

Security Monitoring in Coal Mining using Wireless Underground Sensor Network

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Abstract— Underground communication systems present a variety of new research challenges. Here, the goal is to establish an efficient wireless connection between the transceivers in the challenging underground medium. Typical applications for this type of communication systems include soil condition monitoring, earthquake prediction, communication in mines/tunnels, etc. These applications require a gathering of relevant information from multiple locations, which suggests the use of multiple sensor nodes that would be organized in wireless underground sensor networks (WUSNs).

Due to the harsh propagation conditions in the soil medium (including rock, sand, and water sheds), traditional wire-less signal propagation techniques using electromagnetic (EM) waves can only be applied for very short transmission ranges. In recent years, magnetic induction (MI) based transmission has been proposed to overcome these issues. In this approach, induction coils are utilized as antennas in the transceivers in order to reduce the vulnerability of signal propagation to the soil properties, in particular the soil conductivity. Correspondingly, the design rules for optimum MI-WUSNs have been shown to substantially differ from the design rules for the traditional wireless communication systems due to unique properties of the transmission channel.

In this survey paper, the recent advances in the area of MI-WUSNs are discussed, which range from signal transmission techniques and network design to wireless power transfer and localization. Also, new research challenges in this area are provided.

Index Terms— Magnetic induction, wireless underground sensor networks, review.

I. INTRODUCTION

Communication through the underground medium has been a challenging research area for more than a century. This type of communication proves useful for a wide variety of applications, e.g. soil condition monitoring and earthquake prediction. These applications require the deployment of sensors below the ground surface. Hence, the sensors become part of the sensed environment and might deliver more precise sensing information than if they are deployed aboveground.

Obviously, with increasing number of sensors, the precision of measurements increases as well, which motivates the use of a large number of nodes. However, an independent operation of each sensor node leads to vast exploitation costs, which typically cannot be supported economically. On the other hand, a collaborative effort of multiple sensors organized in sensor networks can be exploited in order to reduce the energy consumption or increase the reliability of measurements. This can be achieved by cooperative information processing and

transmission, respectively. Correspondingly, the complexity of each node and design costs can be reduced. The nodes within one network may not be exclusively interconnected by the wires, but rather employ a wireless communication technique, e.g. electromagnetic (EM) waves. Such networks are called wireless sensor networks (WSNs). In recent years, WSNs have been intensively studied for various scenarios and applications. Among them are military, environmental, health, home, and industrial applications. The design guidelines for all communication layers of WSNs are already well elaborated. Even the use of WSNs in challenging environments has been investigated. In particular, for the underground applications, wireless underground sensor networks. This technique has some beneficial properties.

- Avoidance of possible collisions of the sensors with landscaping equipment such as tractors,
- real-time information retrieval,
- self-healing property in case of device failures,
- ease of deployment and scalability.

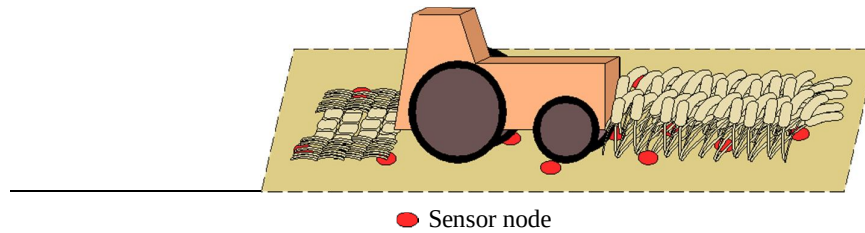


Fig. 1. Application of WUSNs in agricultural monitoring. The deployed sensor nodes do not disturb the work of the tractor

One of the factors that slow down the evolution of the WUSNs is the challenging underground communication channel, which is heavily affected by the heterogeneous soil medium. This medium may consist of rock, sand, and even water sheds.

Especially the water content of the soil has a big impact on the communication range and correspondingly on the overall performance of the WUSNs. In many realistic cases, traditional wireless signal propagation techniques using EM waves can only be applied for very small transmission distances due to a large path loss and vulnerability to changes of soil moisture [4].

Among different alternatives to EM waves, magnetic induction (MI) based techniques have been considered. Magnetic induction based communication has been already investigated in various works, mostly in the context of near-field communication (NFC) [5] and wireless power transfer (WPT)

[6]. In contrast to the traditional EM based signal transmission, MI utilizes induction coils (sometimes referred to as magnetic antennas), which generate quasi-static magnetic fields. These magnetic fields generated by a transmitting coil can be sensed by the receiving coil, such that a signal transmission link can be established.

MI-WUSNs have been first introduced in [7]. This technique has been shown to be less vulnerable to the losses in conductive medium (soil), such that the transmission range and coverage of the sensor network can be significantly improved by using MI based transceivers.

This paper provides an overview of the recent advances in the design of MI-WUSNs. The most relevant applications of the WUSNs are briefly explained in Section II. The advances in the areas closely related to MI-WUSNs are described in Section III. In Section IV, various aspects of communications in MI-WUSNs and the progress in their research are discussed. In addition, new research challenges are addressed in Section V. Subsequently, the paper is concluded in Section VI.

II. APPLICATIONS OF WUSNS

As described in [3], potential applications for WUSNs can be classified into four groups:

- environmental monitoring,
- infrastructure monitoring,
- localization, and
- security.

These four groups will be briefly discussed in the following.

A. Environmental monitoring

Typically, WUSNs have been suggested for agricultural purposes, in order to monitor the soil condition without creating any disturbance for the above-ground devices such as tractors and lawnmowers, see Fig. 1.

Here, more precise information can be acquired from an underground system, such that a targeted irrigation can be done more efficiently than with existing solutions.

Another application of WUSNs is related to the detection of toxic substances that would pollute the environment. In order to prevent the contamination of drinking water supplies, a thorough monitoring of the chemical content of the soil and water is needed. Hence, a hybrid network has been suggested in [3], which would be deployed partially in the underground medium and partially in the underwater medium.

One important application is earthquake and land-slide prediction. For this, the relative movement of the soil layers can be carefully monitored by deeply buried sensors, such that possible disasters can be predicted more reliably than with existing methods and long time in advance [8]. Hence, the affected regions and their population can be warned and evacuated much earlier. Also, the sensors can be deployed in different depths in order to increase the accuracy.

The monitoring of glacier movements and volcanic eruptions using sensor networks has been suggested in [9] and [10], respectively. Here, the deployment of sensors using WUSN technology may provide more accurate observations and protect the nodes from being destroyed either by moving ice blocks of the glacier or by heat of the volcano.

B. Infrastructure monitoring

WUSNs can be further employed in structural health monitoring, if parts of the infrastructure, e.g. the foundation of a building, are connected to the soil, see Fig. 2. Also, the support of a bridge or a dam can be monitored using WUSNs. Hence, possible disasters can be avoided by monitoring various relevant parameters like stress and strain. This might be especially promising for structures deployed in an unstable medium, e.g. water or sand, since the risk of unstable slopes is very high in such areas, cf.

In addition, the underground infrastructure like pipes, electrical wiring, and liquid storage tanks can be monitored using WUSNs. Through this, finding the leakage in a pipe or the disconnection of an electric cable would be facilitated.

Furthermore, the structural health of underground coal mines is of utmost importance for the safety of mine workers. Hence, sensor nodes need to be deployed in the walls and ceiling of the mine galleries in order to detect any structural instability. Similarly, WUSNs can be deployed alongside the tunnels in order to monitor their structural health.

C. Localization

Localization of objects plays a central role in the research on WSNs in general. For the WUSNs, the localization of people and animals seems to be one of the most important applications, especially in case of sudden disasters according to the situations described above, i.e. landslide, earthquake, cave-ins, etc. Assuming that WUSNs have been deployed in the respective hazardous areas and that sensors are still functional after the disaster, the collaborative effort of the nodes can be used in order to localize people in a collapsed building or mine workers trapped in mines. For this, every person inside the building or mine would need to carry a wearable device, which can communicate with the WUSNs by sending a beacon signal. Hence, the location of the trapped person can be estimated and it would be available to the rescue team. This might facilitate the rescue operation and save human lives.

The localization of small animals (e.g. rabbits or badgers) in their natural underground habitat is another application for the localization using WUSNs. This application has, however, a purely academic purpose of understanding the behavior and evolution of these animals.

In addition, the beacon signals from the sensor nodes deployed in the road concrete can be used in order to navigate an autonomous vehicle. This seems to be especially promising in the era of self-driving cars and tactile internet.

D. Security

For the security application, WUSNs can be deployed in order to detect an intruder and alert the security team. As mentioned in [3], the presence of the sensors deployed below the surface can be hardly detected. Correspondingly the security system is less likely to be discovered and disabled by the intruder. Similarly, WUSNs can be deployed along the border in order to detect illegal crossings and notify the authorities. Here, high precision of the crossing detection using WUSNs may help the authorities to easily localize the intruder.

III. ADVANCES IN RELATED AREAS

MI-WUSNs represent an intersection of the following research areas: wireless underground sensor networks

(WUSNs) and MI based transmissions (e.g. NFC). The recent advances in any of these

A. Wireless underground sensor networks

Communication through the underground medium is a challenging task. Due to conductive properties of the medium, the transmission channel suffers from a very high attenuation[4]. Correspondingly, the design of a practical and not too expensive communication system is not trivial. The key properties and challenges for the development of WUSNs have been addressed in

[3]. In particular, the typical shortcomings of the underground sensor networks, e.g. concealment, reliability, and coverage, have been explained. Also, possible solutions for the extension of the transmission range, improved connectivity, etc. have been suggested in [3]. Based on this work, various aspects of system design for WUSNs have been investigated in [4]. Although the original theoretical background for the signal transmission in underground and underwater medium has been provided by various works in the past the channel models have been revisited and extensively characterized. In addition, empirical studies for underground-to-underground and underground-to- aboveground transmission scenarios have been provided. In this context, the multipath propagation in the underground medium has been clarified. Some aspects of the existing channel models have been confirmed by experiments.

A cross-layer network optimization for the WUSNs has been proposed. Furthermore, the problem of limited energy resources in WUSNs has been addressed the network design is considered with respect not only to the information transmission, but also to the charging of the sensor batteries. In additional relay nodes have been deployed in specific positions, such that the connectivity of the network is maintained and correspondingly the lifetime is maximized. Due to signal reflection and scattering in soil, the underground communication channel seems to provide a very high diversity degree, which can be exploited using smart antenna technique .

As mentioned earlier, the typical applications for WUSNs refer to agricultural purposes and communication in mines/tunnels. The latter applications require a very specific channel modeling, since the infrastructure of the mines and tunnels differs significantly from that of the agriculture. Correspondingly, the system modeling for the WUSNs in mines and tunnels has been investigated separately. Furthermore, the special case of data gathering based on a center pivot system has been considered.

B. Magnetic communication in free space

Magnetic induction (also called magnetic resonance, if resonance circuits are employed) based transmission has regained an increased attention in the recent years and even sneaked into the key communication standards that have been adopted for the modern consumer electronics devices, e.g. smartphones, tablets, etc. Typical applications of MI based signal transmission lie in the area of wireless power transfer (WPT) and near-field communication (NFC). It is well known, that the near-field propagation differs from the traditional far-field propagation due to the non-linear behavior of the magnetic field in the presence of multiple magnetic devices in close proximity of each other. Hence, the attempts to generalize the properties of the magnetic transmission channel have not provided sufficient accuracy for the system modeling. Instead, few effects have been discovered that strongly depend on the number of magnetic devices, on their relative distance to each other, and on the set of system parameters. Hence, the complexity of the system design increases with the number of devices, which is atypical for most existing communication systems.

WPT in the near-field has been a research area for decades due to its high efficiency. Some fundamental work has been provided in [6]. In this context, various effects of the transmission channel, e.g. frequency-splitting, coil misalignment, impedance matching , etc., have been investigated. Recently, the wireless charging of electric vehicles and mobile phones has emerged, such that the last cable based connection, that used to reduce the mobility of the wireless devices, can be cut. Unfortunately, high efficiencies of the WPT can only be achieved for very short ranges of few centimeters, for which the coupling between the magnetic resonators is sufficiently strong. In order to extend the transmission distance, the usual point-to-point WPT has been enhanced by utilizing multiple transmitters multiple receiver, and some additional relay devices. Furthermore, multiple transmitters and receivers have been arranged into more general MI based multiple-input multiple-output (MIMO) schemes, which have been investigated as well. In these works, various multiuser scenarios have been considered and the beamforming coefficients of a co-located or distributed transmitter have been optimized with respect to different metrics, e.g. total receive power or minimum receive power among different receiver locations. A special case of magnetic MIMO related to multiple transmitters and receivers has been analyzed where a secured WPT has been achieved for the intended user via magnetic beam-forming.

Meanwhile, several commercial solutions have been presented, among which WiTricity is one of the most popular. NFC has been invented as a special type of radio frequency identification (RFID) for extremely short transmission ranges below 4 cm. Typical applications for such systems are contactless payment, keycards, and social networking. Here, the short-range transmission turned out to be an advantage of the MI transceivers, since it reduces the risk of eavesdropping and the interference to adjacent communication links. The channel model and the corresponding near-field effects have been considered in multiple works, cf. In the meantime, an NFC forum has been established, where the recent advances of the NFC and its standardization are presented. The achievable data rate of an NFC point-to-point link is only 424 kbit/s according to the existing standards ISO/IEC 18092/21481, which are based on the passive RFID standard ISO/IEC 14443. This data rate is mostly dictated by the choice of passive circuit elements and few practical assumptions. In order to overcome this limitation, a simple NFC link has been enhanced using a MIMO technique and additional cooperative relay devices. In addition, NFC might be a good candidate for the upcoming Internet-of-Things (IoT) due to the limited interference created to the adjacent transceivers.

In addition, a combination of NFC and WPT in terms of simultaneous wireless information and power transmission (SWIPT) seems even more promising for the IoT. In SWIPT, the same signal is used for information and power transfer, which is typically more energy-efficient than sequential transmission. For more information on the recent advances in this area we refer to a survey.

C. Magnetic communication in liquids

Underwater communication is a well established research area with various applications in the marine science, marine forces, etc. These applications require signal transmission through the underwater medium, typically sea water, which possesses very high electrical conductivity of up to 4 S/m

due to the active salt ions and free electrons. Correspondingly, the use of EM waves is only possible for very short transmission distances and for extremely low signal frequencies of only a few Hertz. The effective signal bandwidth can be even lower. Traditionally, the underwater communication is done via acoustic waves, which provide a sufficiently high communication range of several kilometers. One of the main disadvantages of this technique is a very harsh time-varying and frequency-selective transmission channel. Alternatively, MI based signal transmission has been proposed. Of course, the communication range of MI transmission is much lower than with acoustic waves, but this drawback is compensated by the stability and simplicity of the transmission channel. In the recent work on MI based underwater communication, the use of tri-directional coil antennas has been suggested in order to improve the spatial diversity and directionality of signal transmission. Another suggestion is the use of multiple frequency bands, such that an additional degree of freedom can be exploited for the resource allocation, which increases the overall achievable data rate. Furthermore, a practical implementation of a magneto-inductive modem has been presented in.

In addition, wireless communication in oil reservoirs and pipelines can be viewed as a special application for MI based communication, where MI-WSNs are employed in order to detect a leakage.

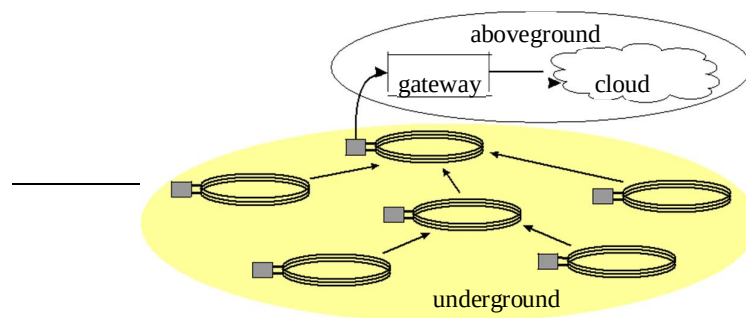


Fig. 3. Example of MI-WUSN for monitoring applications. The direction of the data flow is indicated by arrows

For this, the channel and energy consumption models have been developed. Unfortunately, this application imposes much more strict constraints on the size of the sensors than the underground or underwater applications, such that only coils of relatively small size can be deployed. Correspondingly, the communication range of each sensor node is very short and the system design is even more challenging than the design of MI based underwater communication systems. In this context, an energy-efficient cross-layer solution has been recently proposed, cf.

In general, MI based communication in liquids remains an open issue due to very high path losses and a complicated deployment. However, the corresponding transmission channels are very similar to the transmission channels in MI-WUSNs, such that the advances in one area can be easily adopted in the other one. Hence, the novel methods proposed for MI-WUSNs can be potentially employed also for the design of the more challenging communication in the liquid medium. In the following, we review the methods for MI-WUSNs.

IV. ADVANCES IN MI-WUSNS

With the continuously progressing research on the MI based communication systems, the use of MI transceivers for WUSNs has been suggested in

[74]. Here, the key argument is, that in opposite to the traditional EM waves based approach, MI communication is known to be less vulnerable to the changes of the soil moisture. The principle structure of MI-WUSNs is shown in Fig. 3. Here, multiple nodes communicate with each other through the underground medium. The information is first accumulated at the sink node, which is connected to a gateway, and then uploaded to a cloud for further processing. The main research in the area of MI-WUSNs is focused on the part of the network that is deployed in the underground medium, since the aboveground communication can be established using traditional methods.

The most significant contributions for each aspect of MI-WUSNs are summarized in Table I. These aspects are also discussed in more detail in the following.

A. Channel modeling

The key element of each MI transceiver is an induction coil. This coil generates quasi-static magnetic fields around it, which can be sensed by the coil of another MI transceiver. In addition, a capacitor is connected to each coil, in order to make the circuit resonant and to reduce the path loss at the selected resonance frequency. Due to relatively large transmission distances between sensor nodes of MI-WUSNs (between 10 m and 100 m), coils of a moderate size are usually employed, e.g. solenoids of 15-25 cm radius. This is one of the major differences to the NFC standard, where only small coils of few centimeters radius are utilized, which yields a much smaller transmission distance.

An important property for this type of communication is a much higher path loss exponent (typically six in free space), compared to the traditional EM waves in free space (typically between two and four depending on the environment). Since the propagation medium (soil) is electrically conductive, the magnetic fields in soil are additionally attenuated due to the so-called eddy currents effect. Accordingly, a primary magnetic field from the transmitter coil generates small currents, which in turn produce secondary magnetic fields that oppose the primary field, as illustrated in Fig. 4. Hence, the magnetic induction reduces. This effect becomes stronger with increasing signal frequency. In the numerical evaluations of the proposed methods for MI-WUSNs, a homogeneous conductive medium is typically assumed, which is not always realistic. For a heterogeneous medium, different layers of propagation medium with different conductivity can be assumed. Depending on the position of the coil relatively to the layers of medium, the magnetic fields are attenuated in different ways. For a transmitter coil placed on the ground (between two media with different conductivities), the scaling factor has been calculated in. If the coil is deployed deeply in soil, the signal propagation through the heterogeneous medium with multiple layers has been analyzed, where an equivalent skin depth of the heterogeneous medium has been determined, which corresponds to the harmonic mean of the skin depths among all layers.

Due to the additional path loss, low resonance frequencies between 100 Hz and 1 MHz are preferable for MI-WUSNs with transmission distances above 10 m. As shown in the optimal resonance frequency decreases with the squared distance between the transceivers. Unfortunately, even with the optimal resonance frequency, the path loss scales with not less than the tenth power of the distance, which renders signal transmissions over large distances (i.e. above 100 m) impossible.

The basic characterization of the magnetic field propagation in the underground medium has been provided in various works of J. Wait and others. For the MI-WUSNs, the design of the MI transceivers and the overall channel modeling has been addressed in [7]. Later, all aspects of system and network modeling have been revisited, since MI based transmission channels differ significantly from the traditional EM waves based communication channels. This difference results from a very high frequency selectivity of the employed resonance circuits and from the magnetic coupling between all MI transceivers of the network, such that additional effects of misalignment and frequency-splitting need to be taken into account, as mentioned in Section III-B. The path loss of a point-to-point link in MI-WUSNs has been extensively characterized in [7].

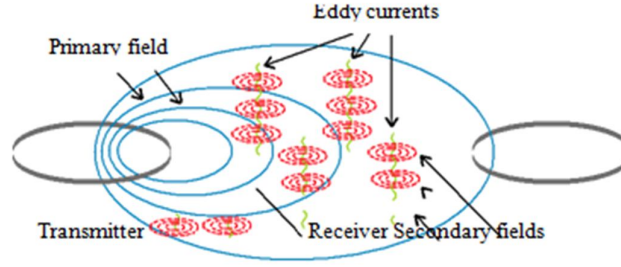


Fig. 4. Basic principle of magnetic field propagation in a conductive medium

TABLE I. INVESTIGATED ASPECTS OF SYSTEM DESIGN FOR MI-WUSNS AND REPRESENTATIVE PUBLICATIONS

Design aspect	Addressed issues	Publications
Motivation and basic analysis	applications, challenges	[3], [4], [74]
Channel modeling	losses in conductive medium	[14], [75]–[77]
	coil alignment	[7], [78]
	transceiver design	[7], [79]–[82]
Channel estimation	estimation of signal attenuation for transmit power control	[83], [84]
Single link performance	channel capacity calculation	[77], [81], [85]
	data rate maximization using practical signal transmission schemes	[79], [80]
	relaying	[85]–[87]
Deployment strategies	optimization of nodes' positions	[88], [89]
	optimization of coils' orientation	[78], [81], [86]
Battery charging	energy harvesting and wireless power transfer to distant nodes	[90], [91]
Cross-layer solutions	network design	[85], [92], [93]
	interference management	[94], [95]
	energy-efficient networking	[90]
Localization	sensor deployment for localization purposes	[95], [96]
	methods for accurate positioning and tracking	[95], [97], [98]
Test and validation	testbeds	[95], [99]
	field experiments	[98], [100]

Recently, a new type of asymmetric transceivers for long distance transmissions in soil has been introduced in order to maintain the connectivity even in case of an unforeseen misalignment. There, multiple small receiving coils and a single large transmitting coil have been attached to each sensor node. Through this, the signal can be received by at least one of the coils of the transceiver even in case of misalignment, such that the probability of disconnection is minimized. However, the applicability of such multicoil transceivers still requires a thorough investigation.

Using the derived channel models for point-to-point signal transmissions, the performance of single MI links and of the whole MI underground networks have been extensively analyzed.

B. Single MI link

The influence of different system parameters on the point-to-point performance of the communication links has been studied.

In particular, investigates the influence of different minerals on the signal propagation and system performance, whereas and focus on the optimization of the resonance frequency and coil geometry. Furthermore, the theoretical system performance in terms of channel capacity has been shown in [7] to be sufficient for the target applications of the WUSNs, which provided a significant motivation for all further research. The channel capacity for dry and wet soil are shown in Fig. 5. Obviously, a data rate of up to 1 Mbit/s can be reached using MI even for moderate transmission distances below 15 m and 8 m in dry and wet soil, respectively. In contrast, traditional EM radiation fails to provide reasonable data rates for transmission distances beyond 5 m even in dry soil. In addition, practical digital communication techniques have been investigated for MI-WUSNs in and showed only moderate losses compared to this performance upper bound. Furthermore, the advances in the area of magnetic meta materials have inspired the use of the so-called MI waveguides (concatenation of multiple passive MI devices, see Fig. 6) and metamaterial-enhanced MI transceivers.

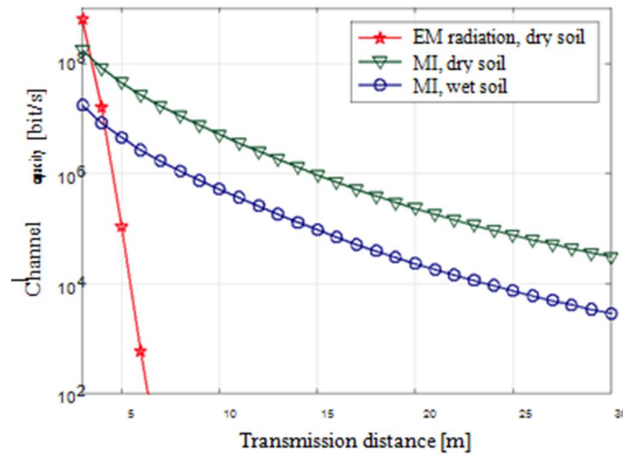


Fig. 5. Channel capacity of a single MI link in dry and wet soil with conductivities $\sigma_{\text{dry}} = 0.01$ S/m and $\sigma_{\text{wet}} = 0.1$ S/m, respectively. The transmit power is set to 10 mW, the coil radius is 10 cm and the number of turns is 100. For comparison, the channel capacity of traditional EM communication with carrier frequency of 150 MHz through the soil is shown (only dry soil due to extremely low capacity in wet soil). Here, only the medium absorption has been modeled, i.e. the performance would be even worse in practice.

These advanced configurations of MI transceivers can be employed in order to improve the directional-ity of signal propagation, which is very low with the usual induction coils¹. In particular, the properties of each passive relay within MI waveguide can be optimized with respect to the overall achievable data rate and bandwidth efficiency. The drawback lies in the increased manufacturing and deployment efforts, which may render the resulting MI-WUSNs too costly.

Alternatively, the use of traditional (active) relaying schemes seems very promising, since it is based on the deployment of a very limited number of additional relay devices, while the overall data rate can be boosted by up to an order of magnitude compared to the basic scenario without relays.

In general, relatively high resonance frequencies between 1 MHz and 20 MHz are preferable for relay based MI-WUSNs due to a short transmission distance of each sublink. Furthermore, the frequency selectivity of the transmission channel heavily depends on the number of MI transceivers and relays, since each device acts as a narrow band pass filter regardless of its main functionality. This is due to the employed resonance circuits. Correspondingly, the resulting effective bandwidth of each communication link and the whole network is reduced compared to the no-relay scenario. A promising extension of the existing solutions of MI-WUSNs is the joint use of active and passive relays. In particular, MI waveguides based on strong couplings between neighboring relays seem to be very promising in terms of WPT, where large bandwidths are not required. The advantage of MI waveguides for the WPT arises from the very low path loss at the resonance frequency compared to the direct MI transmission without relays. Hence, MI waveguides might be useful for the network

¹In fact, the magnetic field created by a solenoid coil is almost omnidirectional and often modeled as a field of a magnetic dipole

charging. This technique can be combined with active relaying in order to create a hybrid scheme, where MI waveguides with passive relays may connect the nodes, while an active relay is deployed in parallel to each waveguide. The active relay would be operated at a low frequency for information transmission and the MI waveguide would be operated at a high frequency for the WPT. Such a scheme is, however, substantially more complicated and remains to be analyzed in future investigations.

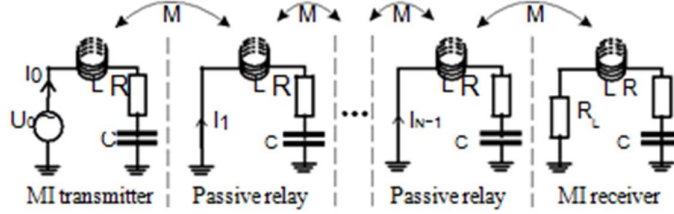


Fig. 6. MI waveguide with $n - 1$ passive relays. L , R , C , and M denote self inductivity of the coil, parasitic resistance, capacitance of the capacitor, and mutual inductance between two neighboring coils, respectively. Also, U_0 , I_N , and R_L represent input voltage, current flow in n th circuit, and the load impedance, respectively

C. Synchronization and channel estimation

Synchronization has rarely been considered in the theoretical works on MI-WUSNs, since the performance of the well-known synchronization methods applied to MI-WUSNs does not change significantly compared to the performance of synchronization of traditional point-to-point communication links and sensor networks described. Similarly, the scheduling of packet transmissions for communication networks has been considered e.g. which is fully applicable to the scheduling of

transmissions in MI-WUSNs. On the other hand, the estimation of the magnetic transmission channel in the underground scenario is an interesting task that has only been addressed in few works. One important observation is that the frequency selectivity of the transmission channel mostly depends on the properties of the resonance circuit and less on the propagation distance or on the conductive soil properties. Hence, with the known set of used circuit elements, the frequency-selective path loss is completely known up to a scaling factor related to the coupling between coils. Moreover, this coupling affects the current flow in all circuits including the transmitters, such that a transmitter-side channel estimation technique has been suggested. The benefit of this technique is that no explicit training sequence is needed for the channel estimation, since the transmitted symbols are perfectly known. This strategy has been adopted, where a protocol for channel estimation in larger MI based underground networks has been proposed. This type of channel estimation may not only enable an automatic transmit power control, but also a localization of damaged nodes, which would trigger a reconfiguration procedure and establish a new signal routing.

Aside from these works, the channel state information (CSI) is typically assumed to be perfectly known to the system designer and to each MI transceiver. This assumption results from the stationary deployment of the WUSNs, such that the transmission channel remains unchanged most of the time. Hence, a channel estimation procedure with sufficiently long averaging can be executed before the main operation of the WUSNs starts. Correspondingly, almost perfect CSI is available in principle. However, future methods of system design for MI-WUSNs should incorporate the uncertainty of the environmental parameters, which may vary in case of sudden rainfalls or earthquakes [4]. Hence, the system parameters might be selected by means of robust optimization according to the probability density of each considered environmental parameter.

D. Deployment strategies

The deployment of sensor nodes within a given area of interest is an important aspect of the network design. Here, different strategies have been developed in the past, which are based on various metrics MI transmission (without passive relays) and MI waveguides, have been compared under realistic design constraints. Another related work gives some insight into the network design mainly from the perspective of the medium access control (MAC) layer.

In addition, a SWIPT scheme for the underground scenario has been studied in [90], where the energy consumption and battery charging have been taken into account for the network design. In this approach, different priorities have been assigned to the sensor nodes based on their battery lifetime, such that the definition of the network throughput has been slightly modified. Nevertheless, this method is very promising, since it prolongs the exploitation time of the network and reduces the risk of disconnection due to the so-called energy hole, which occur if some of the most exploited nodes run out of energy.

E. Charging

An important issue in sensor networks is the battery lifetime [1]. In modern applications of WSNs, in order to charge all sensor nodes, a mobile charging vehicle with optimized charging parameters and travel route is utilized. This strategy is also applicable to the MI-WUSNs with a slight change due to the medium characteristics and transceiver design according to the system model. Also, the well-known methods of energy scavenging can be adopted. However, the efficiency of these methods remains still uncertain for the underground scenario. In addition, several applications of WUSNs require the deployment of sensor nodes in hardly accessible (extreme) environments, e.g. in mines, oil reservoirs, and infrastructure related to structural health monitoring. In such cases, a mobile vehicle may not be able to get close enough to each node for charging. Also, the electromagnetic waves may not be able to penetrate the ground in order to reach the sensors for power transfer, see Fig. 7. Even if some of the nodes can be accessed by the charger, the energy/fuel consumption by the mobile vehicle may become one of the crucial parameters for the overall exploitation costs.

Alternatively, a stationary power source deployed aboveground and connected to one of the sensor nodes, e.g. via cable, can be utilized. This node is then used to wirelessly charge the whole network.

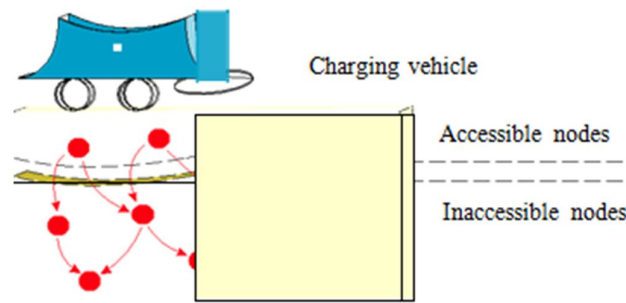


Fig. 7. Charging of the WUSNs using a charging vehicle and multihop relaying of power signals

The optimization of the resulting charging procedure has been addressed in [1], where a virtual magnetic MIMO based relay network and an optimized transmission protocol have been developed in order to reduce the energy losses. Unfortunately, the charging efficiency remains extremely low, even if coils of a moderate size (e.g. 25 cm radius) are used. However, this technique can be improved by optimizing the system parameters as part of the mentioned cross-layer optimization, such that the energy efficiency would increase. Furthermore, additional passive relays can be employed and even arranged in MI waveguides as described earlier. In this context, the use of relays seems very promising due to an increased spatial diversity of the resulting communication system, which is very beneficial especially in combination with the mentioned virtual MIMO approach. In addition, relay devices can be employed, which do not consume any energy during information transmission, but support the energy relaying during the network charging. Such relay devices can be assumed to be fully charged most of the time and do not require any energy for themselves, which is very beneficial. Since the relay would not participate in information transmission, its position is not related to any network link. Hence, it can be deployed among the sensor nodes, such that the maximum distance between the relay and any surrounding sensors is minimized. Correspondingly, the maximum path loss for the energy relaying might be reduced and the charging efficiency increased. With increasing numbers of relays, the charging efficiency would further increase.

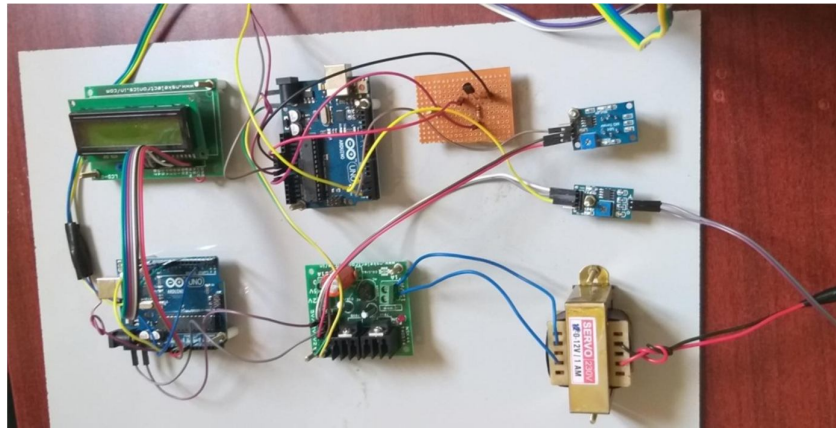
F. Localization

MI based localization has been studied in some previous work. Hence, the performance improvement may not be very high. On the other hand, multiple orthogonal coils can be employed in order to guarantee a certain level of connectivity, even if some of the nodes would be accidentally misaligned. The design of such a multicoil transceiver based network for the underground communication remains still an open issue.

G. Interfaces with other WSNs

The design of various interfaces between MI-WUSNs and other WSNs seems to be the next logical step in the evolution of MI-WUSNs. In this context, we present some of the promising combinations of WSNs that require specifically designed interfaces between their components (see Fig. 8):

- underground WSNs and underwater WSNs (e.g. for the deep sea exploration and border defense),



- underground WSNs and WSNs deployed in vegetation like trees and mushrooms (e.g. for agricultural purpose and biological monitoring of the soil condition),
- underground WSNs and WSNs deployed in animals (e.g. for a more comprehensive study of the animal life and its influence on the environment),
- underground WSNs and electric power grid (e.g. for structural health monitoring),
- underground WSNs and self-driving cars (e.g. for charging and navigation).

In all these combinations, the system design should not be restricted by individual optimization of the respective components, but rather homogenize the operation pattern and provide a balance for their strengths. The respective challenges for the design of these interfaces are likely to be addressed in the near future.

V. CONCLUSION

In this work, the recent advances in MI-WUSNs and related areas (WUSNs, NFC, magnetic communication in liquids) have been reviewed. The advances in the related areas provide an important insight into the typical problems of system modeling and design. For MI-WUSNs, the advances are related to various aspects of wireless communication and networking. In particular, the important aspects of channel modeling, digital signal transmission and processing, synchronization, network design, WPT, and localization, have been discussed. In addition, the implementation and validation attempts by some innovative research groups have been mentioned. Many novel methods appeared in the recent years, which contributed to a substantial improvement of the overall system performance compared to the naive methods in the past. Through this, a better understanding of the underlying research challenges and design problems has been elaborated. Hence, the focus of the research has changed and the research challenges have been extended. In future, the main focus of the research in this area seems to lie in more advanced cross-layer optimization techniques, which would incorporate multiple functionalities of the MI-WUSNs, e.g. design of energy-efficient high throughput MI-WUSNs. Also, the use of mixed active and passive MI relays with different operation patterns is promising, which might reduce the path loss for information and energy transmissions. Furthermore, various important interfaces have been suggested, which are likely to be addressed in future research on WUSNs, e.g. interface between underground WSNs and self-driving cars. These interfaces might give rise to some novel applications of IoT.

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