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Underwater Magnetic Induction Communication Range Enhancement Survey and Comprehensive Evaluation

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Abstract

Wireless communication in underground environments presents formidable challenges due to the diverse and complex transmission mediums, including rocks, icebergs, soil, and water. These environments exhibit distinct properties such as varying densities, salinities, and numerous obstacles. Conventional wireless communication methods encounter difficulties in these scenarios, primarily stemming from issues like electrical conduction, line-of-sight obstacles, high path loss, dynamic channel conditions, and the requirement for large antennas, multiple scattering, and propagation delays constrained by the speed of light. However, electromagnetic induction (EMI) communication has emerged as a promising alternative solution, offering advantages such as reliable connectivity, consistent channel responses, rapid propagation, frequency offset capabilities, minimal propagation delays, and energy efficiency. Despite these merits in underwater environment ecosystems communications, EMI communication suffers from a limited communication range, typically spanning just a few meters. Recent research endeavors have sought to extend the effective range of EMI communication by exploring various strategies, including manipulations of coil parameters, structural enhancements, material advancements, and configuration improvements. This comprehensive study and evaluation delves into the diverse applications, notable advantages, techniques for extending communication range, and the pressing challenges and open issue facing EMI communication in underwater ecosystem environments, requiring further investigation and new research.

Keywords: *Distributed wireless communication, electromagnetic induction (EMI) communication, path loss, range extension, transmission range, underwater communication*

1 Introduction

When contemplating wireless technology, the immediate association often lies with terrestrial networks and their myriad applications. However, it's imperative to recognize that connectivity extends beneath the water's surface. Leonardo Da Vinci pioneered the use of underwater acoustics (UWA) as early as 1490, but it wasn't until the tragic sinking of the Titanic in the early 20th century that this field of engineering came into full focus. The World Wars further catalyzed the development of underwater communication, spawning applications such as underwater observation, telephones, submarine sensor networks,

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military surveillance, and remotely operated vehicles (ROVs). The implementation of submarine sensor networks, submarine communications, military surveillance, and ROVs has given rise to a new frontier in research and development. While many technologies were borrowed from radio frequency (RF) applications, the primary challenge lies in integrating these concepts into the underwater environment, particularly at the physical network medium access control (MAC) layer [1].

The inception of the underwater telephone acoustic system, referred to as UQC (Underwater Telephone Acoustic System) or nicknamed “AN/WQC-2” or "Gertrude," which operates within a frequency range of 2-25 kHz, established the foundation for analog communication, enabling person-to-person communication on submersibles. Subsequently, the concept of "one ping only" emerged in wireless communication for inter-submarine communication [2]. In the matching network, EMI-based communication relies on the coupling coefficient with a limited range, while magnetic resonance-based communication depends on the quality factor and coupling coefficient [3].

Addressing diverse marine applications, such as submarine communications and ocean surveillance, and facilitating the interconnection of various submarine devices like sensors and Autonomous Underwater Vehicles (AUVs), are pivotal issues in Global Marine Information Networks (GMINs) [4],[5]. Given the difficulties associated with installing wired infrastructure like cables and fiber optics, wireless transmission methods are prioritized to enable seamless communication and networking for GMIN. Three primary choices for introducing wireless communication underwater include EMI, acoustic, and optical communications [6], [7], [8]. A novel magnetic induction communication approach was presented, utilizing a highly sensitive magnetic field sensor as a receiver coil to extend the communication range [9]. For reliable and power-efficient underwater EMI communication, a tri-axis coil is employed [10].

Standard techniques using electromagnetic (EM) waves face three primary challenges in underground environments, namely dynamic channel conditions, high path loss, and large antenna size [11]. Path loss is significantly influenced by various soil properties such as composition (sand, silt, or clay), water content, and density, which can change over time and space, posing design challenges for achieving optimal connectivity and energy efficiency. In the deep-water surfaces, electromagnetic radiation (EMR) waves experience high rates of attenuation due to soil, rock, and water absorption. Efficient network deployment is contingent on minimizing antenna size, especially given the super low frequencies ranging from 30 to 300 Hz, which typically require large antennas and high transmitting power [11].

Acoustic communications, presently the most widely used underwater technique, traces its origins to military applications dating back to World War II [12]. Its significant advantage lies in its ability to transmit data over long distances, reaching many tens of kilometers with reasonable energy consumption [13]. However, it suffers from limitations such as low data transmission rates, high transmission delays, extreme multi-path fading, erratic channel behaviours, and potential harm to marine species, particularly dolphins and whales [14],[15].

Optical communications offer a relatively low transmission delay and high data transfer rate compared to acoustics, particularly in the context of of the optimal number of clusters and probability in homogeneous unreliable Wireless Sensor Networks (WSNs) [16]. However, interactions between photons and water molecules and particles result in high absorption and multi-scattering, causing extreme inter-symbol interference and a short transmission range [17].

Electromagnetic induction (EMI) techniques present a promising solution to the aforementioned challenges, enabling effective wireless communication in RF-challenged environments [18]. EMI-based communication utilizes the near field of a coil, offering potential reliability in dense mediums such as soil and oil. Nevertheless, the initial form of EMI communication encounters restrictions in communication range owing to the elevated attenuation rate of the magnetic field in close proximity. Nonetheless, it addresses antenna size challenges by employing small wire coils. Notably, EMI proves generally unsuitable for terrestrial wireless communication due to the rapid drop in magnetic field strength compared to electromagnetic radiation waves [19].

This researched paper provides a thorough investigation in a range of topics, including the diverse applications, notable advantages, techniques for extending communication range, and the pressing challenges confronting EMI communication in underwater ecosystem environments. It emphasizes that while EMI communication presents promising advantages, there are many open challenges and areas of research that warrant further exploration as a focal points for researchers and system designers looking to advance the field in marine information networks with and without Unmanned Aerial Vehicle (UAV).

Following the above introduction, Section 2 surveys the background and related works of EMI communication advantages and applications, and the concepts and principles underlining them. In Section 3 sets out the effects of the methodology and technical solution of EMI communication for the possibilities of extending the range of EMI systems. Section 4 provides a discussion of the challenges and open issues in EMI communication. Finally, Section 5 concludes the paper by summarizing the overall key findings and challenges of potential future research detailed in Section 4.

2 Related Works - EMI Advantages and Applications

In this related works section the advantages and Applications of Electromagnetic Induction (EMI) Communication ccompared with EM, optical and acoustic communications, is primarily presented to show the following three important merits.

Negligible data transmission delay: At the speed of light, the EMI wave penetrates the glossy/gleaming underwater medium much faster than the acoustic wave [20]. This suggests that EMI techniques have the potential to significantly enhance the efficiency of underwater communication delays, ensuring timely data delivery. The desired delay output further encourages the development and application of diverse protocols for underwater networking, including Medium Access Control (MAC), routing, and localization. Additionally, achieving synchronization in the physical network layer among wireless devices becomes notably simpler and more reliable due to the minimal delay and secure channel response characteristic of underwater EMI communications [21].

Cost efficient and stealth underwater operation: The transmission and reception of EMI communications are achieved by the use of non-audible and non-visible waves through small-sized coils. Consequently, the EMI technique allows hidden and energy-saving underwater wireless communication amongst diminutive devices, which is appropriate for a broad range of civil and military applications [22]. For example, underwater surveillance and monitoring required stealthy and cost-efficient operations. Additionally, the cost of implementing EMI coils is typically low, e.g. generally less than $1.00 per coil, which enables the mass production and large-scale deployment of EMI-based underwater nodes [22].

Stable channel response and safety: Unlike acoustic communication, which grapples with the fundamental issue of multi-path fading, EMI communication sparkles in this aspect. This is attributed to the fact that a coil's radiation resistance is significantly lower than that of an electric dipole, resulting in only a minimal fraction of energy being radiated across the EMI channel into the far field [23]. A large range of vulnerabilities and security risks are exposed to the escalating interconnectivity of Internet Connection Sharing (ICS) wired and wireless networks. ICS networks have thus become a priority for cyber-attacks, posing serious risks to the vital operations of critical infrastructures of a country. In order to take control or interrupt the usual functions of the device, cyber-attacks exploit security vulnerabilities, particularly entering and intercepting electromagnetic signal pathways in transient and deceptive ways. It is important to define the risks and evaluate the security vulnerabilities and the deficiencies of these systems in a holistic manner [24]. Also, as an example, it is perceived that narcolepsy illness is believed to be caused from a combination of Information Communication Technologies (ICT) and other EMI emitting devices, interfering in a person’s mental state and health. A specific frequency signal is continuously transmitted by these systems and the receiver receives the reflected signal, which can also interfere with the medical devices implanted in a patient in a given data scenario with changing body functions and movements in real time [25].

EMI channels between Autonomous Underwater Vehicles (AUVs) and other underwater devices are no longer stable and static due to the mobility of AUVs and underwater turbulence, which presents significant difficulties in creating reliable EMI communications. Dynamic EMI wireless communication was introduced to resolve this problem [26]. Moreover, in stark contrast to the atmosphere, the content of seawater, such as turbidity, usually fluctuates over time, space, and depth. However, the magnetic permeability of seawater remains approximately consistent with that of air. Consequently, the channel responses of EMI waves are more stable and reliable compared to the other three communication techniques. EMI also holds a significant advantage in mutual sensing and monitoring when employed alongside underwater swarming robots for the precise and rapid detection of sources of toxicity, waste, and biohazard. Fig. 1 outlines the advantages of EMI Communications.

With the above benefits of instantaneity, stealthiest, predictability and cost-effectiveness, EMI communications have the capability to be applicable to a broad range of marine applications, which are built the following way. Leakage detection: Due to the inaccessible underground conditions, it is difficult to detect leakage of deep water, oil and gas pipelines with high precision. Research has demonstrated that installing high-density EMI sensors along pipelines can offer cost-effective, high-resolution measurements for detecting leaks [27].

Disaster detection: Potential natural disasters such as typhoons, tsunamis and undersea earthquakes endanger marine life. Exploring communication through Underwater EMI opens avenues for the development of timely and dependable disaster detection and warning systems. One example is the implementation of an EMI-based wireless sensor network with adaptable disaster warning capabilities in unconventional environments [28].

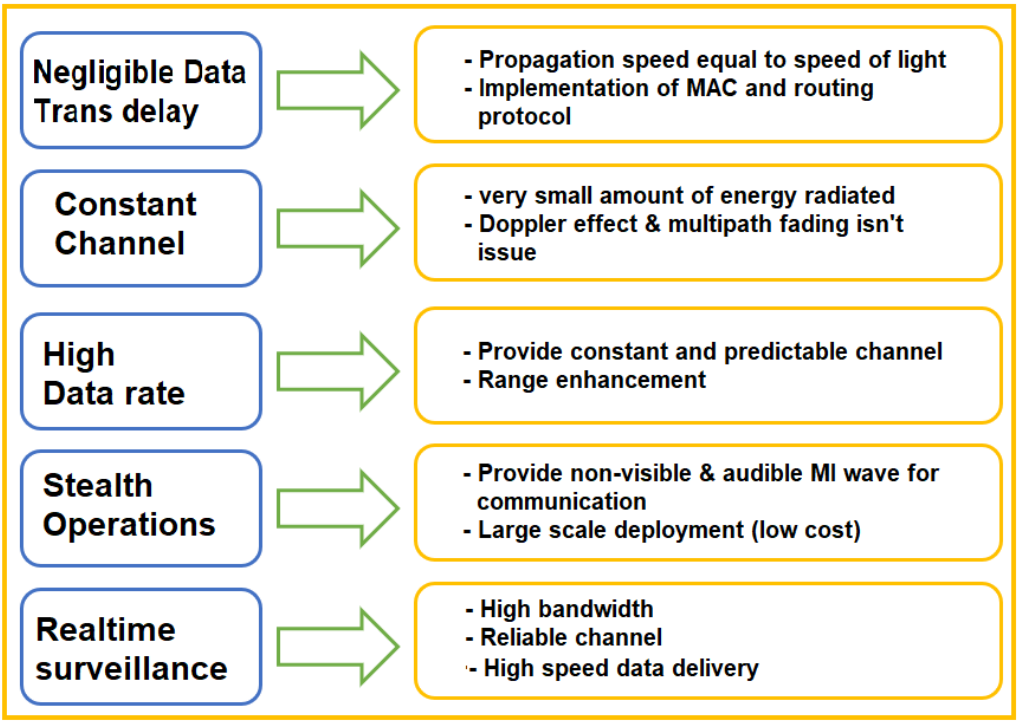

Fig. 1: EMI communication Advantages

Military applications: EMI-based Underwater Wireless Sensor Networks (UWSNs) are used to assist the most of the military application [29]. AUVs are equipped with a range of sensors, including cameras, image sonar, and metal detectors, to aid in the identification of underground mines. These sensor technologies serve to safeguard ports and submarines, as well as to facilitate tracking and surveillance tasks. In the context of networking deployment, the main system and efficiency comparative differences between UWSN and WSNs in terms of basic operational functional parameter features are shown in Table 1.

Table 1. Principle differences between WSN and UWSN.

Functional Parameter Features	**WSN**	**UWSN**
Communication medium	RF waves	Acoustic waves
Spectrum Bandwidth	High	Low
Data transmission rate	High	Low
Dynamic topology operation	Low to medium	High
Propagation delay	Low	High
Speed of propagation	3×10^8 m/s	1200 m/s to 1500 m/s
System efficiency	High	Low
Environmental noise interference	Low to medium	High
System density	High	Low
Energy consumption	Low to medium	Very high

Monitoring: There are some significant underground monitoring applications that involve EMI communications for efficient working. For example, off-shore oil industries, agriculture monitoring, pollution monitoring etc.

Other applications: To monitor the performance of swimmers EMI based UWSNs are used. It is also used to collect important scientific date from the deep ocean and its surroundings. Fig. 2 lists the advantages of EMI Communications [29].

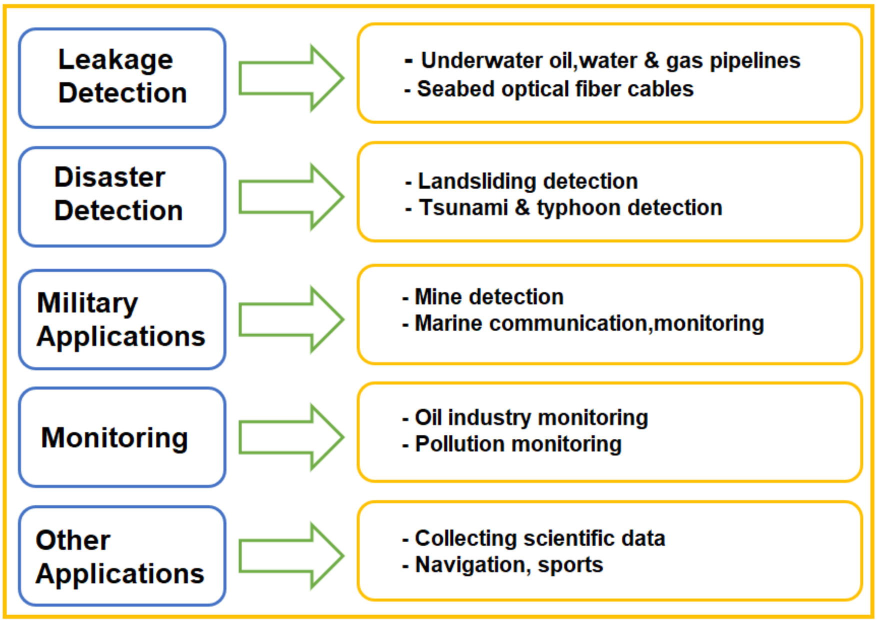

Fig. 2: EMI communication Applications

In addition to these core advantages, EMI communication also excels in mutual sensing and monitoring when used in conjunction with underwater swarming robots. This synergy enables the precise detection of sources of toxicity, waste, and biohazard at high convergence speeds, providing a valuable tool for various applications. These applications demonstrate the versatility and potential of EMI communication in marine environments, offering solutions for diverse challenges and requirements.

Electromagnetic induction (EMI) communication

Herein, we introduce the concept and principles of reflections in accordance with transmission line theory and the importance of matched impedance termination. We also discuss the mutual inductance between coils, which is determined using Stokes' theorem. Additionally, we highlight the significance of considering the permeability of the transmission medium, especially in underwater and underground scenarios.

Suppose the signal is a sinusoidal current in the transmitter wire, this current will cause another sinusoidal current in the receiver and perform the communication. The Near-Field Magnetic Induction (NFMIC) connection budget uses a transformer's age-old concept and therefore a primary referring to a transmitter and a secondary referring to a receiver. The block diagram presented in Fig. 3 illustrates the operational functioning principle of an RLC circuit serving as a communications antenna for a point-to-point connectivity that is ideal for short distances and can be accomplished via a simple network of the RLC series. The EMI transmitter and receiver can be effectively modeled as the primary coil and secondary coil of a transformer as illustrated in Fig. 3 in the second row. Here, *Us* represents the voltage of the transmitter's battery; *M* represents the mutual induction between the transmitter coil and receiver coil; R_t and R_r are the resistances of the coil; L_t and L_r are the self-inductions; a_t and a_r are the radius of the transmitter and receiver coils; Z_t and Z_r are the total impedance of the transmitter and receiver; *r* is the communication range between the receiver and transmitter; U_m is the total voltage transferred from transmitter to receiver.

According to transmission line theory [30], reflections occur unless the line is terminated by its matched impedance. In the context of Fig. 3, it is preferable for the load impedance to match the complex conjugate of the output impedance of the secondary loop. This matching helps optimize the power received at the receiving end. *M* is the mutual inductance that was extracted using Stokes theorem [31] between the coils. Here, N_t and N_r represent the number of turns of the transmitting coil and the receiving coil, respectively. μ is the permeability of the transmission medium. It is important to note that when dealing with underwater and underground media, the permeability must be considered in combination with the respective permeability constants as determined by equation 1:

$$M = \frac{N_r \varphi_{lr} A.dl_r}{dl} \cong \mu \pi N_t N_r \frac{a_t^2 a_t^2}{2r^3} \quad (1)$$

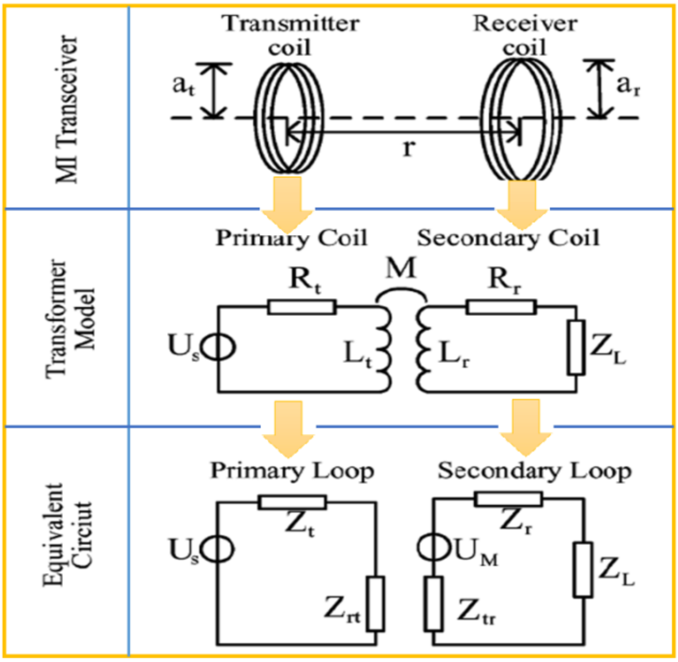

Fig. 3: EMI communication channel model

Path Loss in EMI

For wireless communication using EMR waves, although the radiation power is the main consumption of the *EM* wave transmitter, the EMR wave system's transmitting power (P_t) is a constant and not affected by the receiver's location, i.e. for EMR waves, P_r is a function of distance r. Hence, the loss of direction is determined by the ratio of the obtained power (P_r) to the radiation power. The EMR wave propagation path loss L_{EM} in soil medium is given by [32]:

$$L_{EM}(r) = -10\log\frac{P_r(r)}{P_t} = 6.4 + 20\log r \ \ + 20\log\beta + 8.69\alpha r \qquad (2)$$

Here, r represents the distance of transmission in meters, β is the constant of attenuation in *1/m*, and α is the constant of phase shift in *radian/m.* The values of β and α are based on the dielectric properties of the soil and are derived using the Peplinski principle [33].

In contrast to EMR wave transmission, the radiation power in an EMI system can be ignored due to the small radiation resistance. In an EMI communication system, the primary power consumption arises from the induced power absorbed at the receiver, occurring through coupling in the non-propagating near field. The transmission power in the EMI system is a combination of the power generated by the EMI amplifier and the power consumed by the coil resistance. If the coil resistance is high, the ratio of received power to transmitted power becomes equal to 1, as both the receiving and transmission powers decrease simultaneously with increasing transmission distance. The EMI communication system's Path Loss L_{MI} can be summarized as:

$$L_{MI}(r) = -10\log\frac{P_r(r)}{P_t} \cong -10\log\frac{N_r\alpha_t^3\alpha_r^3}{4N_t r^6} = 6.02 + 60\log r + 10\log\frac{N_t}{N_r\alpha_t^3\alpha_r^3} \quad (3)$$

In underground scenarios, we can compare equation (2) with equation (3) to determine the path loss of the EMR and EMI wave systems. In (2), there are two path loss terms defined by the distance, where the term *(20logr)* is due to the space spread and the term *(8.69αr)* is due to the absorption of the material. Since it defines the propagation constants α and β, the transmission medium has a significant influence on the path loss. In (3), the distance r, which is due to the magnetic field distribution, is calculated by a single term *(60logr).* The transmission medium has no apparent effect on the path loss of the EMI route since the medium's permeability is a constant as shown in Fig. 4.

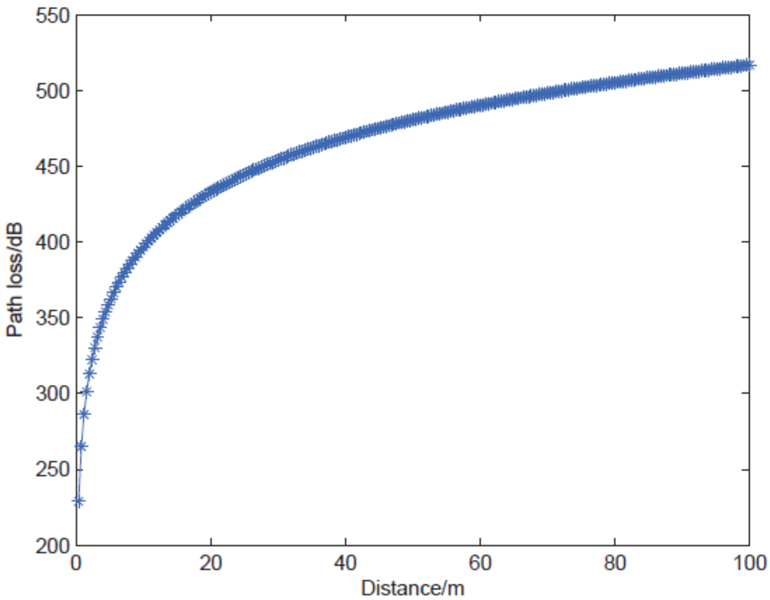

Fig. 4: Path loss

3 Effects of EMI Communication - Methodology & Solution

In the dynamic landscape of wireless communication, the quest for extending the range of EMI systems has become increasingly paramount. The ability to enhance EMI communication range holds the key to advancing various technological domains, from wireless power transfer to near-field communication. This pursuit is encapsulated in the intriguing prospect title of this section "EMI communication range enhancement." Within this realm, three fundamental factors emerge as the cornerstone of influence: coil parameters, directionality, and material as illustrated in Fig. 5:

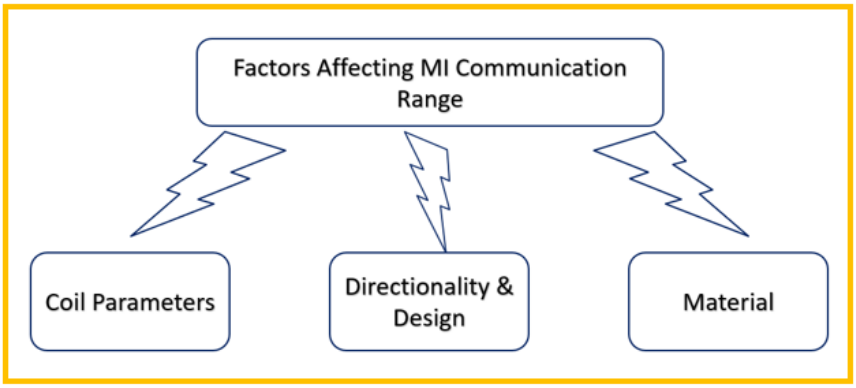

Fig. 5: Factors affecting communication range

Delving into the intricate interplay of these elements, this section explores to seek and unravel the mysteries surrounding the augmentation of EMI communication range. As we embark on this journey, we navigate the nuanced relationship between coil design, transmission directionality, and material properties, aiming to decipher the mechanisms that truly elevate the communicative potential of electromagnetic induction systems.The factors that significantly affect Electromagnetic Induction (EMI) communication basically involve unravelling the impact of coil parameters, directionality, and composite material

Coil Parameters: The parameters of the coils, such as their dimensions, geometry, and material, significantly impact EMI communication. The design and construction of the coils need to be optimized to achieve efficient coupling and maximum power transfer between the transmitter and receiver coils. Factors such as coil shape, size, and orientation can affect the magnetic field distribution and the strength of the induced current in the receiver coil.

Number of Turns in Coil: The number of turns in the coil plays a significant role in EMI communication. The communication range of EMI is directly related to the magnetic field strength (*H*). A higher magnetic field intensity results in a longer communication range, while a lower magnetic field intensity limits the range [27]. The magnetic field intensity (*H*) is determined by the equation:

$$H = \frac{NI}{l} \tag{4}$$

Here, *N* represents the number of turns in the coil, *I* denotes the current flowing through the coil, and l is the path length measured in meters. Increasing the number of turns in the coil increases the communication range.

Current in the Transmitter Coil: Increasing the current (I_t) in the transmitter coil can enhance the transmission range of EMI communication. The transmitting power (P_t) is directly related to the receiving power (P_r) and is expressed by the equation [28]:

$$P_r = \alpha \frac{P_t}{d^6} \tag{5}$$

$$P_t = I_t^2 R \tag{6}$$

Here, α represents the factor of attenuation, d is the distance between the transmitter and receiver, and R is the resistance provided by the system. Higher transmission power (P_t) leads to increased receiving power (P_r) and extended communication range. However, it is important to note that using very high current values in small-sized coils may cause damage to the coils and winding, making it impractical in real-world deployments.

Operating Frequency: The operating frequency (f) of the EMI communication system plays a crucial role in achieving maximum power transmission and increasing the data transmission range. The mutual inductance (M) between the coils is influenced by the operating frequency. The relationship between mutual inductance (M) and operating frequency is described by the equation:

$$M = kJG \times \sqrt{L_t L_r} \tag{7}$$

Here, k is the coefficient of coupling, G is the attenuation power for the magnetic field lines, Lt is the inductance of the transmitter coil, and Lr is the inductance of the receiver coil.

The term G represents the attenuation of the magnetic field lines and is related to the skin depth (δ) of the medium. The skin depth depends on the frequency (f), magnetic permeability (μ), and conductivity (σ) of the medium, defined as:

$$G = e^{-d/\delta} \text{ and } \delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{8}$$

Different media such as seawater, fresh water, and dry land have different skin depths, which in turn affect the mutual inductance.

Directionality Dimensionals (1D, 2D and 3D): Directionality plays a crucial role in EMI communication, with considerations for 1D, 2D, and 3D coil antennas. The proper alignment and orientation of transmitter and receiver coils are essential for achieving optimal coupling and efficient power transfer. Any misalignment or angular deviation can result in diminished power transfer efficiency and a decrease in communication range.

In a three-dimensional space, the directional characteristics of coil antennas vary:

1. **1D Coil Antenna (Unidirectional):**
    - A 1D coil antenna can transmit signals in a single specified direction.
    - This type of antenna has limited coverage as it focuses on transmitting in one direction only.

2. **2D Coil Antenna (Bidirectional):**
   - A 2D coil antenna can transmit signals in two opposite directions (bi-directionally).
   - This configuration increases the coverage area compared to a 1D coil, as it can transmit in both directions.
3. **3D Coil Antenna (Omni-directional):**
   - A 3D coil antenna has the capability to transmit signals in all directions within the three-dimensional space, essentially functioning as an omni-directional antenna.
   - This 3D coil antenna substantially improves coverage in underground and underwater scenarios [29].

In Fig. 6, representations of 1D, 2D, and 3D antennas are depicted. In the 3D configuration, the total received power (P_{rt}) is given by the sum of power received along the x-axis (P_{rx}), y-axis (P_{ry}), and z-axis (P_{rz}):

$$P_{rt} = P_{rx} + P_{ry} + P_{rz} \tag{9}$$

Where $P_{rx} = P_{ry} = P_{rz}$. This equation reflects the combined received power from all directions, emphasizing the omni-directional capability of the 3D coil antenna.

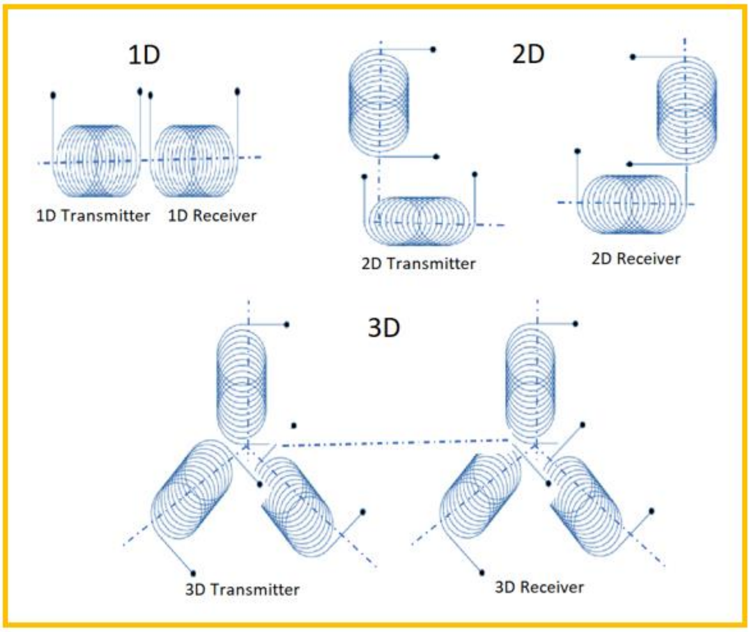

Fig. 6: 1D, 2D & 3D transceiver antenna coils power distribution

Multilayer Coil Inductance: Using a multilayer coil structure is an effective way to enhance the range of EMI communication. The mutual inductance (M) between the transmitter and receiver coils is a crucial parameter in determining the communication range. The mutual inductance of the multilayer coils is given by:

$$M = kJG \times \sqrt{L_{eq.t}L_{eq.r}} \tag{10}$$

Here, k represents the coefficient of coupling, and G denotes the attenuation power for the magnetic field lines, and $L_{eq.t}$ and $L_{eq.r}$ are the equivalent inductances of the transmitter and receiver coils, respectively [30]. The equivalent inductance takes into account the self-inductance of each layer and the coupling between the layered coils [37] presented as:

$$L_{eq} = L_1 + L_2 + L_3 + 2k_{1,2}\sqrt{L_1 L_2} + 2k_{2,3}\sqrt{L_2 L_3} + 2k_{3,1}\sqrt{L_3 L_1} \quad (11)$$

Where $k_{i,j}$ are the coupling coefficient between the layered coils and L_1, L_2 and L_3 are the self-inductance values of the layered coils.

Relay Coils Waveguide: In the context of EMI communication, relay coils placed between the transmitter and receiver, which facilitate signal transmission without amplification, are referred to as waveguides. These waveguides, as shown in Fig. 7, serve to relay the signal to the nearest neighbour coil.

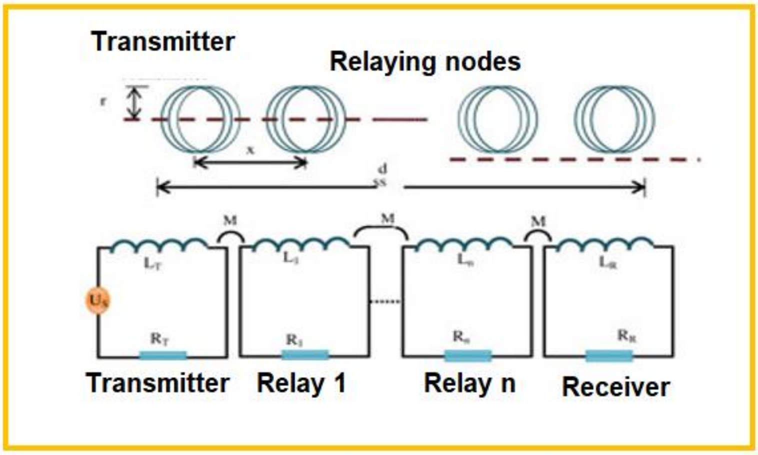

Fig. 7 EMI waveguide overview communication channel model

When utilizing waveguides in EMI communication, it is important to consider the channel noises associated with them. If these noises are not properly addressed, they can mix with the true signal, resulting in an undesired signal reception as noted by [38].

The impedance of the first relay coil can be calculated using specific considerations and parameters to determine the impedance of the relay coil, additional details such as the coil geometry, material properties, and surrounding circuitry are required. Without these specific parameters, it is not possible to provide a calculation for the impedance of the first relay coil. Let's express the information using equations:

Relay Coils Waveguide for EMI Communication Range Enhancement:

EMI communication range (R) can be improved by introducing relay coils (waveguide) between the transmitter and receiver, as illustrated in Fig. 7. The relay coils act as a waveguide, facilitating signal transmission to the nearest neighbour without amplification. Relay coils serve as "jumps," allowing the signal to leap from one relay to another (e.g., relay *1* to relay *2* … relay *n*). This approach increases the transmission distance without a significant power increase and minimizes signal loss. Achieving this requires the use of an acceptable frequency and waveguide technique. However, consideration must be given to the channel noises of the waveguide to prevent interference with the true signal [31], [38].

The following set of related equations describes the EMI waveguide communication channel model, which involves various electrical parameters and formulas for calculating induced voltage and impedance. Here is an explanation of the equations:

Equation (12): Z_1 represents the impedance of the EMI waveguide communication channel model. It is calculated using the following formula:

$$Z_1 = \frac{(R_1 + j\omega L_1 + 1/j\omega C_1)(R_1)}{(R_1 + j\omega L_1 + \frac{1}{j\omega C_1} + R_1)} \qquad (12)$$

Where:

- *R1:* Resistance of the relay
- *C1:* Capacitance of the relay
- *L1:* Inductance of the relay
- *j:* Imaginary unit
- *ω:* Angular frequency

Equation (13): V_{Mi} represents the induced voltage for a coil in the EMI waveguide communication model. It is calculated using the following formula:

$$V_{Mi} = -j\omega M \frac{V_{M(i-1)}}{Z_1 + Z_{(i-2)(i-1)}} \qquad (13)$$

Where:

- V_{Mi}: Induced voltage for the *ith* coil
- *M:* Some coefficient or constant
- $V_{M(i-1)}$*:* Induced voltage for the *(i-1)th* coil
- Z_1*:* Impedance of the EMI waveguide communication channel model

The equation is recursive, where the voltage for the current coil depends on the voltage of the previous coil *(i-1).*

Equation (14): *Z_i(i-1*) represents the impedance between the *ith* and *(i-1)th* coils in the EMI waveguide communication channel model. It is calculated as:

$$Z_{i(i-1)} = \frac{\omega^2 M^2}{Z_1 + Z_{(i+1)i}} \qquad (14)$$

Where:

- $Z_{i(i-1)}$*:* Impedance between the *ith* and *(i-1)th* coils
- *M:* Some coefficient or constant
- *ω:* Angular frequency
- Z_1*:* Impedance of the EMI waveguide communication channel model

Equation (15): $Z_{(i-1)i}$ represents the impedance between the *(i-1)th* and *ith* coils in the EMI waveguide communication channel model. It is calculated as:

$$Z_{(i-1)i} = \frac{\omega^2 M^2}{Z_1 + Z_{(i-2)(i-1)}} \qquad (15)$$

Where:

- $Z_{(i-1)i}$: Impedance between the *(i-1)th* and *ith* coils
- *M:* Some coefficient or constant
- *ω:* Angular frequency
- *Z*1*:* Impedance of the EMI waveguide communication channel model

These equations are used to model the behaviour of the EMI communication channel, considering the electrical properties and interactions between coils in the system. The impedance and induced voltage calculations are crucial for understanding the performance and behaviour of EMI waveguide communication. The primary benefit of this approach is the enhancement of transmission distance (*R*) without a significant increase in power (*P*) and substantial signal loss (*SL*). This can be achieved by optimizing the choice of frequency (*f*) and utilizing an effective waveguide technique. Mathematically, this advantage can be represented as:

$$R_{improved} = f.Waveguide\_Technique \qquad \text{(X)}$$

where:

- $R_{improved}$ is the improved transmission distance,
- *f* is the selected frequency, and
- *Waveguide Technique* represents the effectiveness of the waveguide technique.

The significant advantage of optimising of frequency and the utilization of an efficient waveguide technique contribute to minimizing power consumption and reducing signal loss, thus making the communication system more efficient and reliable.

Superconductor: To overcome the challenges associated with communication range, superconductor wires can be employed. The presence of superconductor wires directly affects the coupling coefficient between the coils. A demonstration of superconducting wire is shown in Fig. 8.

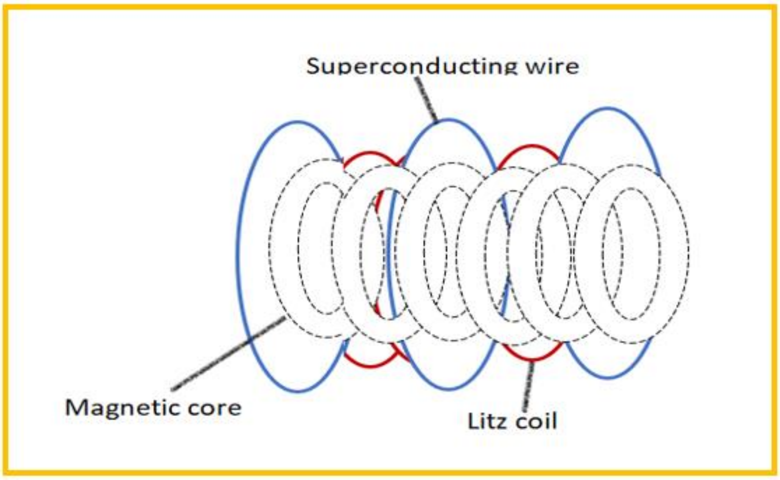

Fig. 8: EMI superconducting coil antenna

The analysis of the coupling coefficient and the flux related to a superconductor coil can be conducted as described in [37], that is, k is defined as the ratio of the magnetic flux associated with the superconductor wire in the receiver coil $\varphi_{s\text{-}sc}$ to the magnetic flux in the transmitter coil $\varphi_{p\text{-}sc}$, calculated as:

$$k = \frac{\varphi_{s-sc}}{\varphi_{p-sc}} \quad (16)$$

The coupling coefficient k is also related to the mutual inductance M between the coils and the square root of the product of their respective inductances L_1 and L_2, of the transmitter and receiver coils, respectively expressed as:

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (17)$$

Superconductor Metamaterial Shell: In the context of EMI communication, the use of a metamaterial shell outside the EMI coil is a theoretical approach to increase the range of communication [40]. This approach as shown in Fig. 9 involves incorporating a specially designed metamaterial structure around the EMI coil to enhance the propagation and transmission of electromagnetic waves.

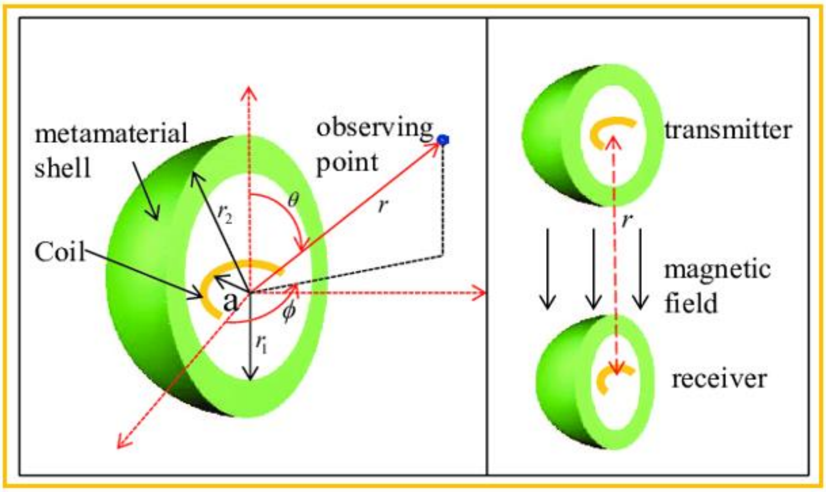

Fig. 9: Structural representation of metamaterial in EMI

The metamaterial mutual inductance is given by these two equations:

$$M_m = \frac{\bar{h}_1}{\bar{S}_m^2} \quad (18)$$

$$\bar{S}_m = \bar{h}_2 \begin{bmatrix} 2r_1^3(\mu_1 - \mu_2)(\mu_3 - \mu_2) \\ -2r_2^3(2\mu_2 - \mu_1)(2\mu_3 - \mu_2) \end{bmatrix} + \varrho \quad (19)$$

Where: r_1 and r_2 are the shell thickness and outer shell radius respectively. μ_1, μ_2 and μ_3 are the inner shell and outer permeability, and $\bar{h}_1$, $\bar{h}_2$ are the coefficient and ϱ is an asymptotically minuscule value.

The metamaterial shell is engineered to have unique electromagnetic properties that manipulate the behaviour of electromagnetic waves. By carefully designing the structure and composition of the metamaterial, it is possible to control and manipulate the electromagnetic fields in a desired manner.

The concept of using a metamaterial shell in EMI communication systems aims to improve the range of communication by optimizing the propagation characteristics of the electromagnetic waves. By utilizing metamaterials, it is theoretically possible to extend the effective communication range beyond what can be achieved with traditional EMI coil designs.

It's worth noting that the practical implementation and performance of such metamaterial-based systems would depend on various factors, including the specific design of the metamaterial shell, the operating frequency, and the environmental conditions. Experimental validation and full-wave simulations are typically conducted to assess the effectiveness and feasibility of these concepts.

1. ***Presence of Metal Plate:*** The presence of a metal plate between the EMI coils can affect the induced voltage. Placing the coils on opposite sides of the metal plate can increase the induced voltage, while facing the metal plate can result in poorer communication. Simulations and experiments have been conducted to assess the impact of the metal plate on EMI communication [41].
2. ***High-Sensitivity Magnetic Field Detector:*** Using a high-sensitivity wideband magnetic field sensor as a receiver can increase the range of EMI communication. By replacing the traditional receiver coil with a high-sensitivity sensor, smaller receiver devices can achieve a wider range of communication. This technique takes advantage of the improved sensitivity and detection capabilities of the magnetic field sensor [42].
3. ***Applying Minimum Detection Threshold:*** Using an *AMR* (*anisotropic magneto-resistive*), equations (20) and (21) describe the relationship between the magnetic flux density *B* and the transmission range [43]:

$$B = \frac{\mu_0 \mu_r, TNIr_T^2}{2d_{cAMR}^3} \tag{20}$$

Here, *N* represents the number of turns in the transmitter coil, μ_0 is the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$), and I denotes the current flowing through the transmitter coil. The transmission range d_{cAMR} is specified by:

$$d_{cAMR} = \sqrt[3]{\frac{\mu_0 \mu_r, TNIr_T^2}{2B}} \tag{21}$$

By replacing *B* setting with the detection threshold of the magnetic sensor *Bmin* as the minimum value, the communication range can be maximized. This technique optimizes the detection capability of the system.

4. ***Using Large Coil Radii:*** The radius of the transmitter coil r_T has a direct impact on the maximum transmission range as expressed by Equation (20). Increasing the transmitter coil radius can extend the overall transmission distance for both coil-to-coil and *coil-to-AMR* (*cAMR*) communication strategies. B_{min} magnetic field detector defines the optimal transmission distance for the coil-to-AMR device. The radius of the receiver coil also affects the transmission range in coil-to-coil communication [44] as Fig. 10(a) illustrates the transmission range as a function of the transmitter coil radius; meanwhile, Figure 10(b) illustrates the coil-to-coil communication range based on the receiver coil radius.

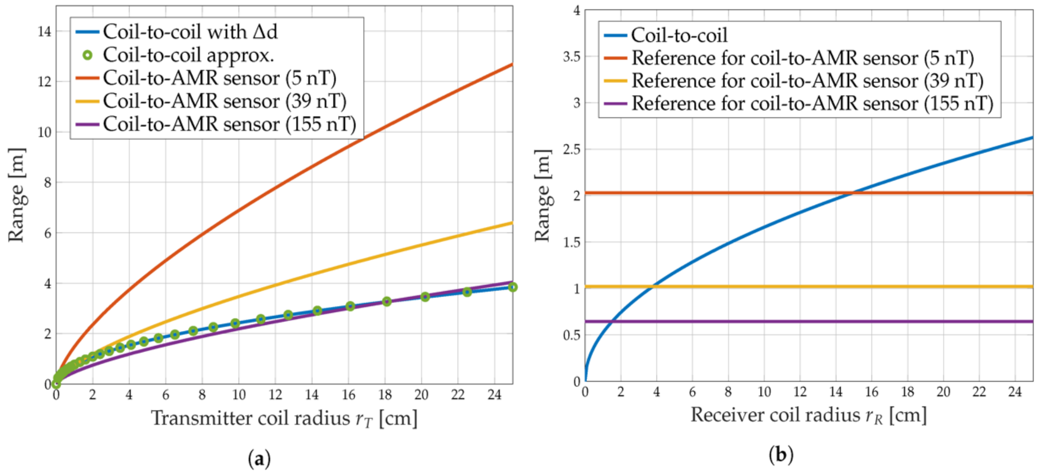

Fig. 10: Transmitter and Receiver coil radius

These techniques and factors highlight various ways to enhance the range of EMI communication, including the use of metamaterials, optimizing coil configurations, employing high-sensitivity sensors, and considering the impact of surrounding materials like metal plates.

The choice of materials for the coils and the surrounding environment can impact EMI communication. The magnetic permeability and conductivity of the materials affect the efficiency of magnetic induction and power transfer. Additionally, the properties of the surrounding medium, such as its dielectric constant, can influence the propagation characteristics of the electromagnetic field and the path loss.

Optimizing these factors is essential for achieving reliable and efficient EMI communication. System designers must carefully consider coil design, directionality, and material choices to tailor EMI as well as Unmanned Aerial Vehicle (UAV) communication systems for specific applications and environmental conditions [39].

4 Discussion: Unveiling Challenges and Open Issue in EMI

In the realm of EMI-based communication solutions, several critical challenges remain that demand attention and resolution for the successful deployment of such systems. Here, we delve into the open issues across various facets of EMI communication.

1. MAC Protocol Design: The exploration of non-conventional EMI-based Medium Access Control (MAC) protocols are an uncharted territory [16]. Traditional underwater acoustic communication struggles with the implementation of Carrier Sense Multiple Access (CSMA) schemes due to variable delays in acoustic wave propagation underwater [46]. However, EMI waves, characterized by negligible propagation delays, offer a promising avenue for implementing CSMA-like schemes in underwater EMI communications [45].

2. Efficient Error Control Approach: The methodology for error monitoring in the underwater EMI channel requires thorough investigation. This channel exhibits distinct characteristics from traditional acoustic channels, showcasing lower variability. A stable channel may necessitate low-complexity Forward Error Correction (FEC) codes with high coding levels to ensure reliability. Research efforts should focus on identifying optimal

FEC coding schemes that strike a balance between complexity, energy efficiency, and error correction capabilities in EMI-based underwater communications [47].

3. Energy-Efficient Routing Protocol: Achieving secure and energy-efficient data transfer over multi-hop communications in large-scale underwater networks poses a challenge due to long channel propagation delays and a high channel bit error rate. The promising features of EMI channels necessitate a revaluation of underwater routing protocols, emphasizing the incorporation of robust three-dimensional functionality tailored for underwater environments with the possibilities of using clustering [48].

4. Cross-Layer Protocol Design: A cross-layer framework emerges as a hybrid solution catering to diverse environments such as oil reservoirs, underground spaces, underwater domains, and soil. This framework's adaptability to alter transmission parameters based on channel characteristics like path loss and bandwidth makes it a valuable tool in optimizing communication performance [49].

5. Energy-Efficient Modulation Techniques: Energy efficiency remains a key challenge in both traditional and non-traditional Wireless Sensor Network (WSN) applications. The deployment of energy-efficient modulation schemes with a high signal-to-noise ratio per transmitted data symbol is an ongoing challenge, particularly for non-traditional EMI-based communication [50].

6. Energy-Efficient Sensor Nodes Model: Energy limitations are a primary concern in any Wireless Sensor Network, be it Electromagnetic (EM) or EMI communication. While the Ray model [24] and the Friss equation (equating the power at the terminals of a receive antenna as the product of power) [26] are applied for energy consumption in Electromagnetic Radiation (EMR) wave communication, determining the optimum energy requirements for non-conventional media dependent on EMI remains an area requiring further advanced exploration and reorientation.

7. Security Issues in EMI Communication: Ensuring the confidentiality and integrity of data in Magnetic Induction (MI) communication is imperative, given the prevalence of both passive and active attacks [51]. Passive attacks involve malicious nodes attempting to interpret operations and acquire transmitted data without disrupting network activity. Examples include message reply, distortion, interference, and impersonation. The most effective preventive measure against passive attacks is encryption mechanisms, rendering data inaccessible to eavesdroppers. On the other hand, active attacks aim to modify, insert, erase, or damage transmitted network data. Intrusion Detection Systems (IDS) play a crucial role in mitigating such attacks, monitoring both inbound and outbound traffic for suspicious activities using known intrusion detection and prevention signatures in all sorts of smart grid ecosystems [52]. Various security issues, types of attacks, and protection mechanisms are illustrated in Fig. 11. as an example.

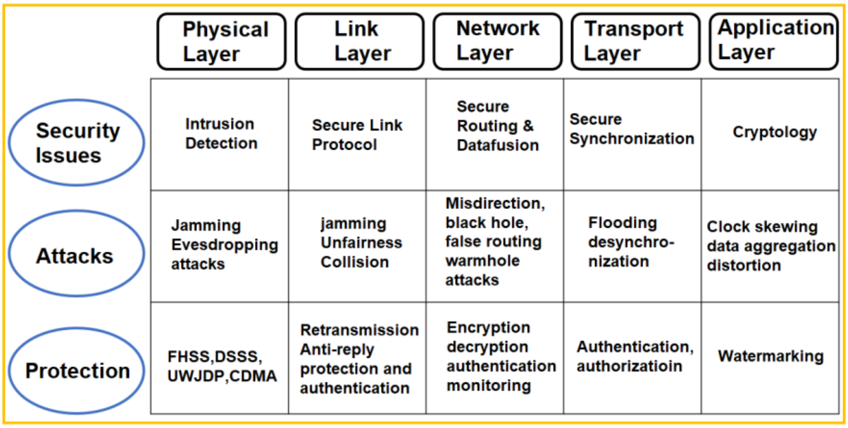

Fig. 11: Security issues, attacks and protection

In Underwater Sensor Networks (UWSNs), where sensor nodes are mobile, network topology changes easily, leading to the multi-path effect and increased error rates. Collision-detection mechanisms help identify and address these issues. Exhaustion attacks, where a malicious node drains a node's battery by keeping the channel occupied, pose a significant threat. Misdirection attacks in the network layer involve forwarding packets on incorrect paths, while desynchronization attacks and synchronization flooding threaten the transport layer. Trust-aware routing, monitoring, filtering, and authorization mechanisms are essential for defense.

The UWSN security framework necessitates cryptographic operations such as authentication and encryption. However, the resource constraints in terms of computing capacity and energy supply in some applications pose challenges to implementing robust data protection. Asymmetric cryptography, though effective, may be deemed expensive for many applications. Addressing these multifaceted security challenges is pivotal for the successful deployment and operation of MI communication systems.

Ensuring the security of EMI communication is paramount, demanding safety, protection and trustworthy reliability to avoid any form of passive cyberattacks involving malicious nodes attempting to discreetly interpret and acquire transmitted data without disrupting network activity, while crippling and hampering active cyberattacks that seek to modify, insert, erase, or damage transmitted data [52]. Proper risk assessment analysis and cryptographic encryption mechanisms are vital for preventing eavesdropping, and intrusion detection systems play a pivotal role in mitigating attacks and blocking new threats [53].

In summary, addressing these open issues is essential for the successful development and implementation of EMI-based communication solutions. Rigorous research and innovative solutions are needed to overcome these challenges and pave the way for robust, energy-efficient, and secure communication protocols in various applications. The journey towards successful EMI-based communication solutions requires interdisciplinary collaboration and persistent exploration of these issues.

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5 Conclusion

In the realm of marine information networks, facilitating seamless underwater wireless communication among various underwater devices for data transmission, information exchange, and networking is a paramount concern. While traditional methods like optical, acoustic, and electromagnetic communication have been employed, magnetic induction communication, often referred to as EMI communication, has recently garnered significant attention as a promising alternative. This attention is attributed to its inherent advantages, which include consistent channel responses, minimal propagation delays, and efficient energy consumption.

By adopting the EMI waveguide technique, it becomes possible to extend the transmission range of EMI communication. Crucial factors impacting the performance of EMI communication include parameters of the coil antenna, such as its dimensions, number of turns, and the lumped distributed impedance. Traditional methods often grapple with challenges like large antenna sizes, high path loss, and dynamic channel conditions. In contrast, the EMI technique offers a distinct advantage in that the path loss is exclusively determined by the permeability of the propagation medium, which remains constant. Consequently, EMI communication maintains a consistent channel state, making it a reliable choice.

Moreover, it is noteworthy that the path loss in the EMI system is a sixth-order function of the transmission range. This characteristic underscores the significance of optimizing coil parameters and external materials to extend the range of EMI communication.

As we conclude, it's essential to highlight the open issues in this field that warrant further exploration. These challenges serve as valuable guideposts for researchers and system designers working towards advancing EMI communication research. In the ever-evolving landscape of underwater communication, EMI stands out as a promising and reliable technology, poised to address the unique demands of marine information networks.

DECLARATIONS

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