# Advancements in Magnetic Induction Communication for Wireless Underground Sensor Networks: An overview

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*Abstract:* **.Underground is a challenging environment for wireless communication because the propagation medium is soil, rock, water and no longer air. Wireless communication technique using electromagnetic (EM) wave do not work well in this environment due to high path loss, dynamic channel condition and large antenna size. New propagation technique using magnetic induction (MI) solve problems of the EM wave technique. Underground Wireless Communication is the enabling technology to realize Wireless Underground Sensor Networks (WUSNs), which is used in a wide variety of novel applications, such as intelligent agriculture, diagnosis of pipeline fault, mine disaster rescue, and crude oil exploration.**

**Magnetic inductive(MI) waveguide is developed to cope with the very harsh propagation conditions in WUSNs. The objective of this paper is to give the overview about the development of MI communication technology specially for WUSNs.**

*Keywords:* **Magnetic induction (MI),Magnetic inductive(MI) waveguide,Wireless Underground Sensor Networks (WUSNs).**

## 1. INTRODUCTION

Underground Wireless Communication is the enabling technology to realize Wireless Underground Sensor Networks (WUSNs), which is used in a wide variety of novel applications, such as intelligent agriculture, diagnosis of pipeline fault, mine disaster rescue, and crude oil exploration [1]. Underground environment is more complicated than the environment above the ground surface as they contain air, sand, rocks and water with electrolytes. In such complex environment it is challenging to realize wireless communication as the propagation medium is no longer air.Traditional techniques using electromagnetic(EM) waves are widely used in terrestrial environment, however those techniques do not work well in underground scenarios. Communication using EM waves encounter problems in soil medium. First, EM waves experience high level of attenuation due to absorption by soil, rocks and water present in underground environment. Second, the electrolytes present in underground medium become one of the main factor that influences the path loss of EM waves which can affect the performance of communication since these factors change with location and vary dramatically over time. Third, there exist conflicts in antenna design for underground communication using EM waves. On one hand, the size of antenna is expected to be as small as possible so that the deployment of the networks become easy. On the other hand, operating frequency must be in MHz or lower ranges to achieve practical transmission range and capable to transmit and receive signals at that frequency, the antenna size is too large to be deployed in the soil.

A promising alternative for underground wireless communication is i.e., Magnetic Induction (MI) has been developed. It solves the dynamic channel condition problem and large antenna size problem of the EM wave techniques as in a MI communication system, the HF band magnetic field generated by a MI transmitter coil is utilized as the signal carrier. Since most natural media have the same magnetic permeability as air, MI keeps the same performance in most materials [2,3]. This fact assure that the MI channel conditions remain constant. Moreover, the MI communication solves the issue of antenna size since the transmission and reception are accomplished with the use of a small coil of wire.Although the MI technique solves the dynamic channel condition problem and large antenna size problem of the EM wave techniques, its receiving power loss is much higher than in the EM wave case.one solution is to employ some relay points between the transmitter and the receiver. Different from the relay points using the EM wave technique, in MI technique the relay point is a simple coil without any source of energy or processing device. The sinusoidal current in the transmitter coil induces a sinusoidal current in the first relay point then this sinusoidal current in the relay coil induces sinusoidal current in the second relay point, and so on. Those relay coils form an MI waveguide in underground environments.

MI-based WUSNs were first introduced by Akyildiz et. al. [1] and make use of magnetic antennas implemented as coils, which are combined in waveguide structures with several passive relay devices between two transceiver nodes. Hence, the transmission range can be greatly improved compared to the EM based approach. This review aims to show the technical advancement of Magnetic Induction Communication for Wireless Underground sensor networks. Paper is organized as follows: Section 2 provides an overview of magnetic induction communication and its advantages. Technical advancement such as reducing antenna size, reducing the MI path loss, to minimize the number of relay coils etc., is shown in details in section 3. Finally, the paper is concluded in section 4.

## 2. OVERVIEW OF MAGNETIC INDUCTION COMMUNICATION

Magnetic Induction (MI) Communication System is a short range wireless physical layer that communicates by coupling a tight, low-power, magnetic field between devices which is non propagating. The concept is, a magnetic field is modulated by a transmitter coil on one device which is measured by means of a receiver coil in another device.The block diagram of communication system based on inductive coupling is shown in figure 1.

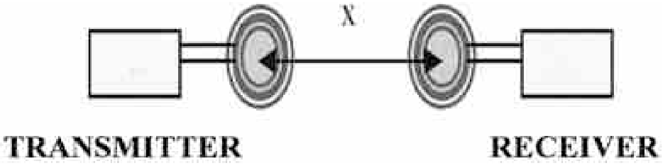

Fig. 1. Communication based on inductive coupling[5]

The communication link is established through the magnetic inductive coupling between the transmitter coil and the receiver coil. The coupling co-efficient is used to qualitatively predict the coupling of the two coils [4] given by equation 1.

$$\boldsymbol{k} = \frac{\boldsymbol{M}}{\sqrt{\boldsymbol{L_1 L_2}}} \qquad \textbf{(1)}$$

Where M is the mutual inductance and $L_1$,$L_2$ is the inductance of the coils of the transmitter and receiver. The equivalent circuit model of the system is shown in figure 2. $R_{L1}$, $R_{L2}$ are the resistances of the coils, and $C_1$, $C_2$ are the capacitors to form the resonance with the transmitter and receiver's coils in order to have the maximum coupling sensitivity.

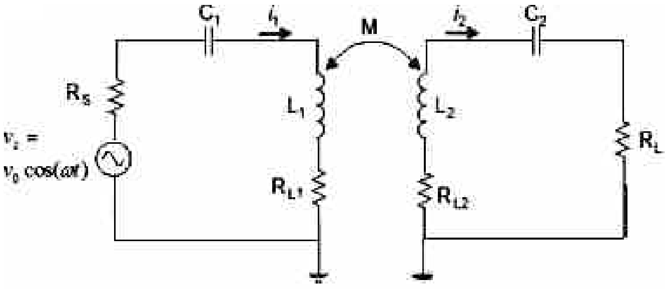

Fig. 2. Equivalent circuit model[5]

$$\boldsymbol{P_L}(\omega = \omega_0) = \boldsymbol{P_S Q_1 Q_2}\eta_1\eta_2\boldsymbol{K^2} \qquad \textbf{(2)}$$

The equation 2 shows that the received power is proportional to the quality factors and efficiency of the transmitter and receiver also the square of coupling coefficient between the transmitter and receiver. The higher Q gives the higher received power because higher Q means the near field distribution is stronger and more power is coupled to the received. Also the received power is totally independent of the radiation impedance of the antenna [5].One of the major problem in soil medium is small communication range ($\leqslant$ 4 m) due to high path loss caused by the soil material absorption. To address the above problem, the Magnetic Induction waveguide technique for wireless communications in WUSNs was developed [6]. The MI waveguide consist of a series of relay coils between two underground transceivers as shown in figure 3.

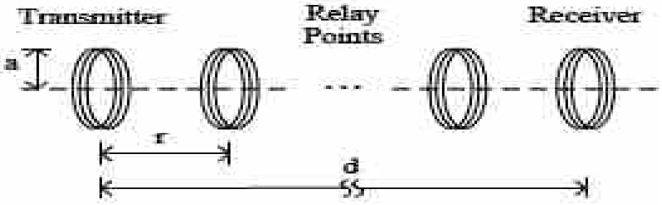

Fig. 3. MI waveguide structure [6]

The communication is achieved by magnetic induction between two adjacent coils. The relay coils are just a simple coil without any energy source or processing device. By using MI waveguide, the feasible communication range between two transceivers can achieve nearly 100 meters also the MI channel conditions remain constant, since the soil medium cause little variation in the attenuation rate of magnetic fields.

## 3. TECHNOLOGICAL ADVANCEMENT

In past few years many efforts have been made to improve the performance of underground wireless communication using magnetic induction which is the enabling technology to realize WUSNs. MI communication is a short range communication. This problem is solved by using MI waveguide and by finding how to wind the coil such that the communication range is extend as far as possible.

Sun et. al. [6] developed MI waveguide technique for communication in order to reduce the MI path loss. A typical wave guide structure is shown in figure 3 where, *n* relay coils equally spaced along one axis between the transmitter and the receiver; *r* is the distance between the neighbor coils; *d* is the distance between the transmitter and the receiver and $d = (n + 1) r$;*a* is the radius of the coils. Mutual induction exists between any pair of the coils and the value depends on how close the coils are to each other. In underground communication, the practical distance between two relay coils is around 1 m and the coil radius is no more than 0.1 m.

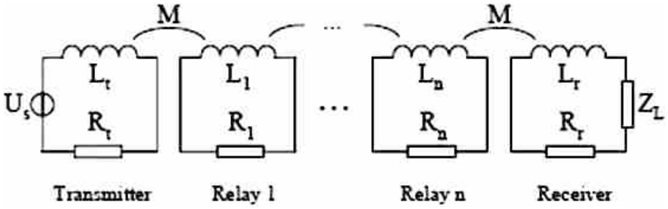

Fig 4: Transformer model of the MI waveguide[6]

the MI waveguide is modelled as a multi-stage transformer, where only adjacent coils are coupled, as shown in figure 4.In practical applications, the transceivers and the relay points usually use the same type of coils, it is assumed that all the coils have the same parameters (resistance, self and mutual inductions). By utilizing the equivalent circuit of the transformer, the ratio of the receiving power *($P_r$)* to the transmitting power *($P_t$)* can be derived as

$$\frac{P_r}{P_t} \simeq \frac{\left(\frac{j\omega M}{R+j\omega L}\right)^2}{4R+\frac{4R\omega^2L^2}{R^2+\omega^2L^2}}\left(R+j\omega L+\frac{\omega^2M^2}{2R+\frac{\omega^2M^2}{R-j\omega L}}\right)\cdot\left(\frac{j\omega M}{R+j\omega L+\frac{\omega^2M^2}{R-j\omega L}}\right)^{2n} \quad (3)$$

By substituting the value of resistance, mutual induction of the two coils M and self-inductionin equation 3, the path loss of the MI waveguide is derived as

$$\frac{P_r}{P_t} \simeq \frac{\omega^2\mu^2N^2a^6}{8r^6}\frac{1}{4R_0\left(2R_0+\frac{1}{2}j\mu N\right)}\cdot\left[\frac{j}{\frac{4R_0}{\omega\mu N}\left(\frac{r}{a}\right)^3+j\left(\frac{r}{a}\right)^3+\frac{\omega\mu N}{4R_0+j\omega\mu N}\left(\frac{a}{r}\right)^3}\right]^{2n} \quad (4)$$

Under the condition that high signal frequency and large number of turns are employed ($\omega\mu N>>R_0$), equation 4 is further simplified as

$$\frac{P_r}{P_t} \simeq \frac{\omega\mu N}{16R_0}\left(\frac{a}{r}\right)^{6n} = \frac{\omega\mu N}{16R_0}\left[\frac{a}{d}(n+1)\right]^{6n} \quad (5)$$

Equation 5 show that the transmission range $d$ is divided into $n + 1$ intervals with length $r$. However, the path loss becomes a $6n^{th}$-order function of the relay interval $r$. Hence, to reduce the path loss of the MI waveguide, the relay interval $r$ needs to be on par with the coil size to make the term a/rapproximately 1.By analyzing equation 4, it is found that if the last term with exponent $2n$ is converged to a value around 1, the MI waveguide path loss can be greatly reduced.Fortunately, this goal can be achieved by adding a capacitor in each coil and carefully designing the capacitor value, the operating frequency and the number of turns in the coil. It is assumed that each coil is loaded with a capacitor $C$. By assigning the capacitor $C$ an appropriate value, the self-induction term can be neutralized. Specifically, the value of the capacitor $C$ is setto be:

$$C = \frac{2}{\omega^2N^2\mu\pi a} \quad (6)$$

Then the MI waveguide path loss becomes:

$$\frac{P_r}{P_t} = \frac{\omega^2\mu^2N^2a^6/4r^6}{2R_0\left(4R_0+\frac{\omega^2\mu^2N^2a^6}{2R_0.4r^6}\right)}\cdot\left[\frac{j}{\frac{4R_0}{\omega\mu N}\left(\frac{r}{a}\right)^3+\frac{\omega\mu N}{4R_0}\left(\frac{a}{r}\right)^3}\right]^{2n} \quad (7)$$

After that, the operating frequency and the number of turns are designed to further reduce the path loss.

If

$$\frac{\omega\mu N}{4R_0}\left(\frac{a}{r}\right)^3 = 1 \quad (8)$$

Then

$$\frac{P_r}{P_t} = \frac{1}{3}\left(\frac{1}{2}\right)^{2n} \quad (9)$$

Equation 10 reveal that the MI waveguide path loss is greatly reduced. The path loss is a function of the number of relay point $n$.Larger $n$ may cause higher path loss. $n$ is determined by the transmission distance $d$ and the relay interval $r$. The longer $r$ is, the lower the path loss would be. $r$ is expected to be as large as possible but restricted by equation 6 and equation 8.

Sun et. al. [7] studied relay coil positioning strategies for WUSNs using MI waveguides is analysed to minimize the number of relay coils. The MST algorithm is given, where the MI waveguides are positioned along the minimum spanning tree of the WUSN. The weight of each link of the network is the optimal relay coil number. Since the WUSN constructed by MST algorithm is not robust to sensor failure, the TC algorithm is proposed. In the TC algorithm, the MI waveguides are deployed around the centroids of the triangle cells that are constructed by the Voronoi diagram [8].

The positioning of MI waveguide is first analysed for one dimensional WUSN then based on the analysis arrangement strategy is developed for two dimensional WUSNs. In one dimensional WUSN where the underground sensors are buried along a line. This one dimensional topology is appropriate for underground pipeline monitoring system. The optimum number of relay coils for each link is find out by using the length of the link and the required bandwidth. According to Sun et. al. [9],the path loss increases monotonically when the signal frequency deviates from the central frequency $\omega_0$.Therefore if the signal with frequency $\omega=\omega_0+0.5B$ is correctly received ,a communication channel is established between the two sensors with bandwidth B .Assuming that transmission power is $P_t$ and the minimum power for correct demodulation a signal is $P_{th}$. Using the path loss, the received power is derived. Then the optimal number of relay coils for this link is:

$$n_{opt}(d,B) = \arg_{n}^{\min}\{P_t - L_{MI}(d,n,\omega^0 + 0.5B \geq P_{th}\} \quad \textbf{(10)}$$

According to equation 10, the optimal number of relay coil is the function of the link length and the required bandwidth. It is the link length that determines the optimal number of relay coil Since the required bandwidth can be viewed as a constant.The development in two dimension WUSNs is more complicated compared with the development in one dimension WUSNs due to following reasons:

1. In two dimensional WUSNs, the optimal route to connect all the sensors needs to be found out; and
2. Some common relay coils can be shared by multiple links in a two Dimensional WUSN.

The MI waveguide deployment is also influenced by the topology of the sensors in the WUSNs. The hexagonal tessellation topology is preferred if full sensor coverage is required in a sensing area. Underground sensors can be buried at any desired positions. It is efficient and simple. The random topology is preferred if only specific positions need to be monitored by sensors also if some positions in the sensing area are not suitable to bury underground sensors

***a.*** *Hexagonal Tessellation Topology:* In this topology the sensors of the WUSN are set in all vertexes of the hexagonal tessellation. It is the most efficient way to cover the entire sensing area. Since the communication range of the underground sensor network is very limited therefore the MI waveguides are used to connect the sensors. The sensor density of the WUSN in this topology is assumed as

$\lambda_{hex}(m^{-2})$.

1. Minimum Spanning Tree(MST) Algorithm: According to MST algorithm the required number of the relay coils to connect K sensors can be calculated as

$$N_{mst}^{hex} = (K-1).n_{opt}\left(2.3^{-\frac{1}{4}}.\lambda_{hex}^{-\frac{1}{2}}, B\right) \quad \textbf{(11)}$$

Where (K-1) is the number of the edges of the minimum spanning tree $n_{opt}\left(2.3^{-\frac{1}{4}}.\lambda_{hex}^{-\frac{1}{2}}, B\right)$ is the optimal coil number for each edge in the tessellation which can be calculated by Equation 10.

2. Triangle Centroid (TC) Algorithm: To enhance the robustness of the network, more edges should be established. Every sensor is connected to 6 neighbors in the tessellation. This is defined as full deployment, and the required number of relay coil for K sensors is doubled

$$N_{full}^{hex} = 2K.n_{opt}\left(2.3^{-\frac{1}{4}}.\lambda_{hex}^{-\frac{1}{2}}, B\right) \quad \textbf{(12)}$$

Further to reduce the number of relay coils,the position of the MI waveguide is changed so that the multiple link can share one set of the MI waveguide. The three MI waveguides along the three edges of one triangle cell can be replaced by one MI waveguide with a shape of three- pointed star as shown in figure 5. Then the total required number of relay coils to connect K sensors using TC algorithm is:

$$N_{tc}^{hex} \simeq \frac{K}{2}.n_{opt}\,(2.3^{\frac{1}{4}}.\lambda_{hex}^{-\frac{1}{2}}, B) \quad \textbf{(13)}$$

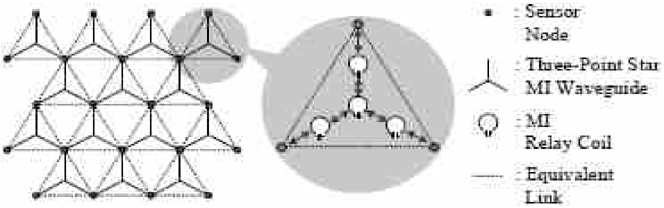

Fig. 5.MI waveguide deployment using TC algorithm in the WUSN with hexagonal tessellation topology[7]

***b***. *Random Topology:* Similar to hexagonal tessellation topology, the spatial density $\lambda_{rand}\,(m^{-2})$ is assumed for the underground sensors uniformly distributed

1. MST Algorithm: The MST algorithm for random topology is similar with that in hexagonal tessellations. The edge lengths between any two underground sensor nodes and the optimal number of relay coils for each edges are calculated. Then the minimum spanning tree of the WUSN is found out.At last the MI waveguide with optimal coil number are developed along the edge of the minimum spanning tree.
2. TC Algorithm: TC Algorithm encounters problem for random topology. So the Voronoi diagram is introduced. The Voronoi diagram of the sensor partition the entire area into polygons, each of which contains only one sensor shown in figure 6.

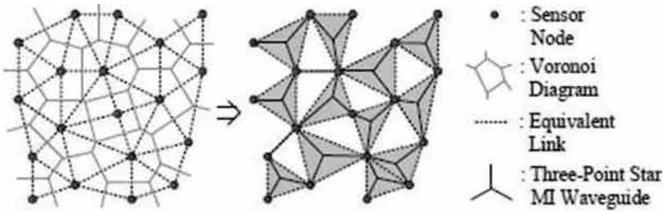

Fig. 6. MI waveguide deployment using TC algorithm in the WUSN with random topology [7]

For random topology, the WUSN constructed by MST algorithm is 1-connected and by TC algorithm is k-connected, where $k \geq 3$.

Meybodi et. al. [10] proposed optimal design for transmitter and receiver coil antennas. Winding the coils such that the communication range is extended as far as possible is a very interesting point. Coil design criteria is as below:

(i) The Tx coil should have the smallest possible radius *a* while the Rx coil should have the largest possible *a*.

(ii) The cross section of the Rx coil should be circular or square (when a circular shape is difficult to manufacture), while the cross section shape of the Tx coil can be chosen freely based on practical winding issues.

(iii) The Rx coil center ought to be located on the Tx coil axis.

(iv) When the coils and their locations are known, the receiver should face the right direction such that **B** is perpendicular to the Rx coil surface. In worst case, when **B** and the coil's surface are parallel, no signal will be received.

## 4. CONCLUSION

In wireless underground communication, traditional techniques using EM waves encounter three major problems: high path loss, dynamic channel condition and large antenna size. MI is an alternative technique that can solve two of the three problems: the dynamic channel condition problem and large antenna size problem, however, the high path loss problem is even worse in the MI case. MI communication is a short range communication. This problem is solved by using MI waveguide and by finding how to wind the coil such that the communication range is extend as far as possible. The MI waveguide technique can greatly reduce the path loss, which is attributed to the relay coils deployed between the transceivers. The relay coils do not consume any energy and the cost is very low. Further, more efforts have been made to reduce path loss and increase the communication range by using different methods such as MST algorithm, TC algorithm, found best conditions for Tx and Rx antennas.

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