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Energy harvesting techniques for sustainable underwater wireless communication networks: A review

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ABSTRACT

The emergence of various underwater wireless communication systems has been on the rise due to increasing human activities in the marine environment. In underwater wireless communication networks (UWCNs), several communication devices, such as sensors and autonomous underwater vehicles (AUV) are interconnected to expand communication coverage, monitoring, information gathering, and surveillance. These devices operate on batteries, making their replacement and recharging difficult. Consequently, sustaining the operational lifetime of UWCNs is deemed a major challenge. This leads to the development of various energy harvesting (EH) techniques to perpetuate the power supply to underwater devices. In this paper, we present a review of various energy sources and EH techniques applicable to UWCNs. To achieve this, we classify the energy sources into various categories in order to establish the peculiarities of each source and the type of harvester applicable to each category. Based on this classification, we present discussions on various contributions of articles related to applications of EH techniques in UWCNs. In addition to various insights gained from the presented papers, we establish that energy harvesters based on triboelectric effect, piezoelectric effect, sediment microbial fuel cell, acoustic, and optical power transfer are suitable for low-power (milliwatt-order) consuming devices such as sensors. Also, for devices with high power consumption requirement, such as AUV, solar and inductive power transfer-based harvesters should be employed. Furthermore, we identify several technical challenges that should be taken into consideration during the planning and system design phases. Finally, we highlight open research areas that could further improve the EH and communication processes in UWCNs.

1. Introduction

With about 71 percent of the earth's surface covered by water, several human activities in this environment, such as commercial, scientific research and exploration, military operations, etc., are increasing day by day [1]. To support these various activities, efficient communication technologies suitable for the underwater environment are required. Though submarine cable-assisted communication, such as fiber optic infrastructure is considered effective, it may be restricted due to operational difficulties and expensive installation cost [2]. Fortunately, different wireless communication solutions based on acoustic, optical, magnetic induction, and radiowave propagation have proven to be efficient in the underwater environment [3]. As depicted in Fig. 1, typical examples of systems where these underwater wireless solutions are employed include underwater wireless sensor networks (UWSNs) and autonomous underwater vehicle (AUV) networks.

Interestingly, the devices in these networks are already being smartly connected on a large scale to create a scenario that can be referred to as the internet of underwater things (IoUT) [4]. However, the increase in energy consumption of different units of IoUT devices such, as sensing, processing, communication, and propulsion units, caused by long transmission distance, large data size, and harsh channel conditions remains a daunting challenge in underwater wireless communication networks (UWCNs) [5].

The conventional IoUT devices mainly rely on batteries for their operations, however, limited battery capacity remains a major bottleneck for prolonging the network lifetime. Moreover, opting for the traditional means of recharging or replacing batteries in the underwater environment is expensive and impractical [6]. One of the promising solutions to this problem is energy harvesting (EH) from the ambient environment. Though research on EH techniques in terrestrial communication systems continues to mature [7], they are not directly applicable in the underwater environment [8]. Consequently, alternative EH techniques are required for powering the IoUT devices.

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In recent years, research on EH for sustainable UWCNs has become a hot topic in the industrial and academic sectors. To this effect, several efforts have been channeled towards exploring various energy sources suitable for powering underwater communication devices. For instance, different forms of renewable energy from hydro-kinetic and biological resources are available in the marine environment. As a result, investigations in these directions have led to the discovery and development of various underwater EH systems. Therefore, in this paper, our goal is to present a review of contributions from various research articles on underwater EH techniques that apply to UWCNs.

1.1. Review of related survey articles

In this section, we present a review of notable survey articles related to EH in underwater communication networks. The contributions and a summary of these articles can be found in [9–18] and Table 1, respectively. In [9], advances in inductive wireless power transfer (IWPT)--based AUV systems are presented. The article categorizes various IWPT solutions under linear coaxial winding transformers, loosely coupled transformers and resonant IWPT systems. In each category, the design and implementation of IWPT structures are highlighted. In the latter part of the article, the effect of underwater environmental factors such as conductivity, temperature, ocean current, and biofouling are discussed. In addition, technical challenges associated with alignment and retention, docking station stability, pressure-tolerant electronic design, AUV hall design, circuit realization for power and data transfer, the effect of ambient temperature on battery charging rate, and interoperability of ducking station are also presented. In addition to the design challenges in the aforementioned study, the authors of [10], discuss the impact of coil shape, orientation, and topology on the IWPT efficiency. Moreover, the effect of frequency tracking on maintaining frequency stability is also highlighted. Furthermore, the study highlights the advantages of using multiple inductive coils to realize magnetic induction beamforming. In another related article [11], the authors focus on the relevance and various advances in magnetic coupler design, ducking methods for AUV, compensation circuit design, and evaluation of eddy current losses. In addition to the technical areas highlighted, other issues such as developing a system for accurate measurement of eddy current losses, and suppressing the effect of electromagnetic interference, are discussed. In [12], a comparative review of the effect of the AUV hull on IWPT and capacitive wireless power transfer (CWPT) systems is presented. In the paper, different hull placement models are developed. Further to this, simulation and experimentation are carried out for rectangular and curved metal plates for the hull design. Results obtained suggest that placing metal plates out of the coupler improves the power transfer efficiency. Moreover, it is established that the metal shape has a negligible effect on power transfer efficiency.

From the viewpoint of hydro-kinetic energy harvesters, the authors of [13] categorize energy harvesters into large and medium-scale, and small-scale harvesters. Further to this, the triboelectric nanogenerator (TENG) which is classified under large-scale harvester is later discussed in details due to its advantages in terms of lightweight and environmental friendliness. Moreover, design challenges such as durability of materials, large-scale wiring network, pollution control and impact on marine ecosystem are presented. However, details on the structure and operating principle of TENG are not adequately captured. To address this limitation, the authors of [14], in their study first present discussions on materials that constitute the TENG structure. Further to this, different physical and chemical techniques for improving TENG performance are highlighted. Furthermore, TENG architecture is categorized and discussed under four operating modes namely, vertical contact-separation, single-electrode, lateral sliding, and freestanding triboelectric-layer. In the latter part of the article, studies on the combination of other sources of energy with TENG to develop a hybrid TENG are presented. Also, areas of TENG applications in the marine environment such as the use of rolling spheres, multilayered-stacked TENG, and TENGs with direct water contact are highlighted. In another related article [15], the study is extended to provide an elaborate discussion on the treatment of TENG materials for performance enhancement. These treatment approaches include improving surface roughness, increasing charge density, and enhancing the hydrophobicity of nanowires conducting harvested electricity. Also, the use of biodegradable materials for system and cabling networks is highlighted to achieve an eco-friendly design. In the latter part of the article, various power management strategies for improving EH efficiency are discussed. In addition to TENG, the authors of [16], extend their investigation to electromagnetic and electroactive polymer, and hybrid harvesters. Findings from the comparative analysis of the harvesters show that the triboelectric nanogenerator is most suitable for harvesting energy from waves with low frequency and amplitude, and random motion.

While the studies in [13–16] focus on the application of TENG, the authors of [17] provide a review of different piezoelectric harvesters in ocean applications. In the article, the harvesters are categorized based on their configurations such as cantilever, diaphragm, stacked, etc. Also highlighted are the coupling modes which can be used to alter their structures to achieve a desired configuration. Further to this, the

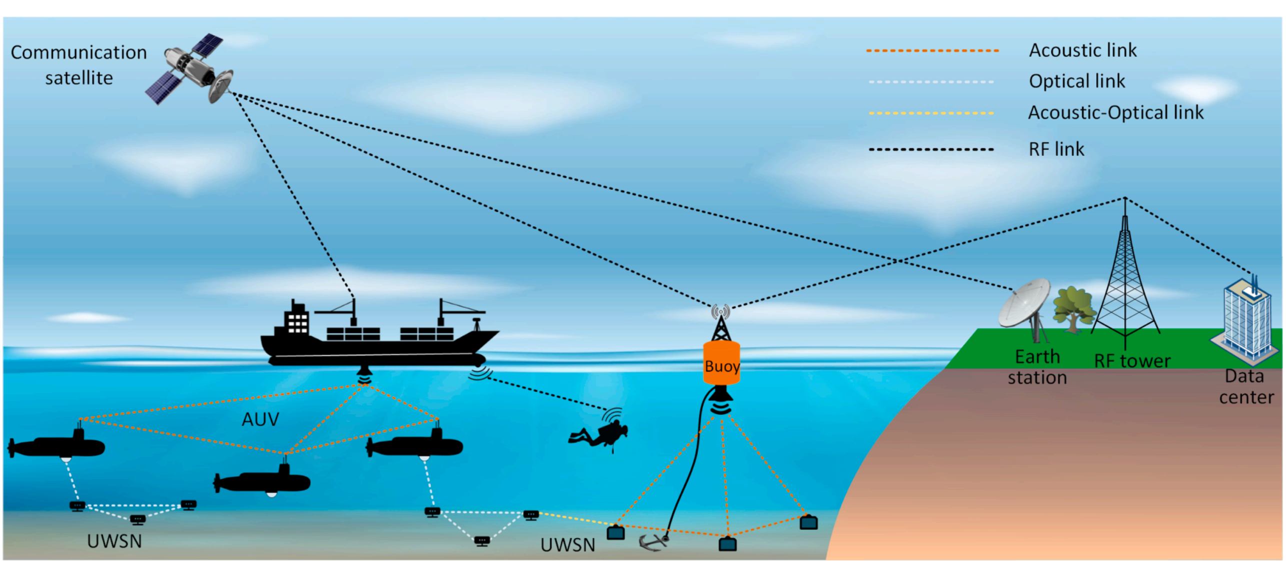

Fig. 1. Underwater Wireless Communication Networks.

Table 1
Summary of related survey articles on underwater EH in underwater communication systems.

Ref.	Main contribution	Energy sources discussed						Year
		Hydro-kinetic	MFC	Solar	Acou-stic	Optics	IPT	
[9]	Presents various IWPT solutions under linear coaxial winding transformers, loosely coupled transformers, and resonant IWPT. Furthermore, underwater environmental factors coupled with design challenges are discussed.	×	×	×	×	×	✓	2019
[10]	In addition to the impacting factors presented in [9], the effect of coil shape, orientation, and topology are discussed. Also presented is the effect of frequency tracking and the use of multiple coils for improved IWPT performance.	×	×	×	×	×	✓	2022
[11]	Focuses on relevance and various advances in magnetic coupler design, ducking methods for AUV, compensation circuit design, and evaluation of eddy current losses.	×	×	×	×	×	✓	2022
[12]	Presents a comparative review of the effect of AUV hull on IWPT and CWPT. Also, it is established in the study that the metal shape for the hull design has a negligible effect on power transfer efficiency.	×	×	×	×	×	✓	2022
[13]	Presents a broad classification of ocean energy harvesters into large and small-scale harvesters with a focus on TENG. Moreover, design challenges such as durability of materials, large-scale energy transmission networks, pollution, and impact on marine ecosystems are highlighted.	✓	×	×	×	×	×	2019
[14]	Discusses various materials that constitute the TENG structure. Moreover, physical and chemical properties for improving TENG performance are highlighted. Also, four categories of TENG are identified and discussed in detail.	✓	×	×	×	×	×	2020
[15]	In addition to contributions in [14], various treatment strategies of TENG materials for performance enhancement are discussed. Moreover, the importance of the power management system in improving EH efficiency is also highlighted.	✓	×	×	×	×	×	2021
[16]	Discusses various studies on the operating principles of TENG, electroactive polymer, and electromagnetic induction. The study concludes that TENG provides better performance under low frequency and amplitude, and random wave motion.	✓	×	×	×	×	×	2021
[17]	Provides a review of various configurations of piezoelectric harvesters. Furthermore, the operating principle of all notable solutions under each configuration is presented.	✓	×	×	×	×	×	2022
[18]	Highlights the impact of energy harvesters on marine ecosystems, socio-economic impact of ocean energy, and the related design, installation, and operation challenges.	✓	×	×	×	×	×	2022
[19]	Discusses various sources of energy and their power harvesting capabilities. Further to this, various challenges related to EH in underwater sensor networks are provided.	✓	✓	✓	✓	×	×	2022
This paper	We extend our review to capture other relevant energy sources in underwater communication systems that are not considered in the existing review article. Also provided is the operating principle of the energy conversion process under each source in the context of UWCNs. Moreover, the output characteristics of each source are established to guide the choice of harvester suitable for specific applications. Also presented is a discussion of several design challenges and open areas for future research.	✓	✓	✓	✓	✓	✓	2023

Note: All acronyms used in this Table 1 have been defined in previous texts and are also provided under list and definition of acronyms in Table 2.

working principle of notable designs under each configuration is discussed. From another viewpoint, the authors of [18] highlight the impact of ocean harvesters on marine ecosystems, the socio-economic impact of ocean energy, and the challenges associated with the design, installation, and operation of EH systems. Different from [9–12] and [13–17], where IPT and hydro-kinetic energy are the center of focus, respectively, the article [19], considers various energy sources such as water temperature gradient, solar, microbial fuel cell (MFC), AUV flywheel, turbine, and acoustic signals. Several challenges, such as low power output from energy sources, complex circuit design, the intermittent nature of natural energy sources, and so on, are discussed.

1.2. Motivation and contributions

To fully comprehend the theory and application of EH in UWCNs, it is pertinent to have a background understanding of various EH techniques applicable to UWCNs. These include the operating principles, output characteristics in terms of harvested power, power transfer efficiency, and their integration with wireless communication systems. Though the aforementioned survey papers highlight areas of application and technical challenges of the energy sources presented, detailed discussion and advances in underwater communication systems that can support simultaneous data and power transfer are not adequately captured. Therefore, we aim to bridge this gap by providing the following contributions.

- We present an overview of various energy sources and EH techniques applicable to UWCNs in order to have a background understanding of their operating principles. Unlike other review articles, we extend our discussion to underwater communication systems with a dual function of wireless power and data transfer. These systems include acoustic, optical and inductive systems. In this regard, we establish the synergy between various components of energy harvesting and communications units.
- Based on the proposed EH classification structure, we present a detailed review of various contributions toward EH in order to provide insights into state-of-the-art research, technical challenges, and solution approaches adopted. Further to this, we highlight various experimental works where maximum EH output is achieved. This is needed to guide the selection of energy harvesters suitable for a specific application.
- Based on the insights gained from the presented articles, we identify various challenges that need to be considered in order to aid a realistic and optimal design of the EH system. Lastly, we highlight open research areas that can be explored for improved EH in underwater environments.

The rest of the article is structured as follows: In Section 2, we present the classification structure and detailed description of various EH techniques in UWCNs. In Section 3, we provide a detailed review of notable articles on EH in UWCNs. Lessons learned from the reviews are provided in Section 4. Design challenges and research directions are discussed in Sections 5 and 6, respectively. Conclusions are drawn in Section 7. The list and definition of all acronyms used frequently throughout this article are provided in Table 2.

Table 2
List and definition of acronyms.

Acronym	Full meaning
AC	Alternating current
AP	Access point
AUV	Autonomous underwater vehicles
ADS	AC-to-DC separation
ARQ	Automatic repeat request
BER	Bit error rate
CEC	Charge excitation circuit
C-NOMA	Cooperative non-orthogonal multiple access
CSI	Channel state information
CSK	Colour shift keying
CWPT	Capacitive wireless power transfer
DC	Direct current
DDPG	Deep deterministic policy gradient
DQN	Deep Q network
EH	Energy harvesting
FD	Full duplex
FTENG	Freestanding triboelectric nanogenerator
FPGA	Field programmable gate arrays
GaN	Gallium nitride
HD	Half duplex
ID	Information decoding
IoUT	Internet of underwater things
IPT	Inductive power transfer
IWPT	Inductive wireless power transfer
LD	Laser diode
LED	Light emitting diode
LSTENG	Lateral-sliding triboelectric nanogenerator
MFC	Microbial fuel cell
NOMA	Non-orthogonal multiple access
OFDMA	Orthogonal frequency division multiple access
PAPR	Peak to average power ratio
PCB	Printed circuit board
PD	Photodetector
PEH	Piezoelectric harvester
PEM	Proton exchange membrane
PMS	Power management system
PS	Power splitting
PQC	Post quantum cryptography
RIS	Reflecting intelligent surface
SPAD	Single Photon Avalanche Diode
SETENG	Single-electrode triboelectric nanogenerator
SLIPT	Simultaneous lightwave information and power transfer
SPDT	Simultaneous power and data transfer
SWIPT	Simultaneous wireless information and power transfer
TENG	Triboelectric nanogenerator
TS	Time switching
UWSN	Underwater wireless sensor networks
UWCN	Underwater wireless communication network
VCTENG	Vertical contact-separation triboelectric nanogenerator
VLC	Visible light communication
WPT	Wireless power transfer

2. Classification of EH techniques in UWCNs

The EH techniques employed in UWCNs can be broadly classified into two categories based on the source of energy. These sources include the ambient natural environment and man-made wireless communication signals. These sources can further be categorized, as depicted in Fig. 2.

In the following, we present the operating principle of each technique in the context of UWCNs.

2.1. EH from natural environment

The water environment consists of various types of energy sources that can be utilized for different applications. An example of this type of energy is the hydro-kinetic energy generated from ocean waves, tides, and vibration. Other energy sources include microbial fuel cell (MFC) and solar irradiance. In the following, we present an overview of each technique.

2.1.1. EH from hydro-kinetic energy

Energy harvesting from ocean heaving and rotating waves constitutes one of the well-established means of generating electricity for maritime applications, and several technologies in this direction have been developed over the years. These technologies can be broadly categorized under oscillating water column, oscillating body column, and overtopping [20]. Though some of these technologies are known to provide the highest output energy compared to other types of sources, [21,22], they rely on cable infrastructure for their power transmission. Consequently, this may limit the scalability of the network, especially in the case of mobile nodes such as AUVs. However, due to the need for the expansion of deep water exploration, other types of wave harvesters that are robust to low-frequency, low-amplitude, and random-direction wave energy are required. Also, essential for the scalability of the underwater wireless networks is the use of lightweight energy harvesters that can easily be integrated with wireless communication devices. For these purposes, various energy conversion solutions based on the principles of the tribolelectric effect [23], and piezoelectric effect [24], have been developed and widely adopted. In the following, the operating principles of triboelectric and piezoelectric wave energy harvesters are discussed.

- Triboelectric harvester: Also known as triboelectric nanogenerators (TENGs), their operations are based on Maxwell's displacement current as given in (1) [25].

$$J_D = \frac{\partial \mathbf{D}}{\partial t} = \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \varepsilon \frac{\partial \mathbf{P}_s}{\partial t}, \tag{1}$$

where $\boldsymbol{D}$ represents the displacement field, ε is the permittivity of the

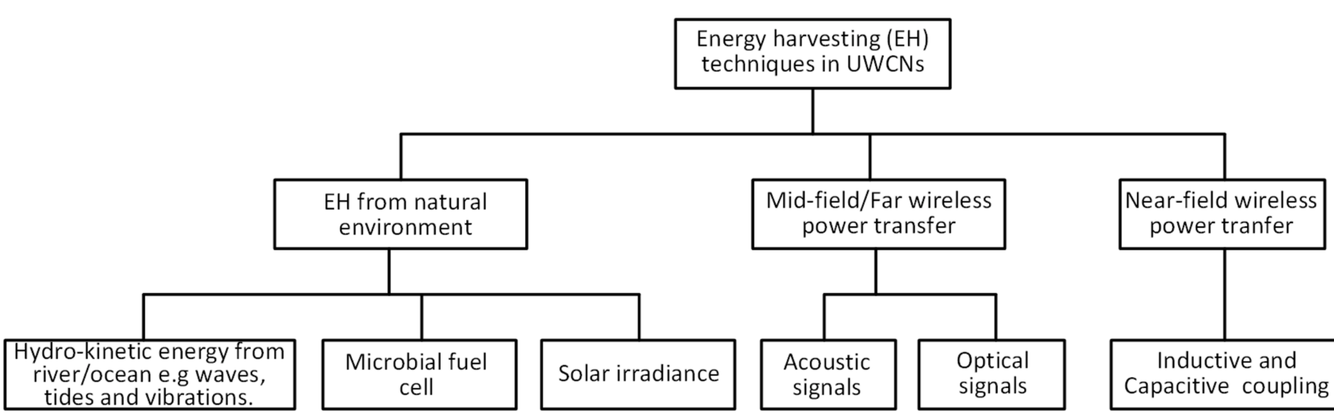

Fig. 2. Classification structure of EH techniques in UWCNs.

medium, $\boldsymbol{E}$ is the electric field, and $\mathbf{P}_s$ is the polarization created by the triboelectric effect. TENGs are broadly classified under four working modes, namely vertical contact-separation (VCTENG), lateral-sliding (LSTENG), single-electrode (SETENG) and free-standing triboelectric (FTENG) layer mode [26]. An illustration of these modes is depicted in Fig. 3.

The VCTENG mode in Fig. 3(a) comprises two dielectrics for contact electrification (based on relative vertical motion) and two electrodes each placed on the top and bottom surfaces of the dielectrics. When the dielectrics are in contact (due to the impact generated by water motion), opposite charges are induced on their surfaces. As the impact level decreases, the dielectric interface is separated again. Consequently, the potential difference generated through this process causes electrons to flow through the external load and move between the electrodes. The LSTENG mode in Fig. 3 (b) has the same working principle as VCTENG only that the relative displacement is in parallel direction to the dielectric interface [27]. In the case of SETENG mode in Fig. 3(c), it can use either the vertical or sliding movements discussed in the aforementioned modes to generate electricity. However, the structure comprises a dielectric and uses ground as the reference electrode [28]. The FTENG mode in Fig. 3(d) can be regarded as the modified SETENG except that a pair of symmetric electrodes are used instead of ground as the reference electrode. Also, a rolling object which is another triboelectric material is allowed to move freely on the dielectric placed on the electrodes. As a result, when the rolling object changes its position, asymmetric charges are induced, which provide an electrical output [29]. Details on the application of TENGS are provided in Section 3.1.

- Piezoelectric harvester (PEH): The PEH comprises a piezoelectric material coupled with a mechanical structure as illustrated in Fig. 4.

At the edge of the cantilever beam is attached a mass m_a. The cantilever beam oscillates as the ocean wave impacts the structure. Consequently, a bending (mechanical) stress along the beam is generated [30]. As a result, the piezoelectric material becomes polarized and produces a voltage between the electrodes. This working principle can be regarded as a direct piezoelectric effect. However, when a mechanical deformation is induced by connecting an electrical potential to a piezoelectric material, this case can be referred to as converse piezoelectric effect [31]. The governing equations for direct and converse piezoelectric effects are given in (2) and (3), respectively [32].

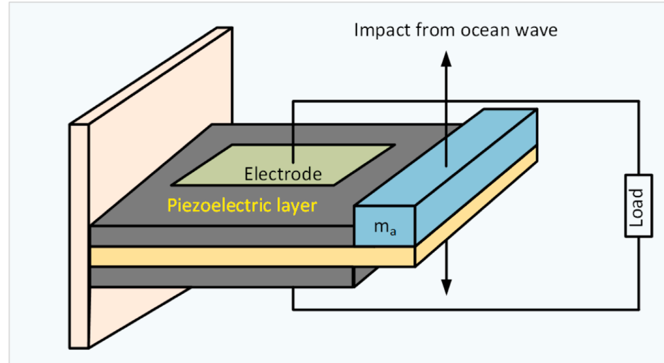

Fig. 4. Piezoelectric harvester (adapted from [16]).

$$D = dT + \varepsilon E, \tag{2}$$

$$X = sT + dE \tag{3}$$

where D is the electrical displacement, d is the piezoelectric coefficient, T is the stress, ε is the permittivity of the material, X represents the strain, and s is the mechanical compliance. Notable studies on the application of piezoelectric harvesters are also provided in Section 3.1.

2.1.2. EH from microbial fuel cell

The MFC is a bioelectrical system that uses micro-organisms such as bacteria and certain electrochemical reactions to convert chemical energy stored in biodegradable substances to electricity [33]. The MFC works based on the principles of anodic oxidation and cathodic reduction [34]. Moreover, the anodic and the cathodic compartments are separated by a proton exchange membrane (PEM) [35]. As illustrated in Fig. 5, in a typical MFC design for underwater applications, the anode is buried in the anaerobic sediment, which also acts as PEM, and the cathode is suspended in the aerobic water column above the sediment [36,37].

The bacterial metabolic activity in the sediment offers limitless

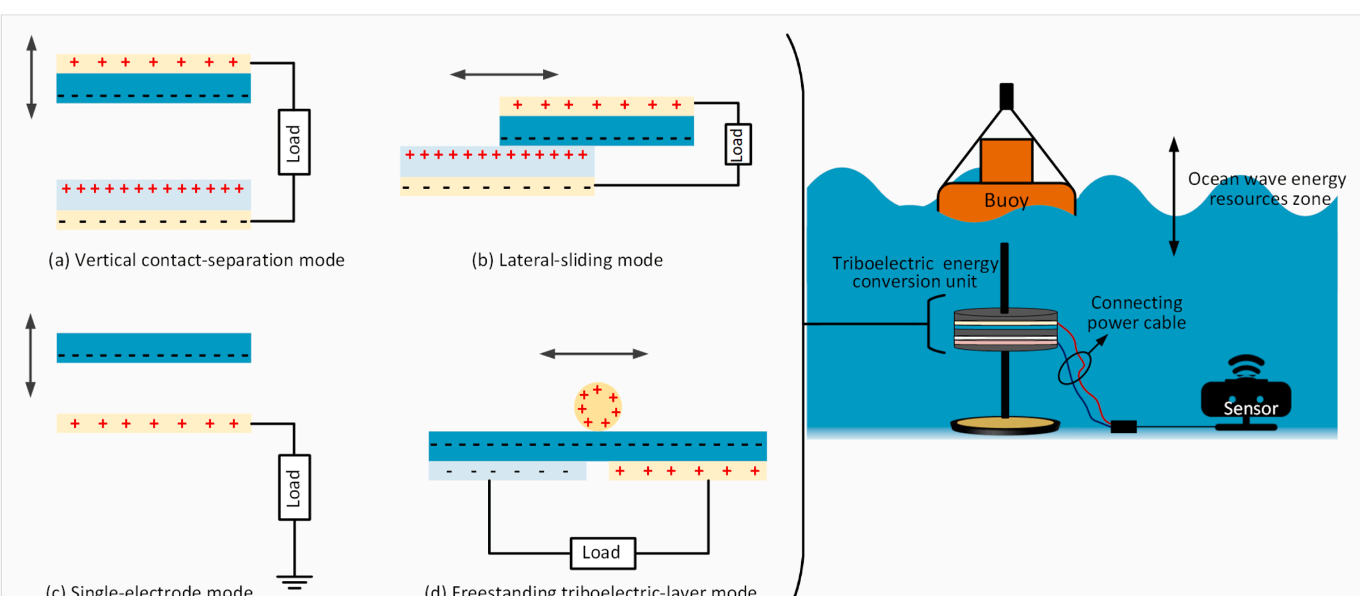

Fig. 3. Four working modes of TENG (adapted from [27]). (a) VCTENG mode. (b) LSTENG mode. (c) SETENG mode. (d) FTENG mode.

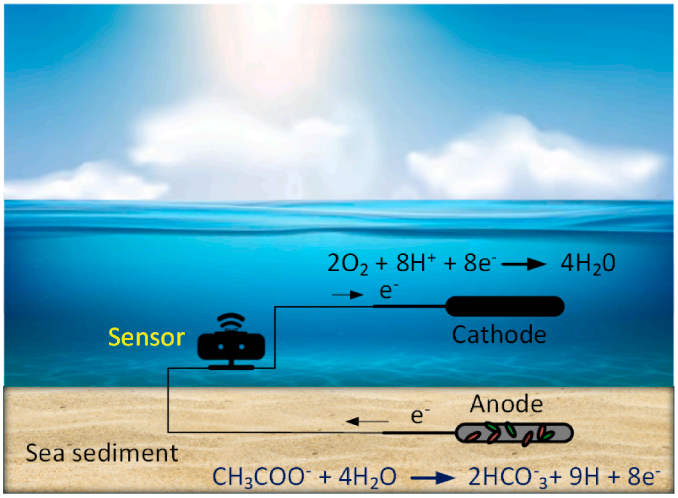

Fig. 5. Sediment microbial fuel cell (adapted from Kumar et al. [38], Algar et al. [39]).

electrons, and the oxygen gradient in the water column acts as an electron acceptor [39]. Therefore, by embedding an anode electrode in the sediment and a cathode in the overlying water surface, the two electrodes can be connected across a load to harvest the energy present in the sediment as electric current [40]. As summarized in [38], the overall reaction of the process depicted in Fig. 5 and the corresponding output voltage can be given as

$$CH_3COO^- + 2O_2 \rightarrow 2HCO_3^- + H^+ \ (emf = 1.094V) \tag{4}$$

It is noteworthy that the output potential from the sediment MFC is usually below the required operating voltage in practical circuit applications [41]. Thus, a power management system basically comprising a charge pump, supercapacitor and booster is usually incorporated into the design. The charge pump draws a low current from the source to charge the supercapacitor while the boost converter increases the output voltage from the supercapacitor [42]. Details on the application of sediment MFC are provided in Section 3.2.

2.1.3. EH from solar irradiance

Solar energy is considered impractical for powering most IoUT devices due to a rapid decline in sunlight penetration with water depth [43]. Mounting a solar panel on floating objects such as buoys is one of the practical examples of exploiting solar energy for powering IoUT devices. However, in the case of solar-powered AUVs, these devices are pre-programmed to submerge and also to operate at the surface during the daytime for battery charging [44]. For a specific operating mode (such as diving, thrust, communication, and floating modes) during a given nth time slot, the harvested power of a solar-powered AUV can be given in (5) [45], as

$$\Phi_{in,k}[n] = \xi k \Psi_{0,water}[n] \exp\left(-c z_{A,k[n]}\right).\cos\Omega[n], \tag{5}$$

where ξ is the efficiency of the solar panel, k represents the equivalent area of the solar panel, $\Psi_{0,water}$ is the intensity of light after passing through the water, c is the extinction coefficient of the water, $z_{A,k[n]}$ is the AUV depth in water, and Ω is the tilt of the solar panel. Details of studies based on the application of solar-based EH are presented in Section 3.3.

2.2. Wireless power transfer

Wireless power transfer (WPT) represents a branch of EH technology that can be classified under two categories with respect to the transmission distance; that is, the radiative far-field power transmission and non-radiative near-field [46]. Here, the energy content of the transmission signals is gleaned for charging purposes. In the context of underwater wireless communication systems, acoustic, optical, and electromagnetic signals are the main WPT techniques adopted for EH purposes. The acoustic and optical EH can be grouped under radiative far/mid-field WPT, while the inductive and capacitive EH can be categorized under near-field WPT. EH techniques based on WPT are discussed in the following.

2.2.1. EH from acoustic signals

A typical EH underwater acoustic transceiver architecture is illustrated in Fig. 6.

In this technique, the encoded data packets to be transmitted are modulated onto the carrier signals. The electrically modulated signal is then amplified to ensure that it is within a tolerable level for detection at the receiver [47]. The amplified electrical signal is converted into an acoustic signal using an electroacoustic transducer known as a projector, which projects sound waves towards the receiver via an acoustic channel [48]. Various challenges associated with acoustic channels, such as strong absorption, severe fading, rapid time variation, and extended multipath, have been addressed over the years in a bid to develop a perfect model [49]. A good review of these channel models can be found in [50,51]. The pressure variations of the acoustic signals reaching the receiver are detected by the hydrophone, which produces an output voltage proportional to the pressure [52]. The matching network minimizes the impedance mismatch between the hydrophone and the information/rectification unit such that the maximum signal power captured by the hydrophone is transferred to these units. Finally, the EH and information decoding (ID) operations are performed separately in order to avoid distortion of the information content of the signal [53]. To overcome this challenge, the partitioning methods applicable to simultaneous wireless information and power transfer (SWIPT) in terrestrial wireless communication networks, such as time switching (TS) or power splitting (PS), can be adapted for this purpose [54,55]. For a typical underwater communication device, the total power harvested from an acoustic signal can be given in (6) [56].

$$P_h^{acoustic} = (1-\beta)\zeta n \frac{10^{\frac{RL+RVS}{10}}}{4R_p}, \tag{6}$$

where β signal partitioning factor, ζ is the energy conversion coefficient, n is the number of hydrophones, RL is the received acoustic signal level transmitted from the projector, RVS is the receiving voltage sensitivity of hydrophone, and R_p is the impedance of the hydrophone. Also, the expression for the ID rate can be given in (7) [57], as

$$R_{acoustic} = \frac{\beta P_a \big/ A_o l^k a(f)^l}{N(f)\Delta f}, \tag{7}$$

where P_a is the transmission power of the acoustic projector, A_o is the unit normalizing constant, l is the transmission distance, K is the spreading factor, $a(f)$ is the absorption coefficient, $N(f)$ is the ambient noise and Δf is the receiver noise bandwidth. Details of studies based on the application of acoustic WPT are presented in Section 3.4.

2.2.2. EH from optical signals

The application of visible light communication (VLC) technology in UWCNs has proven effective in terms of high data and bandwidth efficiency thanks to the transparency of water to the blue-green region of visible light coupled with a reduced absorption window [58,59]. Energy harvesting from underwater VLC signals can be achieved via a well-established technique known as simultaneous lightwave information and power transfer (SLIPT) [61]. A typical SLIPT architecture is depicted in Fig. 7. At the transmitter, the message to be transmitted is converted into a digital signal and modulated via a modulator. Further to this, a DC bias is added to the modulating signal to ensure that a real-valued and non-negative signal is transmitted [62]. At the access

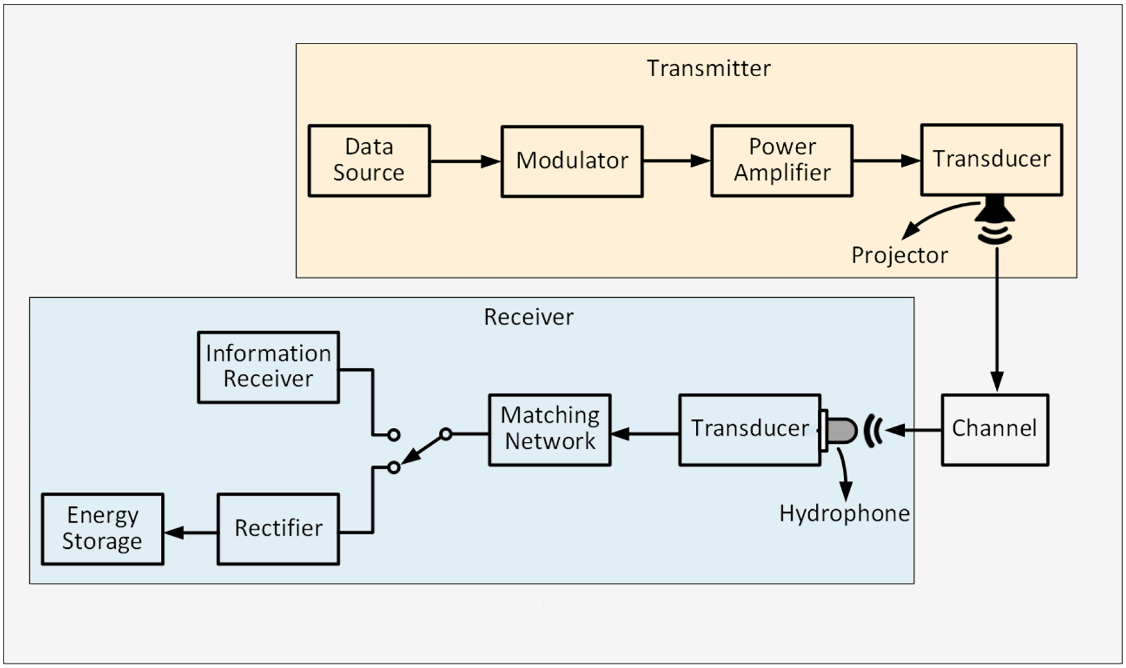

Fig. 6. Transceiver architecture of an underwater EH acoustic device.

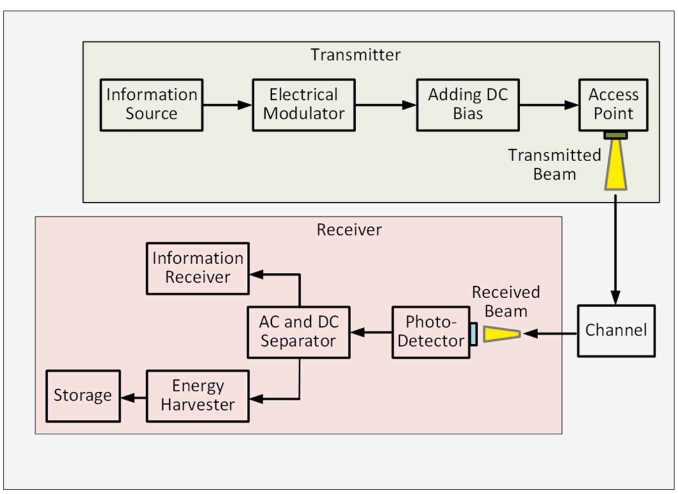

Fig. 7. SLIPT transceiver architecture [60].

point, the electrical signal is converted to an optical signal and beamed towards the receiver using a light-emitting diode (LED) or laser diode (LD) [63]. For practical system model development, it is noteworthy that the underwater SLIPT-based VLC channel plays a vital role, hence, its attributes should not be ignored. The widely adopted model is based on the Beer-Lambert formula [64], however, this model only results in an overestimation of pathloss since losses caused by scattered rays are neglected. Moreover, the water turbulence factor, which is another practical impairment is not accounted for. To address these limitations, the authors of [65] modify the Beer-Lambert model to capture the contributions of scattered photons. Also, it has been demonstrated that the Lognormal and Gamma-Gamma probability density functions can accurately model weak and moderate/strong turbulence factors, respectively [66]. At the receiver front-end, the photodetector (PD) such as solar, PIN or avalanche photodiode, converts the received optical signal back to electrical signals. Finally, the AC and DC components of the electrical signal are separated simultaneously for the ID and EH processes, respectively. This separation process can simply be achieved using a capacitor in the case of ID and an inductor in the case of EH. The reader can refer to [67], for details on other types of signal partitioning methods. For the basic AC-DC architecture depicted in Fig. 7, the expression for harvested power can be computed as given in (8) [68].

$$P_h^{optical} = f\eta h P_{LED} B V_t \ln\left(1 + \frac{\eta h P_{LED} B}{I_o}\right), \tag{8}$$

where f is the fill factor, *eta* is the photodetector responsivity, h represents the channel mode, $P_{LED} istransmissionpowerofLED$, B is the DC bias, V_t is the thermal voltage, and I_o is the dark saturation current. Also, the achievable rate over the optical communication link can be computed as given (9) [69,70]

$$R_{optical} = \frac{1}{2}\log_2\left(1 + \frac{e}{2\pi}\frac{\eta^2 |h|^2 P_{LED}}{\sigma^2}\right), \tag{9}$$

where e is the Euler's number and σ^2 is the Additive White Gaussian Noise introduced at the receiver. Details of studies based on the application of optical WPT are presented in Section 3.5.

2.2.3. Inductive and capacitive wireless power transfer:

The main technologies developed to support wireless EH in the near-field region include inductive power transfer (IWPT) and capacitive power transfer (CWPT). WPT based on the former technology relies on the principle of electromagnetic induction, while electrostatic induction is employed in the latter [71]. These techniques have been extensively investigated in the context of terrestrial communication systems, however, their application in marine environments poses challenging problems. These challenges include the effect of water dielectric conductivity on electrical parameters, coil radiation resistance and losses, water motion on the coupling gap, and the choice of operating frequency where losses are highly frequency dependent [11,72]. In recent studies, the application of inductive coupling for simultaneous power and data transfer (SPDT) has been the center of focus due to its advantages over CWPT systems. The CWPT has a low coupling capacitance that requires a lossy water medium between the plates and a high operating frequency [9]. Whereas the IWPT systems can efficiently operate at lower frequencies, thus imposing fewer requirements on the converter components [73]. An illustration of an inductive SPDT architecture is depicted in Fig. 8.

In this illustration, the power transfer process is similar to the conventional IWPT operation [74]. However, due to the integration of the data transmission unit, extra circuit components such as a frequency modulator and power amplifier are included at the transmitter side. The data is retrieved at the receiver side via the incorporation of a bandpass filter, power amplifier, and demodulator. For a system with a pair of single transmitting and receiving coils, the ratio of the received power to the transmitted power and the corresponding data rate can be given in (10) [76], and (11) [77], respectively.

$$\frac{P_r}{P_t} = \frac{\mathbb{R}\left\{Z_L|V_i|^2 \Big/ |Z_t^{'} + Z_L + Z_r|^2\right\}}{\mathbb{R}\{|V_s|^2\} \Big/ (Z_t + Z_r^{'})^*}, \tag{10}$$

where Z_L is the load impedance, V_i is the induced voltage on the secondary coil, $Z_t^{'}$ and $Z_r^{'}$ denote the reflected impedance on the transmitter and receiver sides, respectively, Z_r and Z_t represent the total intrinsic impedance of the receiver and transmitter sides, and V_s is the source voltage.

$$R_{IWPT} = \log_2\left(1 + \frac{P_T/PL_{MI}}{N_t}\right), \tag{11}$$

where P_T is the transmit power, PL_{MI} denotes the pathloss of a magnetic induction communication system, and N_t is the number of transmitter coil turns. Details of studies based on the application of IWPT are presented in Section 3.6.

3. A review of contributions to EH techniques in UWCNs

In this section, we present a review of notable studies devoted to underwater wireless communication networks with energy harvesting capability. We adopt the classification method proposed in Section 2 for the structure of our review, as presented in the following:

3.1. Energy harvesting from hydro-kinetic energy

As discussed in Section 2, the kinetic energy of water produced by waves, tides and vibrations can be harnessed to power underwater wireless communication devices. Notable studies in this direction can be found in [78–87]. A summary of these studies in presented in Table 3. In [78], the application of an FTENG-based structure as a power source for a water quality monitoring sensor is demonstrated. The main goal of the study is to increase the output power of the harvester. To achieve this, the dielectric materials in the structure are coated with a frosted acrylic substrate in order to minimize the frictional force between them, consequently the motion of the free-moving dielectric. Experimental results show that a 58% reduction in the frictional force is achieved, thus increasing the peak and average output power to 45 mW and 5.7 mW, respectively. Furthermore, a power management system (PMS) unit comprising a transformer and rectifier is incorporated into the design, leading to a boost in the short-circuit current from 650 μA to 11 mA. Nonetheless, the dielectric coating may reduce the charge density output. In [79], the application of VSTENG for monitoring the structural health of underwater pipelines is demonstrated. In the study, the bending force created by the ocean waves produce a vibrational force on the pipeline which in turn creates to the vertical motion on the VSTENG attached to the pipe. Further to this, the expression for the dynamic response of mass spring is derived in order to optimize the output performance of the system. Experimental results show that an output power and power density of 14.0 μW and 5.56 Wm^{-2} respectively is achievable. In [80], the authors propose the incorporation charge excitation circuit (CEC) to increase the charge density generated from the TENG structure. The CEC comprise two identical capacitors which are charged in parallel during the separation phase and become uncharged during the contact process. In the contact phase, the capacitor connection is similar to a series connection thereby doubling the capacitor voltage. Based on this approach, a maximum output power and power density of 28 mW and 49.3 Wm^{-2} is achieved.

In addition to the ocean wave, the use of various sources of vibrations in water for the excitation of TENGs has also been investigated. In [81], the authors propose the use of contact-separation TENG with dielectric based spherical pellets. The ultrasonic waves reaching the bottom electrode excites the negatively charged pellets which drift toward the top electrode. Experimental results show that an output power and average power conversion efficiency of 0.362 Wm^{-2} and 13%, respectively are achieved. In another related article [82], the authors developed a sectorized FTENG-based location sensor using water vibrations to stimulate the rolling body in order to generate electricity. The sensor in turn uses the detected ultrasonic signals from the vibrations to estimate the location of the vibration source. The use of the sectorized FTENG is to improve the accuracy of the angular resolution information from the the localization sensor. Aside from the maximum power density of 1.28 μW cm^{-2} obtained, an angular resolution of 15 degrees with localization accuracy of over 95% is achieved. In the study, the use of multiple rolling dielectric bodies is proposed, deriving an optimal number of these dielectrics can enhance the system's performance.

From the viewpoint of piezoelectric harvesters, the authors of [83], propose the use of water current for driving a rotating object to achieve a continue impact on on a piezoelectric cantilever beam. To achieve

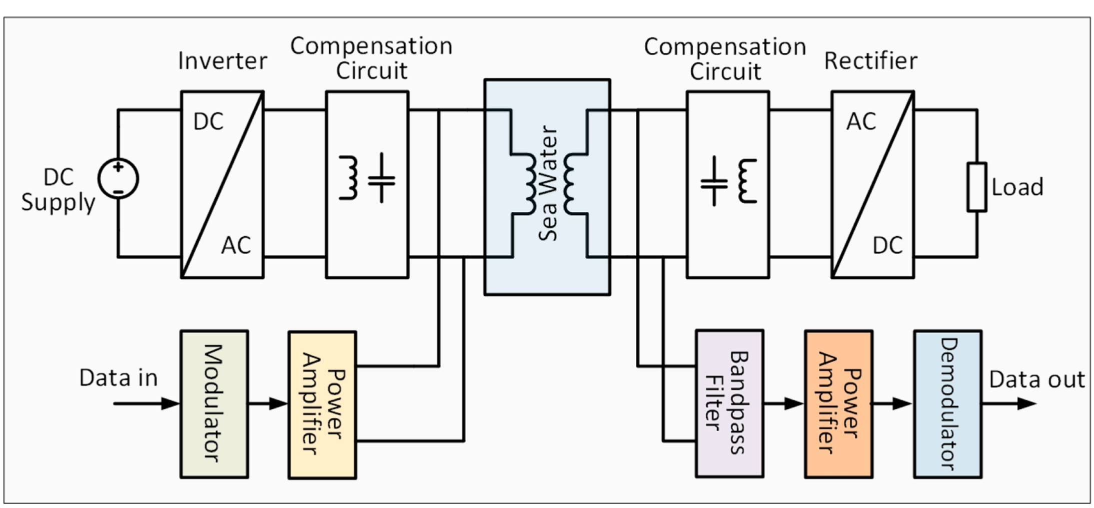

Fig. 8. Inductive power and data transfer circuit architecture (adapted from Kodeeswaran et al. [74] and Yang et al. [75]).

Table 3
Summary of contributions to EH from hydro-kinetic energy.

Ref.	Harvester type	Main objective	Solution approach	Results/Findings	Application domain	Limitation
[78]	FTENG	EH maximization based on ocean waves	Minimizing frictional force between dielectrics using acrylic coating substrate coupled with the incorporation of PMS unit in the device	A 58% reduction in the frictional force is achieved. Also, an average output of 7.5 mW and short-circuit current from 650 μA to 11 mA are achieved	Water quality monitoring sensor	The dielectric coating can lead to a lower charge density output, and using a highly conductive substrate may not be cost effective.
[79]	VSTENG	EH analysis based on ocean waves	Experimental setup using vibration exciter, oscilloscope and a galvanometer	An output power of 14.0 μW and power density of 5.5 Wm^{-2} are achieved	Pipeline monitoring sensor	Incorporation of PMS unit in the design which can boost the output power is not considered.
[80]	VSTENG	EH maximization based on ocean wave	Incorporation of capacitor-based charge excitation circuit to increase the charge density of TENG structure	Maximum output power of 28 mW and power density of 49.3 Wm^{-2} are achieved	Underwater sensor transmitter	Design complexity and implementation cost may increase due to the incorporation of the charge excitation circuit.
[81]	VSTENG	EH analysis based on ultrasonic waves	Incorporation of dielectric pellets on the bottom electrode which are excited by ultrasonic waves	Output power and average power conversion efficiency of 0.362 Wm^{-2} and 13%, respectively are achieved.	Not specified	Ultrasonic waves especially from the ambient environment may not be sustainable due their to intermittent nature.
[82]	FTENG	Location accuracy estimation and EH analysis based on ultrasonic wave	Development of sectorized FTENG to improve the estimation of angular resolution of the propagating ultrasonic waves	A 95% localization accuracy is achieved and also maximum power density of 1.28 $\mu W\ cm^{-2}$ obtained	Underwater localization sensor	The derivation of an optimal number of the rolling dielectric in the proposed FTENG is not considered.
[83]	Piezo-electric	EH maximization	Frequency matching of propeller (driven by water current) with the natural frequency of the piezoelectric material	Output power of 17 mW and power density of 57.4 $mWcm^{-2}$ is achieved	Underwater obstacle detection sensor	The design is limited to scenarios with a directional flow of water current which may be inapplicable in ab oceanic environment.
[84]	Piezo-electric	EH analysis	Generating vibrational force based on magnetic coupling	An output power of 0.016 μW is achieved.	light-emitting diodes and sensors	An excitation circuit may be needed to create a strong magnetic field in order to improve the output power.
[85]	Not specified	Throughput maximization	Branch-and-bound method and multi-armed bandit learning	Increase in throughput performance due to improved predictability of the best routing distance and harvested energy rate	Acoustic IoUT networks	Optimization factors such as power and channel allocation are not considered.
[86]	Turbine	Network lifetime maximization	Content caching at the sensor nodes	Network lifetime is extended by 45%	Optoacoustic sensor networks	Energy consumption minimization during the content caching process is not considered.
[87]	Pulley system	EH maximization	Use of relative motion of pulley generated from heaving motion of water to drive the AUV generator	Average power 10.18 W is achieved	Cooperative UWSNs	The impact of gravitational force on the EH process is not considered.

maximum output power, the expression for frequency matching is developed to match the frequency of the rotating object to the natural frequency of the piezoelectric plate. Experimental result shows that an output power of 17 mW is achievable. However, the proposed design may not be applicable in an oceanic environment where direction flow of water may not be available. This challenge is addressed in [84] where the magnetic coupling is adopted to create a simple harmonic motion in order to establish vibration in the piezoelectric materials. An output power of 0.016 μW is achieved.

Aside from TENG and piezoelectric harvesters, other types of wave harvesters have been explored. Moreover, the aforementioned studies presented studies only focus on analysis and optimizing the harvested power with no clear link between the EH unit and units. This limitation is addressed in [85], where a throughput maximization problem is addressed in an acoustic-based network with tidal EH capacity. The authors argued that an AP may not be able to optimally schedule its transmission to nodes with high energy level due to the stochastic nature of the tidal energy. To solve this problem, a branch-and-bound optimization method is proposed to deal with the uncertainty problem. The study is extended to the scenario where global network information is not available at the AP. Due to this limitation, a distributed learning algorithm based on the multi-armed bandit learning technique is developed where each node can independently choose a random window for channel access. Results obtained show that when EH probability increases, the number of nodes ready for transmission also increases though at the cost of a high data collision rate at the receiver. In [86], the application of content caching in a turbine-based EH acoustic-optical network is proposed for offloading computational tasks when the EH nodes are low on residual energy. The network lifetime is improved by 45% compared to studies where content caching is not used. Although the studies in [85] and [86] focus on the communication unit of the system design, details on the EH process are not captured. Form the harvester design perspective, the authors of [87], propose a cable-pulley mechanism for harnessing the ocean wave energy to power AUV. During the energy harvesting phase, the AUV releases its cable-connected floater which oscillates vertically. The pulley system which is connected to a generator module of the AUV in turn converts the vertical motion such that the generator is rotated in one-way. Experimental results shows that an average instantaneous power of 10.18 W is achievable.

3.2. Energy harvesting from sediment MFC

As pointed out in Section 2.1.2, a major challenge associated with the sediment MFC is the low potential generated by the EH process which is below the operating voltages of most sensors and acoustic circuits. To address this problem, different PMS designs have been proposed over the years as discussed in the following. A summary of these contributions is presented in Table 4. In [88], the proposed PMS unit comprises a supercapacitor, voltage comparator, charge pump, and boost converter. The voltage comparator ensures a maximum threshold voltage that appears across the capacitor is reached before activating the charge

Table 4
Summary of contributions to sediment MFC-based energy harvesting.

Ref.	Main objective	Solution approach	Results/Findings	Application domain	Limitation
[88]	Power management system (PMS) design for improved EH efficiency	Development of PMS unit based on voltage comparator and charge pump	A boost from 52 mV sediment MFC potential to 3.3 V output voltage is achieved	RF wireless sensor networks	High possibility of delay in charging time due to the direct connection of the supercapacitior to the sediment MFC electrodes
[89]	Improvement on PMS unit efficiency	Incorporation of solid-state switch between supercapacitor and boost converter to prevent current drainage.	A stable output voltage of 3.3 V is achieved	Underwater acoustic networks	Power consumption minimization in the sensor device which can improve the system's performance is not considered.
[90]	Improvement on PMS unit efficiency and energy consumption minimization	Incorporation of a microcontroller for scheduling different activities	The highest power density of 158 mW/m^2 is achieved over a period of 50 days	Underwater acoustic networks	The efficiency of the PMS system can be improved by optimizing the boost converter. However, this factor is not considered
[91]	PMS design for output power maximization	Incorporation of two DC-to-DC boost converters which are optimized for low and high potentials from the sediment MFC	Output power of 3 mW to 10 mW is achieved	Submersible ultrasonic sensor	Circuit complexity may be a major challenge compared with previous studies where one DC-to-DC converter is employed
[92]	Average power density maximization	Use of multiple anodes coupled with switch-based alternation technique	An average power density of 23.5 mW/m^2 is achieved compared to a single-anode case with 6.3 mW/m^2	Not specified	Implementation of a switching circuit in the water sediment may not be practically feasible
[93]	Lifetime maximization of MFC EH operation	Incorporation of rechargeable Li-ion batteries in the PMS unit	Output power of 9 mW in a water depth of 890 m is observed over a period of 12 months	Underwater acoustic modem	Li-ion batteries require a protection circuit to operate them within a safe limit. Consequently circuit complexity may become high
[94]	Lifetime maximization of MFC EH operation	Incorporation of rechargeable Li-ion batteries in the PMS unit	Output power in the range of 5–50 mW in a water depth of 580 m is observed over 35 months	Underwater acoustic modem and sensors	High circuit complexity due to the need for a protection circuit to operate Li-ion batteries within a safe limit.

pump and the boost converter otherwise they remain idle. The process is able to increase an output voltage from 52 mV to 3.3 V. However, the design considers the direct connection of the supercapacitor to the sediment MFC electrodes. This could to a delay in the charging time of the supercapacitor since the potential across the electrodes is considered low. This limitation is addressed in [89] where the charge pump is connected directly to the sediment MFC electrode. Moreover, they highlight that it is impractical to connect the boost converter directly to the supercapacitor. The reason is that at a fully-charged state, the boost converter will start drawing current from the supercapitor which will eventually lead to a voltage drop. Thus, a switch that disconnects the boost converter from the superconductor when its fully-charged is incorporated in the PMS unit. In addition to the aforementioned PMS components, the authors of [90] incorporate a microcontroller in the PMS design. The main goal is to minimize power consumption by scheduling various activities such as communication events and sensor readings. In [91], the authors adopt a similar PMS unit adopted in [88], however, two DC-to-DC converters are proposed and optimized to handle the minimum and the maximum potential difference from the sediment MFC electrode. As a result, the downtime of the PMS unit is minimized. Experimental result shows that a 3 mW to 10 mW output power is achievable. From another viewpoint, the authors of [92] propose the use of two anodes and a switching circuit in order to alternate the cathode connection between the anodes. The goal is to improve the average power density of the system. Other similar studies with the advantage of an extended number of operating days in the deep sea due to the incorporation of Li-ion batteries in the PMS unit are experimented in [93,94].

3.3. Energy harvesting from solar irradiance

The application of solar-based EH is demonstrated in [95,96] and [45]. A summary of these contributions is presented in Table 5. In [95], a solar panel and RF transmitter are mounted on a buoy surface such that the harvested solar energy can power the surface transmitter and the underwater transceiver suspended by the buoy. In the study, the authors develop a reinforcement learning data routing protocol based on the combination of the Markov decision process and Q-learning. The available residual energy, predicted harvestable energy capability and link quality serve as criteria for selecting a data-forwarding node for a next-hop transmission. Simulation results in terms of energy consumption, off time, latency, and packet data delivery outperform a similar

Table 5
Summary of contributions to solar-based energy harvesting.

Ref.	Main objective	Solution approach	Results/Findings	Application domain	Limitation
[95]	Minimizing energy consumption and latency, and improving packet delivery ratio.	Data routing optimization based on Markov decision process	Result obtained outperformed scenario where technique based on channel reservation via control packets is used.	Sensor networks	Single forwarding node is proposed which may lead to network downtime transmission if it becomes faulty.
[96]	Minimizing energy consumption and latency, and improving packet delivery ratio.	Opportunistic data routing and multiple node selection based on Markov decision process	Results outperforms the study presented in [95] in terms of main objectives considered.	Sensor network	Use of multiple number may increase network complexity. Hence, optimal node selection is required.
[45]	EH maximization	UAV trajectory optimization based on numerical analysis	It is established that an optimal UAV velocity is required to balance the trade-off between energy consumption and operational time.	AUV and sensor networks	Limited duration of AUV in underwater remains a major challenge due to the intermittent nature of sunlight.

study where EH is not considered. Nonetheless, the packet delivery rate of the data can be improved due to the diversity gain if multiple forwarder nodes are selected. To address this limitation, the authors in [96] highlight that the broadcast nature of the transmitted signal can be exploited to create a set of potential forwarder nodes. Though the results obtained outperform study in [95], this may come at the cost of an increase in energy consumption in the network and higher computational complexity due to the use of multiple forwarding nodes. While the aforementioned studies are based on solar-mounted buoys, the application of solar-power AUV is demonstrated in [45]. In the study, the AUV performs the function of data collection from the sensor nodes via a VLC link. To prolong the lifetime of the AUV operation, an EH maximization approach is proposed. The formulated EH problem is solved using a travel sales man and trajectory optimization approaches. In the former approach, the optimal order of the sequence of sensors to be visited is determined while a 3D trajectory optimization between each pair of adjacent for a specific sequence order is considered in the latter. Numerical results outperform the a 2D scenario where the AUV operate at a fixed.

3.4. Acoustic wireless power and data transfer

Compared with optical and RF transmissions, acoustic signals have the advantage of larger transmission distance due to their robustness to absorption and turbidity [97]. This in turn increases the network coverage and range of devices that can be remotely powered. Notable works in this direction can be found in [56,98–103]. A summary of the contributions of these papers is presented in Table 6. In [56], The expressions to analyze the harvested power and sensing range of an underwater acoustic sensor node are developed. Moreover, the effect of operating frequency signal of source and directivity on the system's performance are studied. Findings show that the harvested energy decreases with increasing frequency due to absorption, however, it can be improved by enhancing the directivity of the transmitted signals. Findings also show that the number of nodes that can be accommodated over a sensing range largely depends on the source transmission power. The study in [56] is extended by the authors of [98], where the concept of cooperative communication is incorporated in the system design. In the study, a dual relay selection process based on the harvested energy threshold in the network is proposed. Moreover, EH and data forwarding switching mode based on the EH threshold is also incorporated into the design to optimize the EH duty cycle. Simulation results in terms of node battery lifetime and packet delivery ratio outperform studies where a similar design without EH is demonstrated.

From another viewpoint, the authors of [99], demonstrate the application of NOMA in underwater acoustic EH networks. The goal of the study is to maximize the available channel bandwidth and harvested energy of an AUV. To achieve this, a time-reversal technique which suppresses the scattering effect of multipath channels by converting them to an impulse-like channel is proposed. Moreover, the power-domain NOMA is adopted to maximize the number AUVs over the available channel. Further to this, the expressions for the outage probability and bit error rate (BER) of the system are derived. Though the results obtained outperform the traditional NOMA schemes, however, the assumption of perfect successive interference cancellation and channel state information may be invalid in practice. While the aforementioned studies focus on deterministic transmission processes, the authors of [100], highlight that the amount of energy harvested is stochastic in nature therefore the need for the utilization of harvested energy adaptively. To achieve this, the expression for a weighted penalty cost function based on the relay transmission power and harvested energy is developed and incorporated into the relay transmission rate maximization problem. The problem is solved from the viewpoint of joint relay selection and power allocation and optimized using the Markov-based Q-learning approach. The study in [100] is extended in [101] where the authors highlight the problem of missing the optimal power allocation factor during the process of discretizing the continuous power allocation action space. To address this problem a combination of deep Q network (DQN) and deep deterministic policy gradient (DDPG) algorithms based on the Markov decision process are proposed to derive an optimal number of relay and power allocation factor, respectively. The total uplink capacity and outages based on the proposed solution

Table 6
Summary of contributions to acoustic wireless power and data transfer.

Ref.	System model	Main objective	Solution approach	Results/Findings	Limitation
[56]	Single AP serving multiple receivers	EH and sensing range analysis	Numerical solution based on closed-form method	Harvested power decreases with increasing operating frequency, and low-directivity signals	Optimization of transmission parameters such as power allocation and signal partitioning factors are not considered
[98]	Single source serving a pair of EH relay and far user	Network lifetime and packet delivery ratio maximization	Relay pairing for transmission and EH duty cycle optimization	The network lifetime, packet delivery ratio, latency, and throughput outperforms the non-cooperative scenario	The incorporation of relay placement optimization which can further enhance the system's performance is not considered
[99]	Single source serving two-NOMA user	BER, EH, and outage probability analysis	Numerical analysis based on the joint application of time reversal, NOMA and power splitting protocol	The proposed time reversal approach shows robustness to the multipath effect making it outperform the conventional NOMA schemes	The assumption of perfect successive interference cancellation and channel state information may be invalid in practice
[100]	Single AP serving multiple sensor nodes	Transmission rate maximization	Joint relay selection and power allocation optimization using Markov decision process	A significant reduction in outage probability and an increase in data rate is observed	Optimization parameters such as AP power allocation and time slot for information transmission and EH are not considered
[101]	Single AP serving multiple sensor nodes	Deriving optimal power allocation during the discretization process	Deep Q learning and deterministic gradient policy based on the Markov decision process	A Significant improved is observed in total uplink capacity and data outage	The study can be further enhanced by optimizing the transmission time frame. However, this aspect is not captured
[102]	Single AP serving a sensor node	Development of a batteryless acoustic sensor prototype.	Implementation of acoustic transducer, power, communication and PMS units on printed circuit (PCB) board	For a 53.5 mW of received input power and a 1 kΩ load resistor, a 60% EH efficiency (32.5 mW) in achieved	The proposed design adopts time switching protocol, however, the optimization aspect is not considered.
[103]	Single AP and serving a sensor node	Development of a low-power consuming batteryless device for illumination, imaging and data transmission.	Implementation of hydrophone, FPGA processor, acoustic transducer and CMOS-based imaging and illumination sensor on a PCB	Experimental results indicate that the passive and active imaging requires an average power consumption of 112 μW and 276 μW, respectively.	The use of an array of hydrophones at the receiver can boost the system's performance however, this aspect is not considered.

outperform related studies where only DQN and improved DQN are employed.

From an experimental standpoint, the authors of [102] develop a prototype for an ultrasonic-based WPT and data transmission sensor network. The prototype comprises three main units viz; energy management unit, communication unit and powering unit. Ultrasonic waves sent from marine communication devices are converted to electrical energy via the frontend transducer which is designed to switch to EH or communication mode. Further to this, the signal is rectified and stored in the supercapacitor. The powering unit regulates the required power level needed to operate different components of the communication unit. Experimental result shows that at a separation distance of 1 m, a harvested power of 1 Watt is achievable in less than five minutes. In another related article [103], the application of acoustic EH for powering an underwater device that performs illumination, imaging and data transmission is demonstrated. Once the EH threshold is satisfied, illumination, imaging, and data transmission units which are interconnected via an FPGA-based processor are powered by an EH unit. To further prolong the use of the harvested power, an ultra-low power-consuming data transmission process based on a piezo-acoustic backscatter communication technique is proposed. Experimental results show that passive and active imaging require an average power consumption of 112 μW and 276 μW, respectively. Nevertheless, the studies in [102] and [103] are centered on the EH circuit realization with little focus on the data transmission processes.

3.5. Optical wireless power and data transfer

The optical signals have been considered as a potential solution to the problem of limited bandwidth associated with underwater acoustic waves [104]. Though the power transfer distance of optical signals is shorter than that of acoustic signals their applications have been significantly demonstrated in SLIPT-related studies [105–117]. A summary of the contributions of these papers is presented in Table 7. In

Table 7
Summary of contributions to optical wireless power and data transfer.

Ref.	System model	Main objective	Solution approach	Results/Findings	Limitation
[105]	Single LD serving a solar-based receiver	Evaluation of solar cell sensitivity and BER analysis	Experimental testbed measurements	At 660 nm light, the solar panel has the highest sensitivity when the output transmission power is 30 mW. Also, BER reduces with increasing modulation order.	A system with a higher modulation order suffers from noise and interference. Hence, an optimal modulation order is required.
[106]	Single LED/LD serving a solar-based receiver	Charging of temperature sensor and camera	Development of EH unit based on time switching protocol	At a separation distance of 1.5 m and 30 cm, sensor and camera batteries are fully charged at 124 and 90 min, respectively.	Solar-based receivers are characterized by low bandwidth. However, no optimization scheme is proposed to address this.
[107]	Single AP with multiple LDs serving a receiver with multiple solar cells	Average BER and EH maximization	The use of a colour shift key modulation scheme to alleviate the low-frequency response of solar cell	The BER under the proposed CSK a similar outperform similar study where an on-off keying scheme is adopted	Signal partitioning based on time switching protocol is proposed but the optimization aspect is not considered
[108]	Single LD serving a hybrid Solar-SPAD receiver	EH and ID maximization	Iterative solution based on power splitting optimization	The performance of the system is significantly impacted by SPAD dead time and link distance.	Receiver complexity is likely to be high due to the integration of different photodetectors
[109]	Single LED serving a solar-based receiver	BER minimization	Increasing negative bias in order to maximize Solar cell bandwidth, and PAPR reduction	An increase in bandwidth from 440 kHz to 780 kHz is achieved	Increasing the negative will improve the EH rate but at a cost of lower ID rate. Hence, optimal bias value is required
[110]	Single LED serving an IoUT node	Throughput maximization and energy consumption minimization	Markov-based error correction method using automatic repeat request strategy and probing packets	Higher throughput is observed when compared with a system without an acknowledgment signal and probing packet	Details on the signal partitioning protocol adopted are captured.
[111]	Single LD serving a solar-based receiver	Comparative analysis of different SLIPT receivers based on harvested energy	Numerical analysis based on closed-form method	Without optimization, the ADS has the best performance. However, under an optimal condition, Hybrid PS-TS has the best overall performance	Though the hybrid PS-TS receiver outperforms others, the implementation cost may be expensive due to high circuit complexity.
[112]	Single LD serving a solar-based receiver	Achievable rate maximization	Numerical solution based on TS optimization	A trade-off balance between ID and EH is achieved when the TS ratio is less than 0.5	The analysis relies on perfect channel state information which may be invalid in practice
[113]	Single LD transmitter serving an GaN-based LED receiver	Development of miniaturized EH device without battery or supercapacitor	Experimental testbed measurements	A maximum signal output voltage of 3.99 to 4.12 V corresponding to a laser input power of 5 to 55 mW is achieved	The circuit design does not allow energy harvesting and data transmission to be performed simultaneously.
[114]	Multiple APs serving multiple receivers	Throughput maximization and energy consumption minimization	Time switching ratio optimization of duty cycle and shortest route derivation	Simulation result outperforms scenarios where EH and routing optimization are not considered	The system design is based on perfect channel state information which may be invalid in practice
[115]	EH LED source and relay serving a destination receiver	Sum-rate maximization under amplify-and-forward and full-duplex protocols	Optimal power allocation based on reinforcement learning	The results obtained outperformed the scenario where a greedy-based algorithm is employed.	The system may not be robust to noise effect due to the use of amplify-and-forward relaying protocol
Ref.	System model	Main objective	Solution approach	Results/Findings	Limitation
[116]	Single LD serving a solar-based relay and destination receiver	BER minimization and network coverage maximization	Time switching ratio and relay placement optimization under amplify-and-forward protocol	Optimal relay placement improves the communication distance while the TS ratio further balances the trade-off balance between ID and EH	The adoption of amplify-and-forward protocol may lead to higher noise level in the system.
[117]	EH LED source and relay serving a destination receiver	Uplink rate maximization under FD protocol, and transceiver alignment	TS ratio optimization and setting of misalignment constraints between 0^0 to 180^0	The proposed solution outperforms its HD counterpart by 70%	The study is based on the assumption of perfect successive interference cancellation and channel state which may be invalid in practice

[105], the authors evaluate the sensitivity rate of a solar-based receiver. Moreover, the BER of the proposed system is evaluated. Based on 30 mW output transmission power, findings show that the solar panel receiving an optical signal from a laser transmitter is most sensitive to 660 nm light. Furthermore, the experiment reveals that the detection performance and BER of the solar panel increases with a higher number of OFDMA constellation symbols. Nonetheless, details on the EH process are not presented in the study. In [106], the application of SLIPT in charging the batteries of a temperature sensor and camera using the TS protocol is demonstrated. In both applications, a solar-based receiver is proposed whereas, at the transmitter side, a laser transmitter is adopted in the former application while an LED is employed in the latter. The solar panel operates in a photovoltaic or photoconductive mode based on the operating voltages of the sensor and the battery. The module assumes a charging state in the former mode while the data transmission is carried out in the latter case. At 1.5 m separation distance, a fully-charged battery state is realized at 124 min and corresponding data throughput of 500 kb/s. For the camera-based application, at a separation distance of 30 cm, a fully-charged state of 90 min is realized. However, solar-based receivers are characterized by lower bandwidth which may not be suitable for communication purposes. To address this problem, the authors of [107] propose the application of a color shift key (CSK) modulation technique to combat the limitations brought by the low-frequency response of solar panel and water quality. Moreover, due to the higher BER of the CSK scheme, an optimized CSK is proposed where the minimum distance between the constellation points is maximized using the interior point method. Results obtained in terms of BER and harvested energy under the optimized CSK scheme outperform the scenario where on-off keying is adopted. Further approach to the improvement of solar PD is investigated in [108] where a hybrid receiver comprising of solar cell and Single Photon Avalanche Diode (SPAD) for EH and ID, respectively, is proposed. The goal of the study is to maximize the harvested energy while satisfying the throughput, BER and SPAD responsivity constraints. An optimal power splitting approach is proposed to solve the problem. Simulation results show that the feasibility of the optimization solution is largely affected by the increasing value of SPAD dead time and link distance. However, the use of different photodetectors at the receiver can increase the hardware complexity. This challenge is addressed in [109] where the bandwidth of solar cell is enhanced by increasing the negative bias of the transmitted signal. Moreover, the problem of deep fading caused by the degrading effect of peak-to-average power ratio (PAPR) is addressed by employing the application of discrete Fourier transform spread orthogonal frequency division multiplexing (DFT-S-OFDM). The goal in this regard is to minimize the BER in the system. Compared with the OFDM-based system, experimental results show that the -3 dB BW of solar cell can be increased from 440 kHz to 780 kHz while a 1.59×10^{-3} is achievable. However, increasing the negative bias value can lead to a significant rise in LED transmission power.

From a different viewpoint, the authors of [110], propose the joint application of error correction and energy harvesting techniques to improve the network reliability and tackle energy consumption problems. Specifically, the Automatic repeat request (ARQ) with an additional probing packet technique is adopted as an error correction scheme while a multi-harvester architecture is proposed for EH from different sources. Based on the Markov decision process, the probing packet aids the prediction channel condition before the ARQ command for data packet transmission is executed. Furthermore, the optimal number of re-transmission that maximizes the throughput and minimizes latency is derived. However, details on the type of receiver adopted based on the signal partitioning protocol are not captured. This limitation is addressed in [111], where the performance of AC-to-DC separation (ADS), TS, PS and hybrid TS-PS of receivers are evaluated and compared in terms of harvested energy. To achieve this, the expressions for BER and spectral efficiency are derived in closed-form and set as constraints to the formulated harvested energy maximization problem. Further to this, the optimal signal partitioning ratio of the proposed receivers is derived. Based on the harvested energy and the SE region without optimization, the ADS outperformed other proposed receivers while the hybrid TS-PS has the best overall performance in the optimized case followed by PS, TS and ADS. Furthermore, the effect of water turbidity, beam divergence, and receiver aperture diameter are verified. It is shown that the TS-PS protocol is more robust to the degrading effect of high-turbulent water, larger beam divergence and receiver aperture. In [112], the authors highlight that the stochastic nature of energy sources should be considered in the modeling of harvested energy. In the study, the expression that maximizes the rate of the system is formulated. Constrained by the deterministic and stochastic harvested energy rate, the TS factor that optimizes the rate maximization problem is derived. Simulation results shows that a good trade-off balance can be achieved between the harvested energy and throughput when the TS ratio is less than 0.5. It is noteworthy that the harvested energy from solar cells and photodiodes proposed in the aforementioned studies are usually stored in batteries or supercapacitors which can relatively increase the size of the receiver. Consequently, the design and construction of miniaturized underwater wearable or implantable devices may not be feasible. Interestingly, this limitation can be overcome by exploiting the photovoltaic characteristics of Gallium nitride-based (GaN) quantum well diodes. The application of this special diode is demonstrated in [113], where the GaN uses its harvested energy from a Laser source to power its LEDs for the purpose of information transmission. A signal output voltage of 3.99 to 4.12 V corresponding to a laser input power of 5 to 55 mW is achieved.

Some studies have also demonstrated the application of cooperative communication toward the EH and ID rates. In [114], the authors pointed out that for a practical EH-based localization network, the stored harvested energy must be greater than or equal to the present energy consumed. Based on this, an energy causality model is developed and set as a constraint in the formulated throughput maximization problem. To solve this problem, the time splitting ratio of the duty cycle which comprises active and passive states is optimized. In the former state, EH and packet transmission occur simultaneously while EH is performed in the later state. Further to this, a shortest route selection formula is developed to minimize the energy consumption between the nodes in the network. In another related study [115], the battery state based on the energy causality is modeled and set as a constraint for a sum-rate maximization problem. Different from [114], the authors consider a single source-relay-destination scenario with the relay operating the full-duplex and amplify-and-forward transmission protocol. A reinforcement learning framework that optimizes the relay transmission power allocation is developed to solve the problem. In [116], the authors demonstrate the application of a relay-aided dual-hop transmission under amplify-and-forward protocol. The goal is to minimize the BER of the system and also expand the transmission coverage. Constrained by the achievable rate, harvested energy at the relay and the TS ratio, the expression for the average BER minimization at the destination node is derived in closed-form. Further to this, the expression that optimizes BER with respect to the TS ratio and relay position is derived. Results obtained validate that optimal relay placement can increase the communication distance and moreover, optimizing the TS ratio can improve the tradeoff ID an EH rates. In [117], the uplink achievable rate of HD and FD C-NOMA networks is maximized and compared. Moreover, the impact of relay misalignment on the performance of the system is also investigated. In the system model, the source and the relay nodes harvest energy from the optical signal transmitted from the destination node. The achievable rate maximization problem is solved by optimizing the TS ratio. Moreover, a compensation scheme for the misalignment caused by the receiver orientation is addressed by constraining the rotation angle of the source-destination and source-relay between 0^0 and 180^0. Results obtained show that the system design under C-NOMA outperforms its HD counterpart by 70%.

3.6. Inductive wireless power and data transfer

For a loosely coupled region, the SPDT based on inductive coupling can be achieved using resonant frequency of the coupling circuits. However, the power of resonant frequency reduces in the strongly coupled region making the application of resonant frequency in this case unrealistic [118]. Moreover, the constant output characteristics of the traditional IWPT may be impaired due to the introduction of the data transfer circuit [119]. Notable works to address these challenges are presented in [120–122]. A summary of the contributions of these papers is presented in Table 8. In [120], the effect of device mobility on the system's performance is investigated. In the study, motion control policies are developed based on network integrity, energy transfer efficiency and AUV tasks. Though the authors stress that the use of tri-axis coil minimizes the losses associated with coil misalignment due to the motion of the AUVs, they further propose the use of channel state information (CSI) and the maximum received power transmission policies without CSI. Results obtained in terms of achievable upper bound data rate and received energy indicate that the UAV swarm can accomplish their task without violating the QoS constraints in the network. In [121], the problem of low self-resonance frequency when the coil size is increased, and data distortion caused by the voltage stress on data channel is investigated. To alleviate this problem, two resonant frequencies are generated by connecting the transceivers to the last turn of coupling coils. Consequently, these frequencies are exploited to realize full-duplex communication. Experimental result shows that an output power and data rate of 518 W and 700 kbps is achievable. In another related study [122], the application of time-division multiplexing is proposed for isolating the power and data transmission processes. The switching transistors for the power and data transfer circuit are complimentary turned on in one switching cycle. Moreover, the frequency shift keying data modulation scheme is adopted for data modulation in order to increase the bandwidth. Experimental results show that at 35% water salinity, an SNR of 30 dB, an 8 Mbps data rate and 60% power transfer efficiency is achievable over a distance of 10 cm.

4. Lessons learned

In this section, we discuss various insights gained from the articles presented.

- *Stochastic nature of energy sources:* During the modeling of systems especially hydro-kinetic EH-based and solar-based systems, the harvested energy by the EH nodes and data arrival at a central AP should be treated as stochastic quantities [85]. This is due to the intermittent nature of the energy sources and the propagation delay in the transmission channels. Thus, optimizing the system performance requires the use of suitable approaches such as the Markov decision process [100], which can adequately capture the dynamic processes in the system.
- *Robust power management system:* The output power realized from the underwater energy sources may be inadequate to operate most IoUT nodes. This is peculiar to the microbial fuel sources, which usually produce low current [88]. Thus, additional circuit components such as a charge pump, boost converter, a micro-controller for scheduling EH and data transfer processes, and a solid-state isolation switch [89, 90], are needed to increase the output potential of the MFC unit to the required operating circuit voltage.
- *Exploiting wireless communication signal for EH:* The use of acoustic, optical, and inductive-based electromagnetic signals for concurrent data and power transfer is deemed cost-efficient compared to other EH sources since there is no need for additional infrastructure in the existing network. For instance, wave harvesters and MFC can be regarded as dedicated energy sources for underwater communication networks. However, in the case of underwater wireless data and power transfer, the harvested power is gleaned from the energy content of the communication signals in the network. Thus, dedicated energy sources are not required.
- *Receiver design for wireless power and data transfer:* In order to avoid information distortion, the received signals are separated for ID and EH. In the case of acoustic and optical data and wireless power transfer, receiver architectures are established based on different signal partitioning protocols. These include AC and DC separation (a special case under optical systems), power splitting, time switching, and hybrid protocols [99,111]. In the case of inductive data and power transfer, transistors are usually employed to isolate the data and power transfer circuits in a switching cycle [122].
- *Cooperative communication:* Due to the deployment of several IoUT nodes, the advantages of cooperative communication have been explored in UWCNs. Here, any IoUT node with strong channel gains can be selected as a relay in the network [98]. As a result, cooperative communication does not only improve throughput but also minimizes power consumption at each node by incorporating the shortest route selection [114], and content caching techniques [86].
- *RF-based energy harvesting:* Though RF signals have limited applications in underwater communication networks, they are the main communication link to terrestrial and satellite communications systems. Interestingly, a few studies have demonstrated the application of RF-based EH where the energy content of the RF signal is harvested by a floating transceiver [123,124]. In this scenario, the transceiver which could be RF-acoustic is attached to floating objects such as buoys. The harvested energy by the surface RF rectennas is used to power the acoustic sensor immersed in water in order to establish a connection with the sensors on the sea floor.

In addition to the aforementioned insights presented in Section 4, we provide an overview of works in Table 9, where maximum experimental outputs are achieved.

We can infer that for low-power consuming devices such as sensors, energy harvesters such as TENG, piezoelectric, MFC, acoustic, and

Table 8
Summary of contributions to inductive wireless power and data transfer.

Ref.	System model	Main objective	Solution approach	Results/Findings	Limitation
[120]	Multiple mobile AUV chargers serving multiple receivers	Minimizing losses incurred by misalignment of the transceiver and data rate maximization	Incorporation of tri-axis coil to tackle the misalignment problem and the use of CSI and maximum received power for optimizing data rate	Results obtained show that the UAV tasks are successfully accomplished without violating the QoS constraints	The analysis of the data transmission and the achievable rate is not captured in the study
[121]	Single transmitter serving a receiver	Voltage stress minimization on data channel	Generating two resonant frequencies to exploit full-duplex transmission by connecting the last turn of each coupling coil to the transceiver.	Experimental result shows that an output power and data rate of 518 W and 700 kbps is achievable	Self- interference remains a major issue due to the use of full-duplex transmission.
[122]	Single transmitter serving a receiver	Isolation of power and data transfer circuits, and data rate maximization	Incorporation of switching transistors for circuit isolation and FSK for enhancing data rate transmission.	8 Mbps data rate and 60% power transfer efficiency is achieved over a distance of 10 cm.	The use of multiple coil and coil selection technique can further boost the system's performance. Nonetheless, this point is not considered

Table 9
Overview of experimental works on EH in underwater wireless communication networks.

Energy source	Ref	Harvester type	Maximum output power	Data rate	Power transfer distance	Application domain
Natural sources	[80]	TENG	28 mW	N/A	N/A	Sensor networks
	[83]	Piezoelectric	17 mW	N/A	N/A	Sensor networks
	[45]	Solar panel	161 W	N/A	N/A	AUV and sensor networks
	[94]	Sediment MFC	50 mW	N/A	N/A	Sensor networks
Wireless power transfer	[102]	Acoustic	32.5 mW at 60% WPT efficiency	> 80 bps	> 1 m	sensor networks
	[105]	Optical	18 mW at 60% WPT efficiency	22.65 Mbps	7 m	Sensor networks
	[121]	IPT	476.56 W at 92% WPT efficiency	700 kbps	30 mm	AUV networks

N/A - Not applicable.

optical power transfer should be employed. For devices with high power consumption requirements such as AUV, solar and IPT-based harvesters should be employed. Moreover, depending on the network objectives and quality of service requirements, other factors that could influence the choice of a suitable harvester include the achievable data rate and power transfer distance.

5. Design challenges

In the following, we highlight critical challenges needed to be considered in the design phase of UWCNs with energy harvesting capabilities.

- *Electrical output of TENG and piezoelectric harvesters:* Applications of TENGs and piezoelectric harvesters continue to increase significantly in underwater communication systems, however, their low power output remains a major limitation to their usage. To address this challenge, different strategies such as material optimization [78], the incorporation of charge excitation circuit [80], and power management system [83] have been proposed to improve their output performance. However, this may increase the hardware complexity which may not be suitable where a less sizable hardware structure is required.
- *Concentration level of biodegradable materials in sediments MFC:* The MFC sources are known for energizing low-power-consuming devices due to the low power density of the biodegradable substances in sea sediments [125]. This can be further complicated when the concentration of organic matter in the sediment is low. Though several voltage-boosting techniques have been proposed, the commercialization of these solutions may be costly due to the expensive circuit components involved [126,127].
- *Solar spectrum in water:* The use of solar-based EH for deep water applications performs poorly due to the strong absorption of higher wavelengths of the sunlight spectrum with increasing water depth [128]. Though in the case of mobile underwater devices such as AUVs, they can be programmed to operate on the surface during the daytime for EH and submerge to continue their tasks when they are fully charged [44]. However, this approach may become ineffective due to the likelihood of missed events during the execution of a critical task.
- *Link alignment issue in optical systems:* Aside from the signal attenuation caused by the effects of absorption, scattering, and turbulence, misalignment caused by the random movement of water is another major cause of link failure [129,130]. However, achieving an accurate alignment may not be feasible in practice due to the uncontrollable nature of the water movement. Consequently, frequent misalignment can degrade the energy harvesting and data transfer rates of the system.
- *Signal attenuation and propagation delay in acoustic systems:* The acoustic system suffers large signal attenuation and propagation delay due to the multipath effect caused by the surface and bottom reflections [131]. Since the EH circuit usually requires a higher power sensitivity level compared with the data circuit, boosting the received signal for efficient charging is required. This may increase the circuit complexity and cost. Also, due to the low propagation velocity, which is in the order of 1500 m/s compared with the velocity of electromagnetic waves in terrestrial communication, i.e., 3×10^8 m/s [132], the energy storage process in acoustic systems may take a longer period of time.
- *Transmission distance and mobility of IWPT-based devices:* For efficient power transfer, a transmission distance between the transmitter and receiver ranging from 150 mm to 300 mm is required [71]. Consequently, the application of IWPT for long-range transmission is not feasible. Moreover, the mobility of IWPT-based devices is limited due to the requirement of a fixed DC power source on the transmitter side. Though recharging from a docking station has been proposed to tackle the issue of mobility, commercialization of this solution is expensive to implement.
- *Alignment and retention of IWPT-based devices on docking station:* To enhance power transfer efficiency, an accurate alignment between the docking station and an IWPT-based device is required. However, due to water turbulence, achieving a stable position on the docking station may become challenging, consequently causing misalignment. This could lead to a lower coupling factor which degrades the power transfer efficiency.
- *Network security:* Aside from the broadcast nature of underwater wireless communication systems, they are also constrained by various factors, that make them vulnerable to malicious attacks. Some of these factors, such as low propagation speed, high bit error rates, and low bandwidth, are specifically related to the acoustic-based UWCNs [133]. Other factors include dynamic network topology, limited energy, storage space, and computational power [134]. Generally, malicious attacks are grouped under passive and active attacks [135]. While a simple encryption mechanism can be employed as a solution to passive attack [136], active attacks such as denial of serve (DoS) [137], fault attack [138–141], exceptional point attack [142], and side-channel attack [143], require sophisticated encryption methods, which may increase the network design complexity.
- *Biofouling:* Biofouling refers to the accumulation of unwanted biological matter on the surfaces of marine structures, which can lead to corrosion, staining, deterioration, and degradation of underwater energy harvesters and communication devices [144,145]. Though various biofouling prevention strategies have been proposed, such as the use of mechanical wipers and scrapers, controlled and uncontrolled biocides [146], their implementation in the underwater environment is expensive.

6. Research directions

In this section, we provide potential areas that can be explored for improving EH and communication performance of UWCNs.

- *Wide-band-gap semiconductors for solar cell:* The traditional silicon-based solar panels are deemed ineffective for underwater EH from sunlight due to the absorption of sunlight in water. This perception

has been discarded in a study carried out in [147], where a wide-band-gap semiconductor developed from Indium gallium phosphide (InGaP) is used for solar cell fabrication. Though significant harvested energy is achieved at a water depth of 9 m, the associated cost of an InGaP-based solar cell is high. However, there are other wide-band semiconductors [148], that are yet to be considered and are worth exploring for EH in underwater environments.
- *Array of transmitters and receivers:* The acoustic and optical signals are known to be suitable for mid-range and long-distance communication, respectively, compared to other wireless transmission links. However, these signals are also degraded by various reflections at the surface and bottom of a water body, which have a degrading impact on EH and data rates. A means of alleviating this is by improving the directivity of these signals using arrays of projectors and hydrophones in the case of acoustic systems, and arrays of LEDs and photodetectors in the case of optical systems.
- *Data buffering:* The use of EH relays in underwater cooperative communications has been investigated in a few studies for improved network performance. However, the relay-destination channels may be degraded due to several impairing factors, such as strong turbulence, water clarity in the case of optical signals, and so on. Incorporating the idea of data buffering at the EH relay will enable the relay to store the received information from the source and only transmit it to the destination device when the relay-destination channel is strong. Hence, this can significantly minimize the amount of harvested power consumped by the relay nodes.
- *EH from interference signal:* In the case of acoustic and optical wireless power transfer, the energy content of the interference signals can be scavenged as additional harvested energy. Hence, this calls for a careful design of the receiver such that the interference signals are retained at the EH unit while the ones appearing at the ID unit are canceled.
- *Coil selection:* Coil misalignment constitutes one of the major limitations of IWPT systems. Though the use of multiple coils at the transmitter and receiver has been proposed as a potential solution, this may degrade the energy efficiency of the system due to the power consumption requirements of each coil. To address this, a coil selection strategy based on the quality factor of each coil [149], can be used to detect the coil with the highest transmission rate.
- *Enhancing EH and ID rates with cutting-edge technologies:* Underwater optical wireless communication channels are known to suffer from the degrading effect of turbulence, blockage caused by obstacles, pointing errors, and beam attenuation. This in turn could lead to poor harvested energy and achievable rates. An efficient means of combating these degrading factors is to recreate the line-of-sight signals and direct them to the intended receivers. In the terrestrial RF communication system, the use of reflecting intelligent surfaces (RIS) has been employed to achieve this purpose [150]. Though few studies have also demonstrated the application of RIS in the context of underwater optical communications systems [151,152], its impact on the EH rate is yet to be investigated.
- *Security:* Achieving secure communication in EH-based UWCNs is more challenging compared with terrestrial radio frequency-based networks. This is more complicated in acoustic-based transmission systems due to long propagation delay of acoustic signals coupled with limited channel capacity, poor channel quality with high dynamics, and transmission leakages due to high transmission power requirement [153]. To address this problem, various lightweight cryptography methods have been developed over the years [154–157]. However, with the advent of quantum computers, the current underwater cryptographic solutions may be less effective due to their ability to decipher the most common form of digital encryption [158]. Though the use of Post quantum cryptography (PQC) is envisioned to serve as a potential solution, not all its variants may be optimal for underwater security framework. Hence, PQC techniques that can minimize communication overhead with small a storage requirement [159,160], and also support efficient hardware implementation [161], should be explored.

7. Conclusions

Various advances in underwater communication systems have been on the increase in order to support diverse human activities in the underwater environment. Moreover, several EH techniques have been developed over time to sustain the operational lifetime of these systems. In this article, we provide a review of EH techniques applicable to underwater wireless communication systems. To begin with, we classify the energy sources and the harvesting process under different categories. Further to this, we provide a detailed review of relevant articles on EH solutions in UWCNs. Moreover, we highlight major technical challenges to be considered for efficient system design. Based on the insights gained from the presented articles, we conclude that basic factors such as the power consumption requirement of a device, achievable data rate and power transfer distance are key in deciding the choice of a suitable harvester for a specific network objective. In this regard, we suggest that for low-power (milliwatt-order) consuming devices such as sensors, energy harvesters such as TENG, piezoelectric, MFC, acoustic and optical power transfer should be employed. For devices with high power consumption requirement, such as AUV, solar and IPT-based harvesters should be employed. Finally, we suggest open areas that can be explored for research work. We anticipate that this article will serve as potential guidelines for researchers with an interest in developing sustainable underwater wireless communication systems.

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Data availability

No data was used for the research described in the article.

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