IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 12 February 2024, accepted 27 February 2024, date of publication 5 March 2024, date of current version 11 March 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3373791

SURVEY

A Survey on Underwater Wireless Power and Data Transfer System

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This work was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education under Grant 2020R1A6A1A03038540; in part by Korean Government through the Ministry of Science and ICT (MSIT) under Grant 2023R1A2C1002656; in part by the MSIT, South Korea, through the ICT Challenge and Advanced Network of HRD Program, under Grant IITP-2024-RS-2022-00156345; and in part by the Faculty Research Fund of Sejong University, in 2024.

ABSTRACT This research extensively explores contemporary techniques in Underwater Wireless Power and Data Transfer (WPDT), as found in recent literature over the past 5 years. These techniques involve Magnetic Induction (MI), acoustic communication, and optical communication. The study aims to evaluate transmission efficiency, propose solutions to overcome range limitations, facilitate integration, and precisely map multilayer networks. The research methodology includes proposed solutions to address the limitations of each transmission technique, multilayer network mapping, and model validation. Evaluation is conducted on the relative efficiency of each method, including power loss at each layer, the connection matrix between layers, and transmission speed. Simulations reveal power loss at nodes in each layer and the connection matrix between layers. The power loss at each node shows random values, providing a realistic aspect close to real-world scenarios, offering in-depth insights into the characteristics and performance of multilayer networks in an underwater context. The research series, involving literature elaboration, technological approaches, illustrations, and simulations, demonstrates the effectiveness of the proposed model. Simulation results indicate the potential of this model in real-world scenarios, with tolerable power loss values, suggesting that multilayer networks could be a solution to classic challenges in underwater power and data transmission. The hope of this preliminary study is to provide new insights and make a significant contribution to understanding and designing reliable underwater power and data transfer systems in the future.

INDEX TERMS Underwater data and power transfer system, magnetic induction, acoustic, optic communication, multilayer network.

I. INTRODUCTION

Over the past five years, there has been significant progress in the development of Underwater Wireless Sensor Networks (UWSN) and the Internet of Underwater Things (IoUT), combined with the mobility of Autonomous Underwater Vehicles (AUV) for data collection [1], [2], [3]. Following this trend, the implementation of Underwater-WPDT technology has emerged, specifically designed to bolster the continuous operation of AUVs [4].

Despite having great potential, further investigation is needed to address technology gaps and issues related to Underwater-WPDT. Aspects such as transfer efficiency, communication range, and integration with underwater infrastructure are key concerns. In this context, we conduct a comparison between power transfer methods to understand the strengths and weaknesses of each approach.

Several Underwater-WPDT methods include MI [5], which is utilized for wireless charging of AUVs through

The associate editor coordinating the review of this manuscript and approving it for publication was Xuebo Zhang.

a docking system [6]. MI is also employed as a node identifier, similar to Radio Frequency Identification (RFID) functionality [7]. Additionally, there is Omnidirectional-MI capable of transmitting power and data in all directions [8], MI transmitted using metallic materials [9], Multiple-Links (MLs) MI for simultaneous power and data transmission [10], 3-Dimensional coil-engineered MI to enhance energy efficiency [11], and optimization of MI power delivery and reception through magnetic coupling mechanisms [12].

The wireless power and data transfer methods for AUVs also involve Acoustic communication techniques, sometimes in combination with MI as a hybrid system. This effort opens up the potential development of acoustic media as an alternative for underwater power and data transmission with a longer range compared to MI [13]. These efforts include the use of Piezoelectric devices in the Frequency Selection Acoustic Power Transfer System (APTS) [14], multi-hop scenarios to enhance energy balance during AUV missions [15], and data modulation using Frequency Shift Keying (FSK) [16]. The use of Acoustic Hologram (AH) as a contactless Ultrasonic Power Transfer System (Contactless-UAET) based on Piezoelectric shows significant potential for the development of advanced acoustic wave transmitter-receiver systems [17]. There is also the use of dynamic routing in Renewable Wireless Sensor Network (Renewable-WSN) for Wireless Power Transfer (WPT) needs, which can adapt based on past experiences due to the embedded Reinforcement Learning (RL) algorithm that updates favorable routes for the vehicles to traverse [18]. Supported by the development of Underwater-Wireless Power transfer (UWPT) technology following the trends of sixth-generation communication technology [19], there is also the idea to strengthen acoustic signal transmission for WPT needs in Wireless Sensor Transponder (WST) by adding special metallic materials [20]. This proposal can be applied to AUV Aided Energy Efficient Data Collection (AEEDCO), where data is obtained on one side, and on the other side, the AUV can simultaneously recharge. Furthermore, for underwater data collection, current AUVs can leverage resources from the scattered Underwater Acoustic Sensor Network (UASN) on the ocean floor [21], where UWSN nodes can be optimized with cross-layer methods. Therefore, when an AUV collects data at one node point, the UWSN node can be optimized using this method [22]. Additionally, the placement of nodal points can be optimized with a multi-layer architecture within one operational area [23].

The optical transmitter-receiver technology is also explained as an alternative for power and data transfer systems, with advantages in speed and distance. Materials such as Perovskite and Micro Light Emitting Diode (Micro-LED) made of Gallium Nitride (GaN) are used to enhance the performance of Underwater Wireless Optical Communications (UWOC) [24], [25], [26]. The use of Single Photon Avalanche Diode (SPAD) can improve the range [27]. Optical Fiber Nanotechnology (OFN) is also considered [28]. The limited coverage area prompts the development of Simultaneous Lightwave Information and Power Transfer (SLIPT), where data and power are transmitted at Different Phases (DP) [29]. The scattered nature of optical properties also encourages the investigation of good receiver components [30], where in light communication, it is crucial to ensure Free Space Optical (FSO) [31]. The use of Two-Dimensional Infrared beam steering (2D-IR) with the assistance of Arrayed Waveguide Grating Router (AWGR) can also be considered [32], [33]. Furthermore, the principle of a good optical transmission receiver antenna can also adapt the function of the eye's retina, where this natural working mechanism can be adapted to devices such as Photovoltaic Cells, Photodiodes, and Electrode Arrays [34].

Overall, this research aims to investigate and deeply understand underwater power and data transfer methods, with a focus on MI, acoustic communication, and optical communication. Specifically, it aims to assess their efficiency, overcome range limitations, facilitate integration, and accurately map multilayer networks. The research comprehensively seeks to provide an in-depth understanding of the complexities inherent in underwater systems. We evaluate the feasibility of the Underwater Multilayer WPDT Network, considered a promising technique to enhance underwater power and data transfer performance by leveraging the synergistic interaction between various methods.

This article also guides readers through key elements, including exploring Underwater-WPDT techniques such as MI, acoustic communication, and optical communication, with an emphasis on multilayer networks. The literature review summarizes recent findings and advancements in MI, acoustic, and optic-based Underwater-WPDT research. The research method involves Proposed Solution, Multilayer Network Mapping, and Mapping Model Validation, with evaluations of method efficiency. Results and Discussion cover simulations and outcomes to understand the characteristics and performance of underwater multilayer networks. The conclusion summarizes the process, key points, model evaluations, and provides insights for further development, contributing to the advancement of the vision of Underwater-WPDT.

II. LITERATURE REVIEW

To elaborate on the characteristics of Underwater-WPDT, encompassing each involved technique such as MI, acoustic communication, and optics, as well as to formulate potential application scenarios along with the respective strengths and weaknesses of each transmission method, we commence with a thorough literature review. In our examination of each transfer technique, we present a comprehensive analysis, focusing on critical aspects such as efficiency, transfer distance, resilience to underwater environmental disturbances, and the implementation complexity. This approach aims to provide a holistic insight into the potentials and challenges associated with each Underwater-WPDT technique, facilitating the design of optimal solutions aligned with the intended application goals.

A. POWER TRANSFER

Starting with the explanation of underwater power transfer methods, in several applications, UWSN along with the IoUT are utilized as data collection nodes for underwater operations involving AUV. Therefore, many studies are focused on thinking about how to improve mission efficiency, ranging from calculating effective node placements to clustering node groups to save AUV energy in data acquisition [1]. Furthermore, Jahanbakht et al. in [2] comprehensively explain the use of IoUT as the backbone of Big Marine Data (BMD) by connecting objects in the underwater environment. In their paper [3], Wei et al. investigate the potential use of power and data transfer methods in the underwater environment between AUVs and IoUT. Additionally, Yang et al. in their manuscript [4] explain the technique of Underwater-WPDT with a shared channel system using FSK. This means that power and data transmission are done simultaneously with a shared channel using changes in carrier frequency to represent digital data and power pulses (see Figure 1).

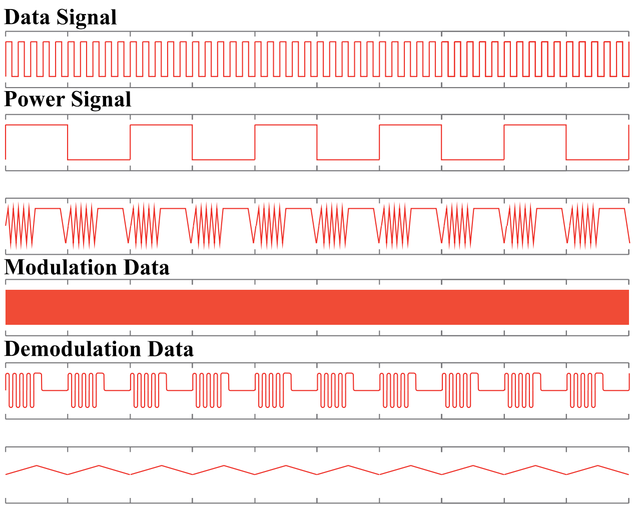

FIGURE 1. Underwater-WPDT shared channel technique using FSK modulation.

Through the survey paper written by Li et al. [5], the option of using MI communication is explained as a promising alternative for transmitting power and data in the underwater environment. The survey paper not only discusses communication media such as acoustic and optic, but also reviews a combining scheme referred to as hybrid relay technique. Additionally, in their writing, Li et al. highlight the potential signal power loss that may occur during transmission through the water medium.

B. MAGNETIC-INDUCTION

MI in the context of Underwater-WPDT refers to a wireless communication method that utilizes the principle of magnetic induction to transfer power and data between devices in the underwater environment. In this scenario, a device acts as a transmitter, generating a magnetic field detectable by the receiving device. This magnetic field is then used to transmit power and data, involving the generation of a magnetic field at the transmitter device, which is then induced by the receiving device to transfer energy and information. Like the Inductive Wireless Power Transfer (IWPT) system introduced by Teeneti et al. [6], composed of at least three main components including Linear Coaxial Winding Transformer (LCWT), Inductive Coupler, and Resonant Coils, where power transfer occurs through electromagnetic induction between two adjacent coils. In [7], not just one coil is used but several coils formed in a configuration, where the distance and placement are calculated using the Neuman formula (see Equation (1)).

$$M = \frac{\mu 0}{4\pi} \oint_{c1} \oint_{c2} \frac{dl_1.dl_2}{R_{12}} \tag{1}$$

where M is the mutual inductance between two coils, dl_1 is the length differential along the electric path for current l_1 in the first coil, and dl_2 is the length differential along the electric path for current l_2 in the second coil, respectively, and R_{12} is the distance between each length differential dl_1 and dl_2.

At the same time, this design provides the advantage of a model that functions like Radio Frequency Identification (RFID), which can be developed for AUV navigation in localization missions and data acquisition in UWSN (see Figure 2).

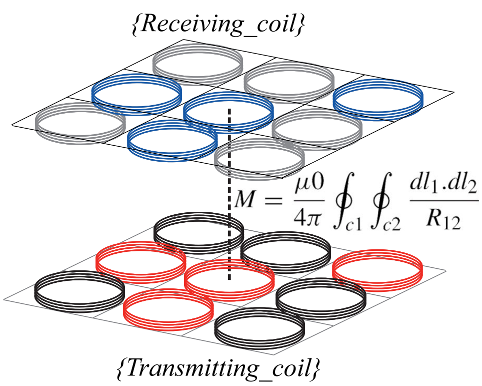

FIGURE 2. Multi-coil transmitter antenna that adopts the working principle of RFID.

But the multi-coil system may have drawbacks when the sender-receiver angles are not aligned in the Line-of-Sight (LoS). This aspect is seen as an opportunity for improvement by Li et al. [8], who developed a transmission receiver system that can adapt to the direction of the incoming signal, as expressed in the equation:

$$\vec{H}_{r,1} = \frac{I_1 S}{2\pi} cos\alpha \left(\frac{1}{r^3} + \frac{jk}{r^2} \right) e^{-ikr} \vec{a}_r \tag{2a}$$

$$\vec{H}_{r,2} = \frac{I_2 S}{2\pi} cos\beta \left(\frac{1}{r^3} + \frac{jk}{r^2} \right) e^{-ikr} \vec{a}_r \tag{2b}$$

where $\vec{H}_{r,1}$ and $\vec{H}_{r,2}$ are the radial components of the magnetic field generated by the respective sender loops 1 and loop 2, S is the area of the loop, k is the wave number, $\vec{a}_r$ is the unit vector in the radial direction, and α and β are the angles formed by the normal of coil 1 and coil 2, respectively, and the normal of the receiving coil. It is clear that α and β satisfy $\alpha + \beta = \pi/2$ (see Figure 3).

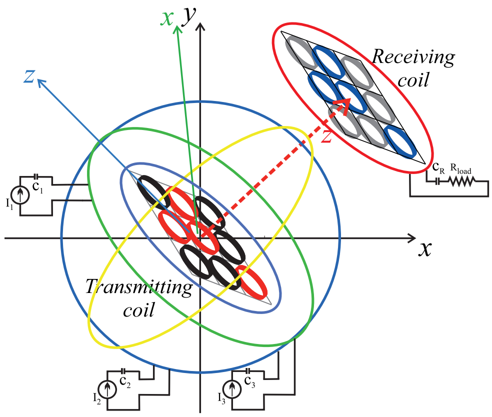

FIGURE 3. The omnidirectional multi-coil transmitter antenna can automatically adjust its direction to the incident signal LoS, ensuring optimal coverage regardless of the direction of signal origin.

With channel separation, power and data can be transmitted by induction, and this can even be enhanced using metal propagation [9], [10]. Furthermore, by utilizing the Microcontroller Unit (MCU) MSP430F5529 and a combination of Fusion Sensor Accelerometer LSM303DLHC, Calendar ICPCF8532, Pore-pressure Sensor, and Inclinometer, the capabilities of the MI Omnidirectional Antenna can be improved [11]. The transmitter-receiver antenna components do not necessarily have to have the same number of coils, as shown in Dai et al.'s research [12], which uses a coupling mechanism to shift the receiver antenna channel. A similar principle is also applied in [35].

In addition to utilizing metal materials to propagate MI transmission signals in air and soil environments, propagation techniques using Inhomogeneous Media have proven successful in [36]. To enhance the induction transfer coefficient, optimization of the coupling mechanism is performed [37]. Furthermore, although it is still a concept, where the Multi-Coil Antenna is assumed to be a matrix representing the channel width of communication that can be varied using spatial diversity configurations, such as matrices (1×1, 2×2, 4×4, 8×8), etc. [38] (see Figure 4).

In addition to using coupling techniques, the FSK approach can also be employed to enhance the power and data reception on MI receiver antennas with only single pairs of coils [39]. Electrodynamic Wireless Power Transfer (EWPT), another term for MI-based WPT, is engineered in such a way that it can be applied to materials like Conductive Silver Inks CI-1036 and PE-872, allowing them to be printed on thin film layers [40]. The concept of wireless power reception in Internet of Things (IoT) devices has proven to be optimal with a distributed or simultaneous sender node model [41]. The engineering of MI antenna materials even drives the

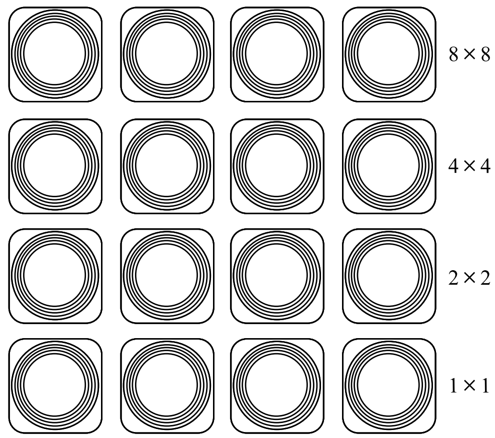

FIGURE 4. Multi-coil antenna with matrix spatial diversity configuration (1×1, 2×2, 4×4, 8×8) etc.

implementation of WPT to a higher level, including its application in pacemakers, making it wearable and even implantable into the body [42], [43]. EWPT combined with a Rotating Magnet Receiver (RMR) has also proven to stabilize the reception of induction-based power transmission [44]. Additionally, as explained in [45], a key technology in WPT lies in the Rectifying Antenna (Rectenna), which is a special type of antenna designed to convert electromagnetic waves, especially microwaves or millimeter waves, into electrical energy that can be used. The Rectenna functions as both a receiving antenna and a rectifier in one unit, where Beam Collection Efficiency (BCE) plays a key role in the efficiency of Microwave Wireless Power Transmission (MWPT) [46]. Even electromagnetic transmission can propagate through concrete material close to metal [47]. Furthermore, based on [48], we assume that the propagation of Electromagnetic signals is feasible in UWSN through the ocean floor layer, as a similar approach has been successfully applied in the model of Wireless Underground Sensor Networks (WUSNs) [48].

Furthermore, Yu et al. [49] adopted the Mixed Coupling technique by combining Magnetic Coupling and Electric Coupling. This technique has proven to enhance the efficiency of wireless power transfer. In the subsequent stage, Kumar et al. [50] proposed the development of a Multi-Layer Coil Antenna. This concept differs from other approaches as it not only arranges coils in rows but also layers them. If this concept is successfully implemented, it could lead to the development of MI antennas with a Hybrid model (Multi Coil and Multi Layer), as illustrated in (Figure 5).

C. ACOUSTIC

Acoustic Underwater-WPDT refers to a wireless communication method that uses sound or acoustic waves to transfer power and data between devices in an underwater environment. In this scenario, sound waves are employed as the transmission medium to convey energy and information. The process involves using the sound waves generated by the transmitting device to transfer power or data to the receiving

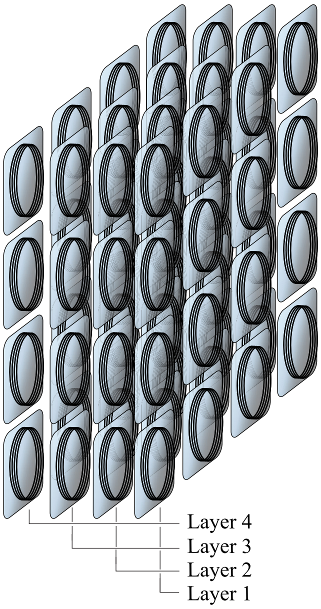

FIGURE 5. Hybrid MI antenna concept (multi coil and multi layer).

device. This method is commonly used in underwater environments because sound waves can propagate well through water, which has different transmission properties compared to air. These sound waves can be utilized to power devices, transmit data, or both. Furthermore, in [13], Underwater Acoustic Communication (UAC) is mentioned to achieve variable distances ranging from 1000 m to a maximum of 8000 m, depending on channel conditions. Utilizing Ultrasonic Piezoelectric (UP) transmitter-receiver antennas, Basaeri et al. [14] successfully applied it for power transfer to Implantable Medical Devices (IMDs) with a successful transmitted power percentage of 86 percent. By implementing a multi-hop AUV-based power and data collection scenario, Yan et al. [15] succeeded in enhancing energy balance, minimizing delays, ensuring connections to the Underwater Acoustic Sensor Network (UASN), and allowing AUVs to operate longer underwater, where the energy collection model can be expressed in the equation:

$$\min \Sigma_j \Sigma_{k\in\mathcal{N}_j} \left(\frac{E_{cos,j}(t)}{E_{res,j}(t)} + \frac{E_{cos,k}(t)}{E_{res,k}(t)} \right) \tag{3}$$

With the condition $0 < E_{res,j}(t) \leq E_{max}, 0 < E_{res,k}(t) \leq E_{max}, \forall j = j, k \in \mathcal{L}_i$, where $E_{cos,j}(t) \in \mathcal{R}^+$ and $E_{cos,k}(t) \in \mathcal{R}^+$ represent the energy consumption required to transmit a packet at time t, defined by (4). $E_{res,j}(t) \in \mathcal{R}^+$ and $E_{res,k}(t) \in \mathcal{R}^+$ indicate the remaining energy of node j and node k at time t, respectively. $E_{max} \in \mathcal{R}^+$ is the maximum energy stored in each sensor node, and $\mathcal{N}_i$ represents the set of sensor nodes around sensor j according to the network topology.

$$E_{cos} = 4\pi l^2 10^{\frac{\mathrm{SL}-20\log l_{\#}-\alpha l_{\#}\times 10^{-3}-\mathcal{A}}{10}} T_{tx} \tag{4}$$

where l is the distance from the sensor to the next step node, $SL \in \mathcal{R}^+$ is the sonar source level, $l_{\#}$ is the transmission loss range, α is the absorption coefficient in dB/km, $\mathcal{A}$ is the transmission loss anomaly that accounts for multipath propagation, refraction, and other phenomena, and T_{tx} is the transmission time required for a single packet.

In another study [16], Yang et al. highlight the potential use of Underwater-WPDT for sharing Marine Renewable Energy (MRE) generated from harvesting (i.e., wave, tidal or ocean current, thermal gradient, and salinity gradient). Furthermore, in the research by Bakhtiari-Nejad et al. [17], contactless Ultrasonic Acoustic Energy Transfer (UAET) using an Acoustic Hologram excited by an Acoustic Source Transmitter is introduced, then received by a Piezoelectric Receiver (see Figure 6), where the transmission coefficient for the wave vibrating the double-layer system is written as:

$$T_n = \begin{bmatrix} \cos(k_n t_n) & jZ_n \sin(k_n t_n) \\ \frac{j\sin(k_n t_n)}{Z_n} & \cos(k_n t_n) \end{bmatrix} \tag{5}$$

where T_n is the transfer matrix for the n-th material layer with acoustic impedance Z_n and thickness t_n, with one of the layers being an acoustic hologram, and k_n is the wave number in the n-th material. The equivalent transfer matrix for the n_{layer} system is obtained by defining $T^{\text{eq}} = T_1 T_2 \cdots T_{n-2}$.

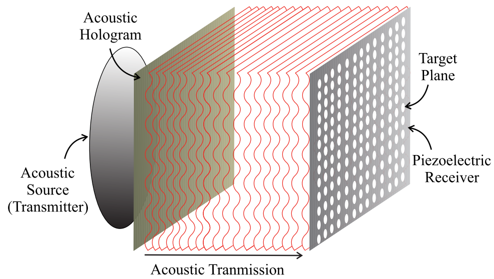

FIGURE 6. Ultrasonic Acoustic Energy Transfer (UAET) uses an Acoustic Hologram sending antenna and a piezoelectric receiving antenna.

Furthermore, Aslam et al. [18] introduced the concept of Parallel Energy Harvesting (PEH) assisted by Reinforcement Learning (RL), referred to as the C-SARSA mechanism. In contrast, Mohsan et al. [19] highlighted the advancements in Underwater-WPDT and its applications, particularly in the underwater charging and docking system for AUVs. Similar to wireless induction charging systems, in acoustic charging systems using Piezoelectric, the propagation through metal-based media is possible. This is related to the efficient transmission of ultra vibrations generated by the device, which propagates well in rigid or hard materials [20]. Zhuo et al. [51] introduced a route design algorithm for underwater data collection missions termed AUV-Aided Energy Efficient Data Collection (AEEDCO). The basic working principle involves clustering head nodes in the UWSN. Liu et al. [21] highlighted developments in Underwater Acoustic Sensor Networks (UASN), focusing on topology and its correlation with energy efficiency in UWSN as a whole. The positive correlation implies that the UWSN network topology influences the power efficiency of UASN.

Furthermore, in [22], the proposal of using cross-layer design to extend the lifespan of UWSN is suggested. In contrast, Shen et al. [23] optimized acoustic signals using Cooperative Routing based on Q-learning/Q-routing in the Underwater Optical-Acoustic Hybrid Wireless Sensor Network (Underwater-OAH-WSN). The hybrid concept was also introduced by Ibrahim et al. [52], comparing induction-based vibration transmission with ultrasonic vibration transmission. This comparison was made based on Power Transfer Efficiency (PTE) and Power Delivered to the Load (PDL) parameters, and they also explored the integration of both methods for optimal transmission. Qu et al. [53] simulated cross-medium Water-Air transmission by combining Acoustic Wave and Millimeter Wave, using a simple mathematical approach. Assuming that the incoming sound pressure is p_i and the arrival angle is 0°, the change in the initial position on the free water surface can be expressed as:

$$g(x) = \frac{2p_{\mathrm{i}}}{\omega\rho c}\cos kx \quad (t = 0, z = 0) \tag{6}$$

where ρ represents the water density, and k represents the wave number of micro-amplitude surface waves. The origin point of the illustrated coordinate system is the center of vibration, and the XOY coordinate plane represents the ideal calm water surface, where z is the vertical axis, and x and y are the two horizontal axes.

Instead of using a single-direction hydrophone, Liu et al. [54] proposed the use of Full-Duplex Directional Medium Access Control (MAC) in UWSN, incorporating operational Directional Transmission with Omnidirectional Reception (DO/OD). The operation of the Full Duplex Directional Transmitter or Vector Hydrophone system can be described by the following equation:

$$p(t) = s(t) \tag{7a}$$

$$v_x(t) = s(t)\cos\theta \tag{7b}$$

$$v_y(t) = s(t)\sin\theta \tag{7c}$$

In this context, $s(t), \theta$ represent the sound pressure and spatial position of a signal, while $v_x(t)$, $v_y(t)$ denote the orthogonal velocity components in the plane. Thus, the integrated velocities $v_h(t)$ and $v_s(t)$ are obtained by combining both components in the plane, as follows:

$$v_h(t) = v_x(t)\cos\phi + v_y(t)\sin\phi \tag{8a}$$

$$v_s(t) = v_x(t)\sin\phi - v_y(t)\cos\phi \tag{8b}$$

Meanwhile, to describe the working mechanism of a multi-modal transducer or omnidirectional reception, it is expressed in the equation:

$$\left.\frac{p(\theta)}{p(0}\right) = \frac{A_0 + A_1\cos\theta + A_2\cos 2\theta}{A_0 + A_1 + A_2} \tag{9}$$

where $p(\theta)$ is the radiation pattern function, θ is the pattern angle, and A_i is the weighting function for the i-th operating mode normalized by $A_0 = 1$.

Similar to the concept of MI multi-coil and multi-layer antennas, piezoelectric devices as acoustic transmission antennas can be designed in a similar manner. This is as revealed by Vinnakota et al. [55] in their research, where they designed a Rectifier Antenna for Wireless Power Transfer (WPT) using the Luneburg lenses principle, which is employed to capture micro-waves using metamaterial/metasurfaces.

D. OPTIC

Underwater optic wireless power and data transfer refer to a wireless communication method that utilizes light or optical waves to transfer power and data between devices in an underwater environment. In this context, laser beams or visible light can be used as a transmission medium to convey energy and information between devices. The process involves using light as an energy source or signal carrier to transfer power or data from the transmitting device to the receiving device. This method may include the use of technologies such as light modulation or frequency modulation to convey the required information. Furthermore, Hajimiri et al. [24] proposed Generation Units (GU) and Recovery Units (RU), which are alternative terms for Optical Transmitter-Receiver designed to minimize data loss in scattered or unfocused light (see Figure 7).

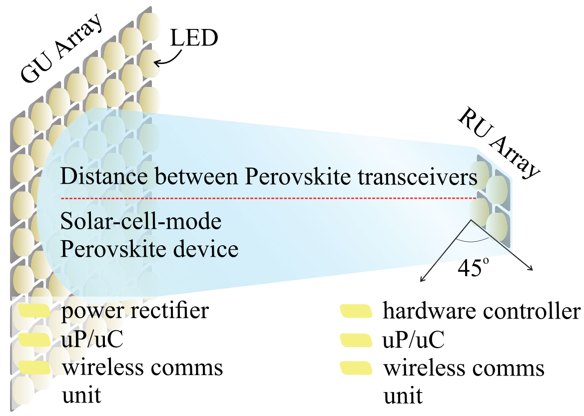

FIGURE 7. An 8 × 8 Generation Unit (GU) array, with a total of 64 units, faces a 2 × 2 Recovery Unit (RU) array, comprising 4 units, at a 45° angle, displaying a conceptual field profile at focus. The caption below illustrates an architecture that allows for a power trade-off between GU and RU.

Furthermore, according to Nguyen et al. [25], the Perovskite method can be used to calculate the optical transmission gain using Light Emitting Diode (LED), and its equation is expressed as follows:

$$H(0) = \begin{cases} \dfrac{(m_l + 1)A}{2\pi d^2}\cos^{m_l}\phi\, g_f(\varphi)\, g_c(\varphi)\cos\varphi : 0 \le \varphi \le \varphi_w \\ 0 : \ \varphi > \varphi_w \end{cases} \tag{10}$$

where A is the physical area of the optical receiver, d is the optical transmission distance, φ is the incident angle (i.e., the angle at which the receiver views the transmitter), ϕ is the radiation angle (i.e., the angle at which the transmitter views the receiver), $g_f(\varphi)$ is the optical filter gain, $g_c(\varphi)$ is the optical concentrator gain, and φ_w is the Field of View (FOV) of the optical receiver. If no optical filter and concentrator are used, their gains are omitted in Equation (10). Additionally, m_1 represents the Lambertian emission order given by the half-illumination angle $\phi_{1/2}$ of the LED as follows:

$$m_l = -\frac{\ln 2}{\ln\left(\cos \Phi_{1/2}\right)} \tag{11}$$

In the context of the Optical Wireless Power Transmission (OWPT) system, $\cos\phi = 1$ and $\cos\varphi = 1$ in Equation (10) when two Perovskite transceiver-receiver pairs are perfectly aligned (see Figure 8).

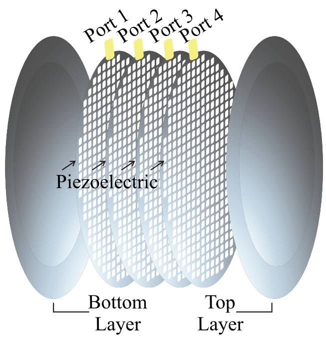

FIGURE 8. Multi-layer piezoelectric design as an antenna rectifier to capture microwaves.

The use of Micro-LED arrays is also mentioned by Arvanitakis et al. in [26] for Underwater Optical Communication (UWOC) experiments, proving its capability to provide high-speed communication in both clear and turbid-water environments. Similar to Chen et al. [27], who investigated the color spectrum of Laser Diodes (LDs), comparing the Blue LD Spectrum with the Green LD Spectrum in UWOC.

In addition to being transmitted directly through the water medium, UWOC for power transmission shows more reliable performance when utilizing fiber-optic media developed with nano-technology [28]. Furthermore, Ye et al. [29] proposed Simultaneous Lightwave Information and Power Transfer (SLIPT) as another model of Underwater-WPDT. What sets it apart is the use of a Relay Node between the Source Node and Target Node to ensure the quality of both transmitted information and power (see Figure 9 Layer 3).

Furthermore, ElAnsary et al. [30] developed a peripheral nerve interface for an integrated wireless power and data transmission system. In contrast, Tawfik et al. [31] investigated Inter-Satellite Optical Wireless Communication (IsOWC) between Geostationary Earth Orbit (GEO) satellites and Low Earth Orbit (LEO) satellites at a distance of 45,000 km.

On the other hand, Koonen et al. [32], [33] investigated the potential development of Infra-Red (IR) Beam Steering Optical Wireless Communication (OWC) for mobile devices in space. Additionally, Lemaire et al. [34] explored the possibility of using Photovoltaic Cells based on Photosdiodes to mimic the working principles of the eye's retina in capturing near-IR beams.

To maximize the Power Transmission Efficiency (PTE), Geyi [56] proposed a technique known as the Method of Maximum Power Transmission Efficiency (MMPTE). This method involves engineering Focused Antennas, Smart Antennas, Shaped Beam Antennas, End-fire Antennas, Multi-beam Antennas, Polarization-reconfigurable Antennas, and Wireless Power Transmission (WPT) systems. In contrast, Mohammad et al. [57] demonstrated 60-GHz channel transmission using Uni-Traveling Carrier-Photodiodes (UTC-PD), opening new insights into millimeter wave (MMW) transmission and the benefits of Multiple Input Multiple Output (MIMO) channels. Furthermore, de Souza and da Costa [58] provided a new understanding of Dipole-Loop Nanoantennas for nano-sized optical wireless communication. Paković et al. [59] introduced a system to shape and launch light patterns using Bessel-Gauss functions, where the Bessel function is utilized to create ring structures in the light intensity distribution, while the Gauss function provides a symmetrical intensity profile.

1) SUMMARY

In this subsection, we will carefully detail the characteristics, application scenarios, advantages, and disadvantages associated with the use of each method, namely Magnetic Induction, Acoustic, and Optical methods, in the context of power and data transfer in underwater environments. Through this comprehensive analysis, it is hoped to provide a more holistic understanding and assist in the holistic assessment of each approach (see Table 1).

2) KEY CHALLENGES

The implementation of Underwater-WPDT using MI, Acoustic, and Optical methods encounters several specific challenges. The following is a description of the main challenges that need to be addressed (see Table 2).

III. METHODOLOGY

From a comprehensive literature review, at least three main methods for power and data transfer underwater can be identified, namely MI, acoustic communication, and optical communication. These methods involve infrastructure such as UWSN and the IoUT. By summarizing the documented advantages of each method in (Table 1), studying the main challenges associated with each transmission method (Table 2), and considering that each method has its own strengths and weaknesses when facing challenging conditions in underwater depths, we propose implementing a multilayer underwater power and data distribution network. This proposal adopts a similar approach implemented in the research by Huo et al. [60], which envisions a Distributed and Multilayer Network as a future wireless power and data transmission solution for unmanned vehicles operating in aerial environments. Although facing different environmental

TABLE 1. Comparison of characteristics, application scenarios, advantages and disadvantages of MI, Acoustic, and Optic transfer methods respectively.

Research	Characteristic	Application	Advantage	Disadvantage
[1], [2], [3]	Utilize the UWSN and IoUT shared channel	MI-based Underwater-WPDT in operations involving AUVs	Can effectively transmit power and data in an underwater environment	Since most UWSN and IoUT applications use MI transmission techniques, this method has limitations in terms of limited transmission distance and angle
[4]	Underwater-WPDT optimization with shared channel system using FSK modulation	Underwater-WPDT based on MI	Can transmit power and data at the same time	The FSK technique has low transmission speed and interference from signals operating at the same frequency
[5]	MI transmission optimization with hybrid relay system	Underwater-WPDT based on MI	Can transmit power and data more effectively	Costly to implement and maintain
[6], [7]	IWPT optimization with multi-coils system formed in formation	Underwater-WPDT based on MI	Can effectively transmit power and data in an underwater environment	Has the disadvantage of limited or Line-of-Sight (LoS) dependent transmission angle
[8]	LoS optimization of IWPT with a self-adjusting antenna system for incident signal direction	Underwater-WPDT based on induction	Can effectively receive power and data transmission	Costly to implement and maintain
[9], [10], [11], [12], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48]	Omnidirectional MI optimization with combination of Fusion sensor and Coupling technique	Underwater-WPDT based on MI	Can effectively transmit power and data in an underwater environment	Has expensive implementation costs because it requires special conductive materials
[49]	IWPT optimization with Mixed Coupling technique	Underwater-WPDT based on MI	Can effectively receive power and data transmission	Has greater power requirements than Single Coupling systems
[50]	Multi Coils IWPT Optimization with Multi Layer development	Underwater-WPDT based on MI	Can effectively receive power and data transmission	Has a more expensive implementation cost than the Single Layer model
[13], [14], [15]	Utilize UASN shared channels	Acoustic-based Underwater-WPDT in operations involving AUVs	Has a distance with a fairly good transmission success percentage	Has a risk of transmission loss due to signal absorption and a longer transmission time than MI
[16], [17], [18], [19], [20], [51], [21], [22], [23], [52], [53], [54], [55]	UAET optimization using Piezoelectric antenna or Hydrophone	Acoustic-based Underwater-WPDT	Can effectively transmit power and data in an underwater environment based on acoustic vibration waves	Implementation costs are high because it requires specially designed metamaterial sender and receiver components to capture microwaves
[24], [25], [26], [27], [30], [31], [32], [33], [34], [56], [57], [58], [59]	Optic Transmitter-Receiver Optimization using Micro-LED circuit to minimize data loss from scattered or unfocused rays	Optic-based Underwater-WPDT	Optic transmission has advantages in terms of transmission speed	Has a risk of transmission loss due to optical signal absorption
[28], [29]	Optimization of optical transmission using a hybrid relay network called SLIPT	Optic-based Underwater-WPDT	SLIPT relay network ensures speed and minimizes the risk of transmission loss due to absorption	Expensive implementation costs due to the need for additional optical relay equipment and backbone networks

conditions, it is possible to adapt such an approach to underwater environments.

A. PROPOSED SOLUTION

Inspired by the successful implementation of similar networks in aerial environments [60], [61], we propose the development of an Underwater-WPDT system using a Multilayer Network approach. This approach is expected to enhance the performance of Underwater-WPDT by leveraging the synergistic interaction between various methods, as reflected in the layered network structure.

Furthermore, Liu et al. [61] provide insights into the placement of UWSN nodes in at least three positions: floating, submerged, and anchored nodes, as well as the influence of ocean waves on node positions through a virtual simulation approach, utilizing mathematical methods:

$$\overrightarrow{F_r} = \overrightarrow{F_g} + \overrightarrow{F_b} + \overrightarrow{F_w} \tag{12}$$

where $\overrightarrow{F_r}$ is the pulling force of the anchor chain to the node. $\overrightarrow{F_g} = \rho V_s g$, and $\overrightarrow{F_g}$ represents the gravitational force. Here, ρ and V_s indicate the density and volume of the node, and g is the acceleration due to gravity. $\overrightarrow{F_b} = \rho_w V_s g$, and $\overrightarrow{F_b}$ represents the buoyant force, which is equivalent to the weight of the displaced fluid (Archimedes' principle). ρ_w is the average density of saltwater. $\overrightarrow{F_w} = -0,5 A_{R\rho} c \overrightarrow{v_w}$, and $\overrightarrow{F_w}$ represents the fluid resistance force, influenced by the cross-sectional area of the node A_R, the average density of

TABLE 2. The main challenges faced by each transmission method (MI, Acoustic, and Optical).

Transmission Method	Key Challenges
MI Underwater-WPDT	MI can experience significant attenuation in water which can limit the effective distance of power transfer
	The presence of conductive materials in the water can cause interference with the magnetic field and reduce the power transfer efficiency of MI
	MI bandwidth limitations can limit the ability to transfer data at high speeds, which is a constraint for applications that require fast data communication
Acoustic Underwater-WPDT	Sound waves are subject to attenuation and propagation in water which results in reduced distance and speed of acoustic signal transmission
	Noisy underwater environments can make it difficult to detect and transmit acoustic signals
	Changes in water layers and ocean floor structure can cause multipath fading and distortion of acoustic signals, which can affect communication reliability and power transfer
Optic Underwater-WPDT	Light waves can be absorbed or scattered by particles in water which can result in reduced distance and clarity of optical transmission
	Light cannot penetrate water over great distances, so optical communication is often limited to underwater environments of a certain depth
	Turbulent water conditions can cause obstacles to light propagation and affect the performance of optical communications

saltwater ρ_w, the shape resistance parameter of the object c, and the velocity of the ocean current $\overrightarrow{v_w}$.

Therefore, we propose the implementation of a multilayer network in the underwater environment by adopting [61]. In this approach, there are at least three main positions for placing transmission nodes: an anchor position on the ocean floor, a submerged position in the middle, and a floating position on the water surface. Furthermore, we adapt concepts from [19], [48],and [53], with the possibility of adding three additional node placement positions: in the underwater ocean floor environment (aligned with signal propagation [48]), in the underwater layers to utilize acoustic vibration transmission (millimeter-wave) [19], and in the air layers to support cross-boundary communication applications [53]. This multilayer approach is designed to overcome the limitations of MI, Acoustic, and Optical transmission in the underwater environment, which is susceptible to signal absorption and propagation issues.

For MI, the Inductive Wireless Power Transfer (IWPT) system will be implemented following the model proposed by Al Sinayyid et al. [7] through the use of IoUT Multi Coil nodes. Li et al. [8] developed Multi Coil nodes that can adapt to the direction of the incoming signal, while Guo and Ofori [36] enhanced Multi Coil transmission by introducing spatial diversity. Kisseleff et al. [48] revealed the possibility of electromagnetic wave propagation in UWSN through the ocean floor layers. Kumar et al. [50] advanced the development of Multi Coil Antennas into Multi Layer configurations.

In the Acoustic Communication approach, this technique will be used to transfer energy and information through sound waves at specific frequencies. Evaluation will be conducted on the maximum range, transfer speed, and energy availability in underwater scenarios. This aligns with the model presented by Bakhtiari-Nejad et al. [17], who introduced the contactless transmitter Ultrasonic Acoustic Energy Transfer (UAET) with a Piezoelectric receiver with an extended range. Qu et al. [53] provided insights into the possibility of cross-boundary Water-Air transmission by combining Acoustic Wave and Millimeter Wave. Liu et al. [54] designed Full Duplex Directional Medium Access Control (MAC) in UWSN, and Vinnakota et al. [55] provided insights into Rectifier Antennas for Wireless Power Transfer (WPT) using Luneburg lenses principles to capture micro transmissions using metasurface materials.

Furthermore, the implementation of Optical Communication, where underwater optical communication technology will be applied using light as the transfer medium. This aligns with what was discussed by Hajimiri et al. [24], who reviewed methods of power and data transfer using engineered light modulation and frequency. Ye et al. [29] introduced the Underwater-WPDT technique using the Simultaneous Lightwave Information and Power Transfer (SLIPT) method with the use of a Relay Node between the Source Node and Target Node.

Measurements involve evaluating data transmission speed and efficiency in underwater environmental conditions. The illustration of the developed Multilayer U-WPDT Network using the aforementioned technologies is depicted in Figure 9.

The underwater environment we envision consists of at least 6 layers. The first layer is above the water surface, including the air. The second layer is the surface layer both above and below the ship, where the AUV performs initial power charging (docking). The third layer is the bright subsurface layer (receives sufficient sunlight). The fourth layer is the dark surface layer (receives minimal sunlight). The fifth layer is the rocky coral area, which is the ocean floor. The final layer is the bottom layer of the ocean, containing moist soil.

We emphasize that in this research, there are limitations specifically related to mapping the multilayer network. We neglect the influence of depth variations, water temperature, obstructions, turbidity, seawater salinity, and their

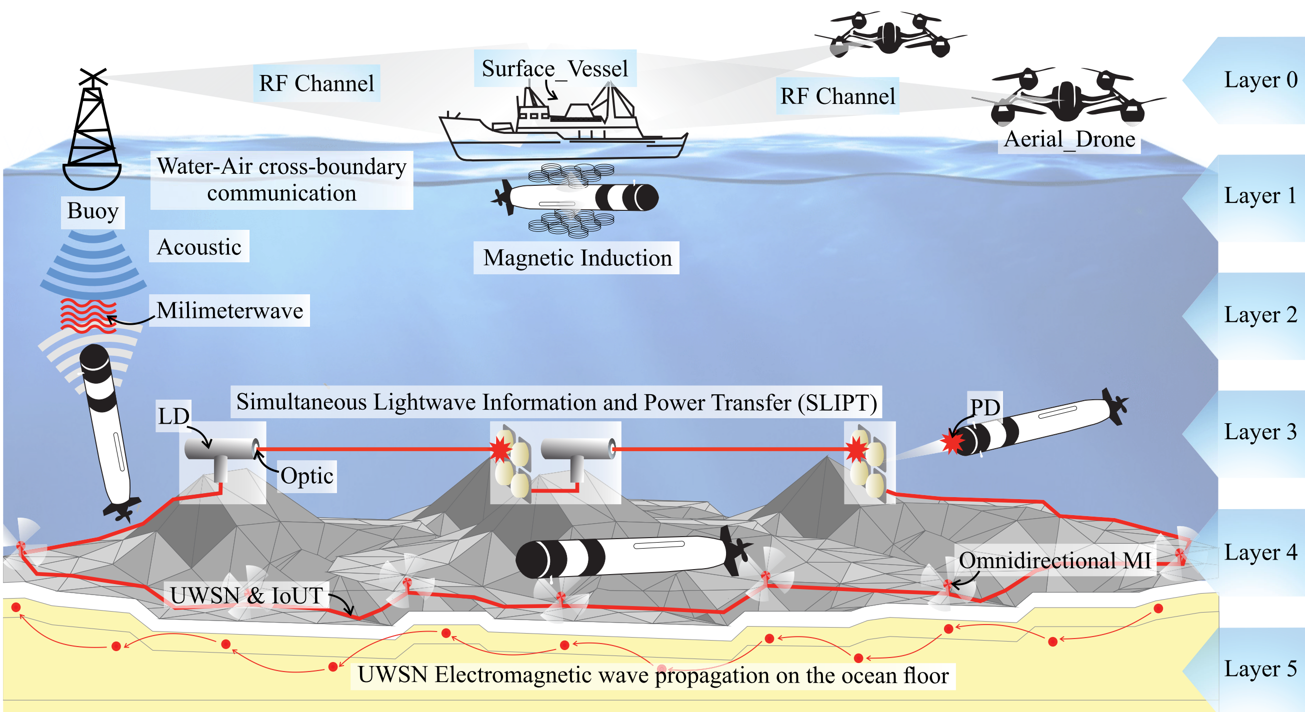

FIGURE 9. The proposed solution aims to overcome the limitations of Underwater-WPDT, where each transfer technique (MI, Acoustic, and Optic) is organized to form a multilayer network. This is based on the descriptions provided in each paper we reviewed, considering the strengths of each transfer technique to minimize their respective shortcomings.

impacts on signal transmission. These aspects will be further investigated in subsequent research or serve as topics for discussion and discourse in future studies.

Nevertheless, through the proposed research and approach we have undertaken, we believe it will still provide a comprehensive insight into the performance of the multilayer network system in the underwater environment.

B. MULTILAYER NETWORK MAPPING

The proposed multilayer network consists of 6 layers. In the top layer or the drone's airspace, buoys and surface ships communicate using Radio Frequency (RF), aligning with the research by Qu et al. [53]. Moving to the second layer, an AUV conducts power and data transfer using the MI Multi Coils technology with a docking system, similar to the study by Al Sinayyid et al. [7]. In the third layer in the bright underwater area, AUVs engage in cross-boundary communication using Acoustic and Millimeterwave communication approaches with buoys on the sea surface, consistent with Qu et al.'s research [53]. The fourth layer in the dark underwater area employs optical communication using the SLIPT approach by Ye et al. [29], where optical communication excels in transmission speed. In the fifth layer, the Omnidirectional Acoustic MI approach is utilized for UWSN and IoUT nodes, similar to Liu et al.'s research [54]. Finally, in the ocean floor layer, the potential signal propagation of MI is employed, following Kisseleff et al.'s findings [48].

C. MODEL VALIDATION

Validation of this Multilayer Network Model will utilize mathematical and computational simulations, involving the configuration of simulation parameters to simulate experimental scenarios such as water depth, transmitter power, transmitter-receiver distance, and the number of nodes in each layer. The next step involves calculating the power transfer model and data transfer efficiency. The validation process is outlined in the following steps:

1) SIMULATION PARAMETERS

Simulation parameters are set, including water depth (10 meters), transmitter power (100 Watts), and the distance between the transmitter and receiver (20 meters). The path loss exponent is determined, and the received power is calculated considering the path loss. Data transfer efficiency is introduced, and the received power is adjusted according to this efficiency.

The number of nodes in each layer is determined, and transmission speeds for different methods are defined. The code then initializes lists to store power loss values for each layer and proceeds to visualize the power loss and transmission speed for each layer using bar charts.

Furthermore, node connections are randomly determined and visualized as a connection matrix, where the color intensity reflects the strength of the connections.

2) MODEL EFFICIENCY CALCULATION

A simple analysis is conducted by calculating the total power loss and total connections between layers. Through this analysis, it is expected to gain in-depth insights into the overall performance of the multi-layer network. The formulas for calculating the total power loss and total connections between layers are as follows:

$$\text{Total Power Loss} = \sum_{i=1}^{N}\sum_{j=1}^{M} \text{Path Loss Layers}[i][j] \tag{13}$$

where N is the number of layers, and M is the number of nodes in each layer. To calculate the total connections between layers, we use the following equation:

$$\text{Total Connections} = \sum_{i=1}^{N}\sum_{j=1}^{M} \text{Connections}[i][j] \tag{14}$$

where N is the number of layers, and Connections[i][j] is an element of the connection matrix between layers, indicating whether there is a connection, denoted as (1), or no connection, denoted as (0), between nodes in layer i and layer j.

IV. RESULTS AND DISCUSSION

We assume that the positions of all nodes have been mapped, and then we design a simulation tailored to the power-data transfer method and the number of nodes involved in the communication scenario for each layer. We implement an algorithm to model the transmission between nodes and the potential power loss in each layer. Initially, the algorithm starts by initializing simulation parameters such as water depth, transmitter power, and the distance between the transmitter and receiver. Subsequently, calculations for power transfer models and data transfer efficiency are performed.

The next step is to initialize the number of nodes in each layer and the transmission method to be used for each layer. After initialization, the algorithm starts simulating power losses in each layer. In this process, power losses between nodes in each layer are calculated and simulated, with the results visualized through bar graphs in the corresponding subplots.

The simulation proceeds by generating a randomly connected matrix representing the connections between nodes in each layer. This connectivity matrix is also visualized in the form of a matrix graph. Following that, an analysis of the multilayer network is conducted by calculating the total power loss and total inter-layer connections. The analysis results are displayed on the console to provide clearer information. To offer a more comprehensive overview, the transmission speed for each transmission method is added to the labels on the power loss subplot. All subplots and connectivity matrices are then visualized in one main graph. Finally, the graphical results are displayed, and information on the total power loss and total inter-layer connections is presented on the console (See Algorithm 1).

Algorithm 1 Underwater-Wireless Power and Data Transfer (WPDT) Simulation Using Multilayer Network Approach

initialize:
$(d, P_t, r, n_{loss}, \eta_{eff})$
parameters:
$d \leftarrow 10$
$P_t \leftarrow 100$
$r \leftarrow 20$
$n_{loss} \leftarrow 2$
$\eta_{eff} \leftarrow 0.9$
calculate power loss each layer using (13)
calculate connection between nodes using (14)
display graph of power loss and transmission speed
display connection matrix

The graphs shown in the above simulation reflect the characteristics of the proposed Multi-Layer network. In this analysis, several key aspects are explained as follows:

Firstly, in the "Power Loss in Each Layer" section, each subplot at the top of the graph displays the power loss at each node in each layer. The bar lines on each subplot represent the power loss at each node in that layer, and the height of the bars indicates the extent of the power loss variation among those nodes. The color of the bars and labels on each subplot help identify the layers and associated transmission methods.

Next, in the "Connection Matrix between Layers" section, the bottom subplot shows the connection matrix between layers. Each cell in the matrix indicates whether there is a connection between nodes in a particular layer or not. The color on the matrix reflects the presence or absence of a connection, with blue indicating a connection, while white indicates no connection.

Then, in the "Total Power Loss and Total Connections between Layers" section, the console output provides information about the total power loss across the entire network, which is the sum of the power loss from all nodes in all layers. The output also includes the total connections between layers, which is the total number of connections between all layers.

Finally, the transmission speed aspect is added to each power loss subplot in the "Transmission Speed" section. The transmission speed is displayed in labels for each transmission method in a particular layer, providing additional information about how fast data can be transmitted through that transmission method.

V. FUTURE RESEARCH DIRECTIONS

Referring to the initial research that has been carried out, which involves a series of simulations to reflect the characteristics of multi-layer networks. It is possible for future research development to increase the complexity and validity of the model. One thing that can be considered is the addition of more heterogeneous parameter variations, so that it is closer to real-world scenarios.

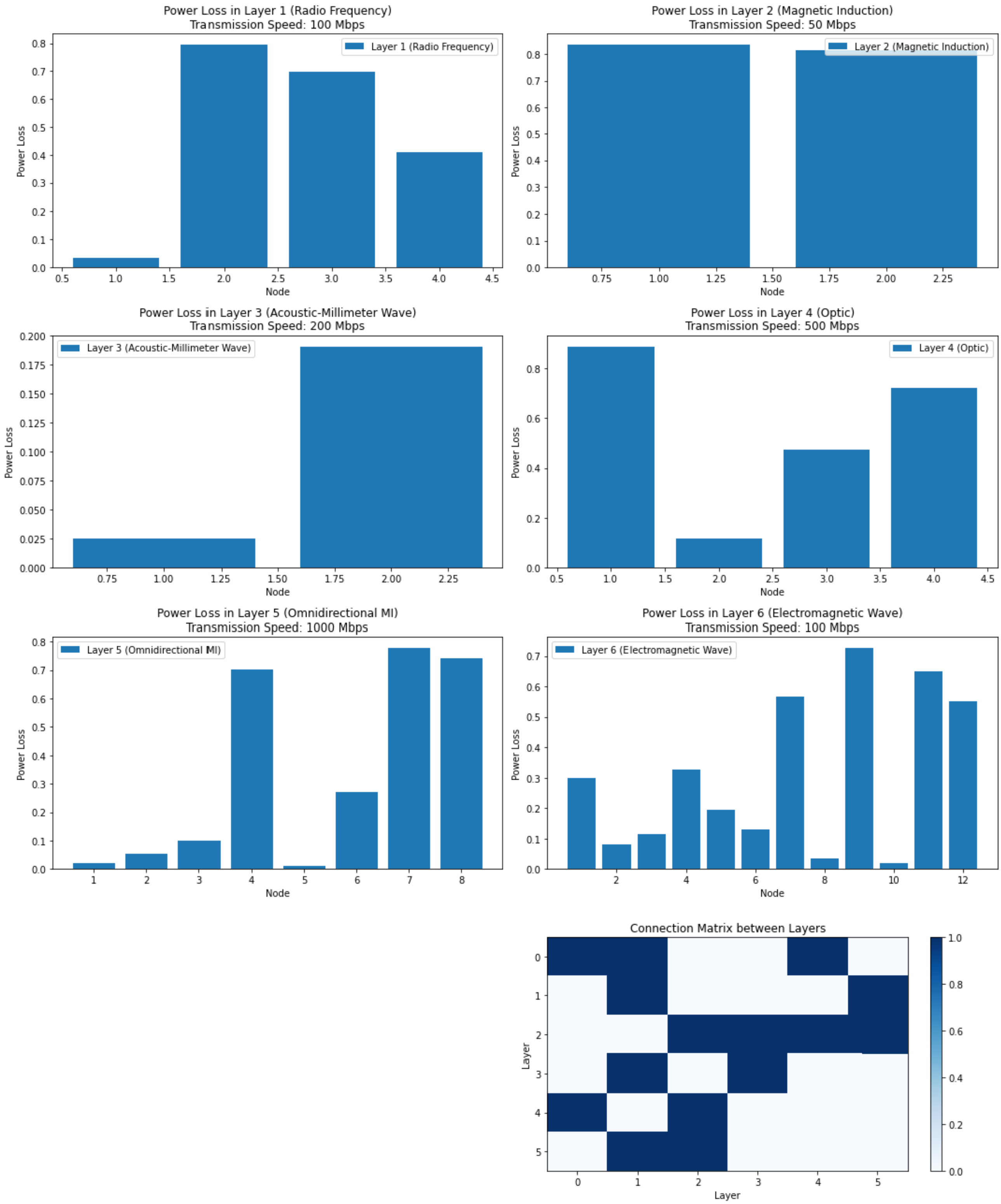

FIGURE 10. **Performance evaluation of communication scenarios for each network layer includes Layer 1 Radio Frequency, Layer 2 Magnetic Induction, Layer 3 Acoustic-Millimeter Wave, Layer 4 Optic, Layer 5 Omnidirectional Magnetic Induction, and Layer 6 Electromagnetic Wave.**

Parameters that can be included in the simulation, such as variations in depth, water temperature, obstruction, turbidity, seawater salinity, increasing the number of communication nodes and investigating their impact on signal transmission

TABLE 3. List of abbreviations.

Abbr.	Full Form
MI	Magnetic Induction
UWSN	Underwater Wireless Sensor Network
IoUT	Internet of Underwater Things
AUV	Autonomous Underwater Vehicle
U-WPDT	Underwater-Wireless Power and Data Transfer
RFID	Radio Frequency Identification
MLs	Multiple Links
APTS	Acoustic Power Transfer System
FSK	Frequency Shift Keying
AH	Acoustic Hologram
UAET	Ultrasonic Power Transfer System
R-WSN	Renewable-Wireless Sensor Network
WPT	Wireless Power Transfer
RL	Reinforcement Learning
WST	Wireless Sensor Transponder
A-AEEDCO	AUV-Aided Energy Efficient Data Collection
UASN	Underwater Acoustic Sensor Network
WPT-AD	Wireless Power Transfer at a Distance
Micro-LED	Micro-Light Emiting Diode
GaN	Gallium Nitride
UWOC	Underwater Wireless Optical Communication
SPAD	Single Photon Avalanche Diode
OFN	Optical Fiber Nanotechnology
SLIPT	Simultaneous Lightwave Information and Power Transfer
DP	Different Phase
FSO	Free Space Optical
2D-IR	Two Dimensional-Infra Red
AWGR	Arrayed Waveguide Grating Router
BMD	Big Marine Data
IWPT	Inductive Wireless Power Transfer
LCWT	Linear Coaxial Winding Transformer
LoS	Line of Sight
MCU	Microcontroller Unit
EWPT	Electrodynamic Wireless Power Transfer
RMR	Rotating Magnet Receiver
BCE	Beam Collection Efficiency
MWPT	Microwave Wireless Power Transmission
WUSNs	Wireless Underground Sensor Networks
UAC	Underwater Acoustic Communication
UP	Ultrasonic Piezoelectric
IMDs	Implantable Medical Devices
UASN	Underwater Acoustic Sensor Network
MRE	Marine Renewable Energy
OAH	Optical Acoustic Hybrid
PTE	Power Transfer Efficiency
PDL	Power Delivered to the Load
MAC	Medium Access Control
RF	Radio Frequency
GU-RU	Generation Units Recovery Units
LED	Light Emiting Diode
FOV	Field of View
UWOC	Underwater Wireless Optical Communication
LDs	Laser Diodes
IsOWC	Inter-Satellite Optical Wireless Communication
MMPTE	Method of Maximum Power Transmission Efficiency
UTC-PD	Uni-Traveling Carrier-Photodiodes
MMWs	Milimeter Waves
MIMO	Multiple Input Multiple Output

TABLE 4. Variable symbols, units, definitions used in equations.

Symbol	Explanation
M	Mutual inductance between two coils
dl_1	Infinitesimal length along the electric path for current l_1 in the first coil
dl_2	Infinitesimal length along the electric path for current l_2 in the second coil
R_{12}	Distance between each infinitesimal length dl_1 and dl_2
$\vec{H}r, 1$	Radial components of the magnetic field produced by the respective transmitting loop1
$\vec{H}r, 2$	Radial components of the magnetic field produced by the respective transmitting loop2
S	Area of the loop
k	Wave number
$\vec{a}_r$	Unit vector in the radial direction
α	Angles formed by the normal to coil 1
β	Angles formed by the normal to coil 2
E_{cos}	Energy consumption required to transmit a packet at time t
$\mathcal{R}^+$	Remaining energy of node j and node k at time t
E_{max}	Maximum energy stored in each sensor node
$\mathcal{N}_i$	Set of sensor nodes around sensor j according to the network topology
l	Distance from the sensor to the next-hop node
$SL \in \mathcal{R}^+$	Sonar source level
l	Transmission loss range
α	Absorption coefficient in dB/km
$\mathcal{A}$	Transmission loss anomaly that accounts for multi-path propagation, refraction, and other phenomena
T_{tx}	transmission time required for a single packet
T_n	Transfer matrix for the n-th material layer with acoustic impedance Z_n and thickness t_n, with one of the layers acting as an acoustic hologram
k_n	Wave number in the n-th material
ρ	Density of water
k	Wave number of micro-amplitude surface waves
$s(t), \theta$	Sound pressure and spatial position of a signal
$v_x(t), v_y(t)$	Orthogonal velocity components in the plane
$p(\theta)$	Radiation pattern function
θ	Pattern angle
A_i	weighting function for the i-th operating mode normalized by $A_0 = 1$
A	Physical area of the optical receiver
d	Optical transmission distance
φ	Angle of incidence
ϕ	Radiation angle
$g_f(\varphi)$	Optical filter gain
$g_c(\varphi)$	Optical concentrator gain
φ_w	Field of View (FOV) of the optical receiver
$\overrightarrow{F_r}$	Pulling force of the anchor chain to the node
$\overrightarrow{F_g}$	Force of gravity
ρ	Density of the node
V_s	Volume of the node
g	Acceleration due to gravity
d	Depth
P_t	Transmitter power
r	Distance
n_{loss}	Exponent of power loss
η_{eff}	Transfer efficiency

can be considered as further development of this initial research. The description of experiments that can be conducted with more heterogeneous parameter variables is briefly described as follows:

1) Depth variation: Experiments are likely to be conducted by varying the water depth and carefully recording system performance data, studying the collected data, analyzing and evaluating the effect of depth variation on power transfer and underwater data.
2) Water temperature: The test steps performed will be similar to the depth variation experiment. Where the purpose of adding water temperature variation in the experiment is to determine the effect of water temperature variation on system performance. This may include assessing power transfer efficiency, data throughput, and system stability under different temperature conditions.
3) Obstruction: In the experiment of obstruction variation and its effect on Underwater-WPDT, the steps will likely involve an experimental design that considers the type of obstruction, variation in distance between the sending and receiving devices, to study its effect on signal strength in each obstruction scenario.
4) Turbidity: Experiments are likely to be conducted by varying the level of water turbidity to study its effect on power and data transfer performance and signal strength in varying levels of turbidity.
5) Salinity of seawater: Experiments are likely to be conducted by varying the salinity level of the water by adding or subtracting salt content to the water, to study its effect on power and data transfer performance and signal strength in various salinity levels.
6) Increasing the number of communication nodes: Experiments may be conducted by placing additional communication nodes into the network and measuring the power and data transfer performance and signal strength in various network configurations. The conclusions from these experiments will provide insight into how increasing the number of communication nodes affects system performance which can be used to design more efficient and scalable networks in underwater environments.

In future research directions, we also recognize the need to consider new aspects and additional complexities to enrich the conceptual framework that has been proposed. This could involve the integration of the latest technologies, modeling of underwater environmental dynamics, as well as field experiments to validate and optimize our models. As such, we are committed to continue contributing to the development of research in this area, bringing a deeper understanding of multi-layer network systems in underwater environments.

VI. CONCLUSION

The model we propose in this study is an initial step based on the consideration of the availability of literature and tools that we currently have. Although it is still an initial study, this research opens up opportunities for further development, especially in developing network simulations at each layer by considering more heterogeneous parameter variations, and adjustments to real-world scenarios.

The focus of future research is likely to further explore the variables we have described in the previous chapter, which will likely involve increasing model complexity, developing more realistic simulations, as well as further exploration of new aspects and additional complexities that can enrich the understanding of network systems in underwater environments.

Nonetheless, through the proposed research approach, we hope to contribute innovative solutions and a more comprehensive understanding of the performance of multi-layer network systems in underwater environments.

Some sentences in this paper use abbreviations, and to assist readers in easily finding some newly abbreviated terms in the survey, we have presented them in Table 3.

Additionally, in our paper, we have included several equations to provide an understanding of the conceptual approach used. To assist readers in easily understanding the symbols used, we have presented them in Table 4.

REFERENCES

[1] M. Chaudhary, N. Goyal, A. Benslimane, L. K. Awasthi, A. Alwadain, and A. Singh, "Underwater wireless sensor networks: Enabling technologies for node deployment and data collection challenges," *IEEE Internet Things J.*, vol. 10, no. 4, pp. 3500–3524, Feb. 2023.

[2] M. Jahanbakht, W. Xiang, L. Hanzo, and M. R. Azghadi, "Internet of Underwater Things and big marine data analytics—A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 904–956, 2nd Quart., 2021.

[3] D. Wei, L. Yan, C. Huang, J. Wang, J. Chen, M. Pan, and Y. Fang, "Dynamic magnetic induction wireless communications for autonomous-underwater-vehicle-assisted underwater IoT," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 9834–9845, Oct. 2020.

[4] L. Yang, X. Li, Y. Zhang, B. Feng, J. Jian, and G. Zhao, "Underwater wireless power and data transfer system with shared channel," in *Proc. IEEE 1st Int. Power Electron. Appl. Symp. (PEAS)*, Nov. 2021, pp. 1–6.

[5] Y. Li, S. Wang, C. Jin, Y. Zhang, and T. Jiang, "A survey of underwater magnetic induction communications: Fundamental issues, recent advances, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2466–2487, 3rd Quart., 2019.

[6] C. R. Teeneti, T. T. Truscott, D. N. Beal, and Z. Pantic, "Review of wireless charging systems for autonomous underwater vehicles," *IEEE J. Ocean. Eng.*, vol. 46, no. 1, pp. 68–87, Jan. 2021.

[7] J. Al Sinayyid, H. Takhedmit, P. Poulichet, M. Grzeskowiak, A. Diet, and G. Lissorgues, "A reconfigurable coil grid for receiver localization in wireless power transfer and magnetic field steering," *IEEE J. Radio Freq. Identificat.*, vol. 5, no. 2, pp. 128–138, Jun. 2021.

[8] J. Li, Y. Yang, H. Yan, C. Liu, L. Dong, and G. Wang, "Quasi-omnidirectional wireless power transfer for a sensor system," *IEEE Sensors J.*, vol. 20, no. 11, pp. 6148–6159, Jun. 2020.

[9] L. U. Daura and G. Y. Tian, "Wireless power transfer based non-destructive evaluation of cracks in aluminum material," *IEEE Sensors J.*, vol. 19, no. 22, pp. 10529–10536, Nov. 2019.

[10] M. J. Karimi, A. Schmid, and C. Dehollain, "Wireless power and data transmission for implanted devices via inductive links: A systematic review," *IEEE Sensors J.*, vol. 21, no. 6, pp. 7145–7161, Mar. 2021.

[11] N. Ahmed, A. Radchenko, D. Pommerenke, and Y. R. Zheng, "Design and evaluation of low-cost and energy-efficient magneto-inductive sensor nodes for wireless sensor networks," *IEEE Syst. J.*, vol. 13, no. 2, pp. 1135–1144, Jun. 2019.

[12] Z. Dai, J. Wang, H. Zhou, and H. Huang, "A review on the recent development in the design and optimization of magnetic coupling mechanism of wireless power transmission," *IEEE Syst. J.*, vol. 14, no. 3, pp. 4368–4381, Sep. 2020.

[13] D. Wei, C. Huang, X. Li, B. Lin, M. Shu, J. Wang, and M. Pan, "Power-efficient data collection scheme for AUV-assisted magnetic induction and acoustic hybrid Internet of Underwater Things," *IEEE Internet Things J.*, vol. 9, no. 14, pp. 11675–11684, Jul. 2022.

[14] H. Basaeri, Y. Yu, D. Young, and S. Roundy, "Acoustic power transfer for biomedical implants using piezoelectric receivers: Effects of misalignment and misorientation," *J. Micromech. Microeng.*, vol. 29, no. 8, Aug. 2019, Art. no. 084004.

[15] J. Yan, X. Yang, X. Luo, and C. Chen, "Energy-efficient data collection over AUV-assisted underwater acoustic sensor network," *IEEE Syst. J.*, vol. 12, no. 4, pp. 3519–3530, Dec. 2018.

[16] L. Yang, J. Huang, B. Feng, F. Zhang, Y. Zhang, X. Li, J. Jian, Z. Wang, and X. Tong, "Undersea wireless power and data transfer system with shared channel powered by marine renewable energy system," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 12, no. 1, pp. 242–250, Mar. 2022.

[17] M. Bakhtiari-Nejad, A. Elnahhas, M. R. Hajj, and S. Shahab, "Acoustic holograms in contactless ultrasonic power transfer systems: Modeling and experiment," *J. Appl. Phys.*, vol. 124, no. 24, Dec. 2018, Art. no. 244901.

[18] N. Aslam, K. Xia, and M. U. Hadi, "Optimal wireless charging inclusive of intellectual routing based on SARSA learning in renewable wireless sensor networks," *IEEE Sensors J.*, vol. 19, no. 18, pp. 8340–8351, Sep. 2019.

[19] S. A. H. Mohsan, M. A. Khan, A. Mazinani, M. H. Alsharif, and H.-S. Cho, "Enabling underwater wireless power transfer towards sixth generation (6G) wireless networks: Opportunities, recent advances, and technical challenges," *J. Mar. Sci. Eng.*, vol. 10, no. 9, p. 1282, Sep. 2022.

[20] V. F. Tseng, S. S. Bedair, and N. Lazarus, "Acoustic power transfer and communication with a wireless sensor embedded within metal," *IEEE Sensors J.*, vol. 18, no. 13, pp. 5550–5558, Jul. 2018.

[21] Y. Liu, H. Wang, L. Cai, X. Shen, and R. Zhao, "Fundamentals and advancements of topology discovery in underwater acoustic sensor networks: A review," *IEEE Sensors J.*, vol. 21, no. 19, pp. 21159–21174, Oct. 2021.

[22] Y. Zhou, H. Yang, Y.-H. Hu, and S.-Y. Kung, "Cross-layer network lifetime maximization in underwater wireless sensor networks," *IEEE Syst. J.*, vol. 14, no. 1, pp. 220–231, Mar. 2020.

[23] Z. Shen, H. Yin, L. Jing, Y. Liang, and J. Wang, "A cooperative routing protocol based on Q-learning for underwater optical-acoustic hybrid wireless sensor networks," *IEEE Sensors J.*, vol. 22, no. 1, pp. 1041–1050, Jan. 2022.

[24] A. Hajimiri, B. Abiri, F. Bohn, M. Gal-Katziri, and M. H. Manohara, "Dynamic focusing of large arrays for wireless power transfer and beyond," *IEEE J. Solid-State Circuits*, vol. 56, no. 7, pp. 2077–2101, Jul. 2021.

[25] D. H. Nguyen, G. Tumen-Ulzii, T. Matsushima, and C. Adachi, "Performance analysis of a perovskite-based thing-to-thing optical wireless power transfer system," *IEEE Photon. J.*, vol. 14, no. 1, pp. 1–8, Feb. 2022.

[26] G. N. Arvanitakis, R. Bian, J. J. D. McKendry, C. Cheng, E. Xie, X. He, G. Yang, M. S. Islim, A. A. Purwita, E. Gu, H. Haas, and M. D. Dawson, "Gb/s underwater wireless optical communications using series-connected GaN micro-LED arrays," *IEEE Photon. J.*, vol. 12, no. 2, pp. 1–10, Apr. 2020.

[27] H. Chen, X. Chen, J. Lu, X. Liu, J. Shi, L. Zheng, R. Liu, X. Zhou, and P. Tian, "Toward long-distance underwater wireless optical communication based on a high-sensitivity single photon avalanche diode," *IEEE Photon. J.*, vol. 12, no. 3, pp. 1–10, Jun. 2020.

[28] H. Yu, P. Li, L. Zhang, Y. Zhu, F. Ahmad Al-Zahrani, and K. Ahmed, "Application of optical fiber nanotechnology in power communication transmission," *Alexandria Eng. J.*, vol. 59, no. 6, pp. 5019–5030, Dec. 2020.

[29] K. Ye, C. Zou, and F. Yang, "Dual-hop underwater optical wireless communication system with simultaneous lightwave information and power transfer," *IEEE Photon. J.*, vol. 13, no. 6, pp. 1–7, Dec. 2021.

[30] M. ElAnsary, J. Xu, J. S. Filho, G. Dutta, L. Long, C. Tejeiro, A. Shoukry, C. Tang, E. Kilinc, J. Joshi, P. Sabetian, S. Unger, J. Zariffa, P. Yoo, and R. Genov, "Bidirectional peripheral nerve interface with 64 second-order opamp-less $\Delta\Sigma$ ADCs and fully integrated wireless power/data transmission," *IEEE J. Solid-State Circuits*, vol. 56, no. 11, pp. 3247–3262, Nov. 2021.

[31] M. M. Tawfik, M. F. A. Sree, M. Abaza, and H. H. M. Ghouz, "Performance analysis and evaluation of inter-satellite optical wireless communication system (IsOWC) from GEO to LEO at range 45000 km," *IEEE Photon. J.*, vol. 13, no. 4, pp. 1–6, Aug. 2021.

[32] T. Koonen, F. Gomez-Agis, F. Huijskens, K. A. Mekonnen, Z. Cao, and E. Tangdiongga, "High-capacity optical wireless communication using two-dimensional IR beam steering," *J. Lightw. Technol.*, vol. 36, no. 19, pp. 4486–4493, Oct. 2018.

[33] T. Koonen, K. A. Mekonnen, F. Huijskens, N.-Q. Pham, Z. Cao, and E. Tangdiongga, "Fully passive user localization for beam-steered high-capacity optical wireless communication system," *J. Lightw. Technol.*, vol. 38, no. 10, pp. 2842–2848, May 2020.

[34] W. Lemaire, M. Benhouria, K. Koua, M. Besrour, L.-P. Gauthier, G. Martin-Hardy, T. Rossignol, S. Roy, and R. Fontaine, "Retinal stimulator ASIC architecture based on a joint power and data optical link," *IEEE J. Solid-State Circuits*, vol. 56, no. 7, pp. 2158–2170, Jul. 2021.

[35] C. Degen, "Inductive coupling for wireless power transfer and near-field communication," *EURASIP J. Wireless Commun. Netw.*, vol. 2021, no. 1, pp. 1–20, Dec. 2021.

[36] H. Guo and A. A. Ofori, "Joint channel and antenna modeling for magnetic induction communication in inhomogeneous media," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 1457–1469, 2020.

[37] J. Bao, S. Hu, Z. Xie, G. Hu, Y. Lu, and L. Zheng, "Optimization of the coupling coefficient of the inductive link for wireless power transfer to biomedical implants," *Int. J. Antennas Propag.*, vol. 2022, pp. 1–12, Jan. 2022.

[38] J. Li, F. Yin, L. Wang, B. Cui, and D. Yang, "Electromagnetic induction position sensor applied to anti-misalignment wireless charging for UAVs," *IEEE Sensors J.*, vol. 20, no. 1, pp. 515–524, Jan. 2020.

[39] J. Pan, A. A. Abidi, W. Jiang, and D. Markovic, "Simultaneous transmission of up to 94-mW self-regulated wireless power and up to 5-Mb/s reverse data over a single pair of coils," *IEEE J. Solid-State Circuits*, vol. 54, no. 4, pp. 1003–1016, Apr. 2019.

[40] K. Sondhi, N. Garraud, D. Alabi, D. P. Arnold, A. Garraud, S. G. R. Avuthu, Z. H. Fan, and T. Nishida, "Flexible screen-printed coils for wireless power transfer using low-frequency magnetic fields," *J. Micromech. Microeng.*, vol. 29, no. 8, Aug. 2019, Art. no. 084006.

[41] K. W. Choi, A. A. Aziz, D. Setiawan, N. M. Tran, L. Ginting, and D. I. Kim, "Distributed wireless power transfer system for Internet of Things devices," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2657–2671, Aug. 2018.

[42] M. Wang, H. Liu, P. Zhang, X. Zhang, H. Yang, G. Zhou, and L. Li, "Broadband implantable antenna for wireless power transfer in cardiac pacemaker applications," *IEEE J. Electromagn., RF Microw. Med. Biol.*, vol. 5, no. 1, pp. 2–8, Mar. 2021.

[43] A. Aldaoud, J.-M. Redoute, K. Ganesan, G. S. Rind, S. E. John, S. M. Ronayne, N. L. Opie, D. J. Garrett, and S. Prawer, "Near-field wireless power transfer to stent-based biomedical implants," *IEEE J. Electromagn., RF Microw. Med. Biol.*, vol. 2, no. 3, pp. 193–200, Sep. 2018.

[44] N. Garraud, A. Garraud, D. Munzer, M. Althar, and D. P. Arnold, "Modeling and experimental analysis of rotating magnet receivers for electrodynamic wireless power transmission," *J. Phys. D, Appl. Phys.*, vol. 52, no. 18, May 2019, Art. no. 185501.

[45] N. Shinohara, "History and innovation of wireless power transfer via microwaves," *IEEE J. Microw.*, vol. 1, no. 1, pp. 218–228, Jan. 2021.

[46] Q. Chen, X. Chen, and X. Duan, "Investigation on beam collection efficiency in microwave wireless power transmission," *J. Electromagn. Waves Appl.*, vol. 32, no. 9, pp. 1136–1151, Jun. 2018.

[47] R. H. Bhuiyan, Md. R. Islam, J. M. Caicedo, and M. Ali, "A study of 13.5-MHz coupled-loop wireless power transfer under concrete and near metal," *IEEE Sensors J.*, vol. 18, no. 23, pp. 9848–9856, Dec. 2018.

[48] S. Kisseleff, I. F. Akyildiz, and W. H. Gerstacker, "Survey on advances in magnetic induction-based wireless underground sensor networks," *IEEE Internet Things J.*, vol. 5, no. 6, pp. 4843–4856, Dec. 2018.

[49] T.-C. Yu, W.-H. Huang, and C.-L. Yang, "Design of dual frequency mixed coupling coils of wireless power and data transfer to enhance lateral and angular misalignment tolerance," *IEEE J. Electromagn., RF Microw. Med. Biol.*, vol. 3, no. 3, pp. 216–223, Sep. 2019.

[50] V. Kumar, R. Bhusari, S. B. Dhok, A. Prakash, R. Tripathi, and S. Tiwari, "Design of magnetic induction based energy-efficient WSNs for nonconventional media using multilayer transmitter-enabled novel energy model," *IEEE Syst. J.*, vol. 13, no. 2, pp. 1285–1296, Jun. 2019.

[51] X. Zhuo, M. Liu, Y. Wei, G. Yu, F. Qu, and R. Sun, "AUV-aided energy-efficient data collection in underwater acoustic sensor networks," *IEEE Internet Things J.*, vol. 7, no. 10, pp. 10010–10022, Oct. 2020.

[52] A. Ibrahim, M. Meng, and M. Kiani, "A comprehensive comparative study on inductive and ultrasonic wireless power transmission to biomedical implants," *IEEE Sensors J.*, vol. 18, no. 9, pp. 3813–3826, May 2018.

[53] F. Qu, J. Qian, J. Wang, X. Lu, M. Zhang, X. Bai, Z. Ran, X. Tu, Z. Liu, and Y. Wei, "Cross-medium communication combining acoustic wave and millimeter wave: Theoretical channel model and experiments," *IEEE J. Ocean. Eng.*, vol. 47, no. 2, pp. 483–492, Apr. 2022.

[54] Q. Liu, G. Qiao, S. Mazhar, S. Liu, and Y. Lou, "A full-duplex directional MAC framework for underwater acoustic sensor networks," *IEEE Sensors J.*, vol. 22, no. 14, pp. 14647–14661, Jul. 2022.

[55] S. S. Vinnakota, R. Kumari, H. Meena, and B. Majumder, "Rectifier integrated multibeam Luneburg lens employing artificial dielectric as a wireless power transfer medium at mm wave band," *IEEE Photon. J.*, vol. 13, no. 3, pp. 1–14, Jun. 2021.

[56] W. Geyi, "The method of maximum power transmission efficiency for the design of antenna arrays," *IEEE Open J. Antennas Propag.*, vol. 2, pp. 412–430, 2021.

[57] A. W. Mohammad, H. Shams, C.-P. Liu, C. Graham, M. Natrella, A. J. Seeds, and C. C. Renaud, "60-GHz transmission link using uni-traveling carrier photodiodes at the transmitter and the receiver," *J. Lightw. Technol.*, vol. 36, no. 19, pp. 4507–4513, Oct. 2018.

[58] J. L. de Souza and K. Q. da Costa, "Broadband wireless optical nanolink composed by dipole-loop nanoantennas," *IEEE Photon. J.*, vol. 10, no. 2, pp. 1–8, Apr. 2018.

[59] S. Pakovic, S. Zhou, D. González-Ovejero, S. C. Pavone, A. Grbic, and M. Ettorre, "Bessel–Gauss beam launchers for wireless power transfer," *IEEE Open J. Antennas Propag.*, vol. 2, pp. 654–663, 2021.

[60] Y. Huo, X. Dong, T. Lu, W. Xu, and M. Yuen, "Distributed and multilayer UAV networks for next-generation wireless communication and power transfer: A feasibility study," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 7103–7115, Aug. 2019.

[61] C. Liu, Z. Zhao, W. Qu, T. Qiu, and A. K. Sangaiah, "A distributed node deployment algorithm for underwater wireless sensor networks based on virtual forces," *J. Syst. Archit.*, vol. 97, pp. 9–19, Aug. 2019.

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