50% of the MI and EM wave cases in a certain range.

## V. CONCLUSION AND FUTURE SCOPE

In this research paper, an overview of underground wireless channel models and corresponding challenges are provided for the purpose of Wireless Underground Communication Networks (WUCN's). More specifically, the WUCN's are classified into two major classes based on the environment they operate in soil medium and underground mines/tunnels. For WUCN's in soil medium, the channel models for EM and MI waves are described. Firstly, a complete underground channel model is derived in order to characterize the EM wave propagation. The analysis shows that the communication success significantly depends on the operating frequency and the composition of the soil. Furthermore, it is shown that the channel characteristics depend on the burial depth of the sensors. For low depth deployments, a single path channel is suitable in order to characterize the process of communication. Besides EM waves, an MI waveguide is developed as an alternative wireless communication technique in a soil medium. Although a traditional MI technique addresses the dynamic channel conditions and large antenna size challenges of EM waves in the soil medium, the MI signal attenuates much faster than the EM wave signal. The proposed MI waveguide technique can greatly reduce the path loss through the relay coils which are deployed between the transceivers.

## VI. ACKNOWLEDGMENTS

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## BIOGRAPHY



My name is Prof. Abhinav V. Deshpande. I have done S.S.C. from Somalwar Nikalas High School, Nagpur in the year 2000 with an aggregate of 73% with Science as the specialization. I have done H.S.S.C. from Jupiter Science Junior College, Nagpur in the year 2002 with an aggregate of 54% with Electronics as the specialization. I have done B.E. in the branch of Electronics & Telecommunication Engineering from G.H. Raisoni College of Engineering, Nagpur in the year 2010 with an aggregate of 63%. I have done M.Tech. in the branch of Electronics Engineering from the same institute in the year 2012 with a CGPA of 7.90 on a scale of 10.00. I have also passed the Ph.D. Entrance Test (PET) which was conducted by RTM Nagpur University in the year 2013 with a valid score of 55 marks out of 100 and in the year 2015 with a valid score of 55.75 marks out of 100. I have also passed the Ph.D. Entrance Test (PET) of Gondwana University, Gadchiroli in the year 2015 with a valid score of 51 marks out of 100. I have published 19 research papers in different and reputed International Journals and 1 research paper in International Conference. I have also published 1 book in Saarbrücken, Germany in the year 2012. I am having the memberships of different and reputed professional organizations like ISTE, IEEE, IE (I), IETE, IET, UACEE. My areas of research include different topics in the field of Electronics Engineering such as Digital Signal Processing, Digital Image Processing, Soft Computing and Applications, Intelligent Transportation Systems, Embedded Systems, VLSI etc. I want to pursue Ph.D. in the branch of Electronics Engineering and also I want to pursue D.Sc. in the branch of Electronics Engineering as a part of future career prospects. At present, I am working in the Department of Electronics & Telecommunication Engineering at Prof. Ram Meghe Institute of Technology & Research, Badnera, Amravati-444701 as an Assistant Professor on Contract Basis.