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Review

Energy Optimization Techniques in Underwater Internet of Things: Issues, State-of-the-Art, and Future Directions

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Abstract: The underwater internet of things (UIoT) has emerged as a booming technology in today's digital world due to the enhancement of a wide range of underwater applications concerning ocean exploration, deep-sea monitoring, underwater surveillance, diver network monitoring, location and object tracking, etc. Generally, acoustic, infrared (IR), visible light (VL), radiofrequency (RF), and magnet induction (MI) are used as the medium of communication in order to transfer information among digitally linked underwater devices. However, each communication medium has its advantages and limitations: for example, the acoustic communication medium is suitable for long-range data transmission but has challenges such as narrow bandwidth, long delay, and high cost, etc., and the optical medium is suitable for short-range data transmission but has challenges such as high attenuation, and optical scattering due to water particles, etc. Furthermore, UIoT devices are operated using batteries with limited capacity and high energy consumption; hence, energy consumption is considered as one of the most significant challenges in UIoT networks. Therefore, to support reliable and energy-efficient communication in UIoT networks, it is necessary to adopt robust energy optimization techniques for UIoT networks. Hence, this paper focuses on identifying the various issues concerning energy optimization in the underwater internet of things and state-of-the-art contributions relevant to inducement techniques of energy optimization in the underwater internet of things; that provides a systematic literature review (SLR) on various power-saving and optimization techniques of UIoT networks since 2010, along with core applications, and research gaps. Finally, future directions are proposed based on the analysis of various energy optimization issues and techniques of UIoT networks. This research contributes much to the profit of researchers and developers to build smart, energy-efficient, auto-rechargeable, and battery-less communication systems for UIoT networks.

Keywords: underwater internet of things (UIoT); energy optimization techniques; systematic literature review (SLR)

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1. Introduction

Water covers 75% of Earth's surface, and 97% of Earth's water is present in oceans [1]. Hence, underwater research plays a significant role in building various applications beneficial to society and nature. Based on Delphin et al., since 2010, most industries and researchers have focused on building UIoT applications concerning ocean exploration, deep-sea monitoring, early warning system, diver network monitoring, navigation, object tracking, and naval network surveillance, etc. Figure 1 shows the core applications, devices, and communication technologies of UIoT networks.

As shown in Figure 1, the UIoT networks consist of UIoT applications, UIoT devices, and UIoT communication technologies [2]: UIoT applications are the applications such as diver network monitoring, object tracking, fish farm monitoring, disaster prevention, and environmental monitoring, that are developed by the industries for protecting, exploring, monitoring, and surveillance in UIoT networks. UIoT devices are heterogeneous underwater devices that are digitally linked to each other with various communication technologies. The heterogeneous devices are the sensor nodes or robots that operate in underwater environments, such as underwater sensor nodes (UW-SNodes), diver nodes, and remotely operated underwater vehicles (ROVs), etc. The UIoT devices can be either mobile or fixed in UIoT networks: the mobile nodes can move from one location to another to gather data and transmit that data through digitally connected devices on water surfaces such as the gateway or buoy; the fixed nodes can act as the sensing or relay node to collect and transfer data in a deep-water environment. In addition, other devices in a water body or terrestrial networks, such as base stations, control stations, and satellites, etc., are utilized to extend the communication technologies of UIoT to terrestrial networks.

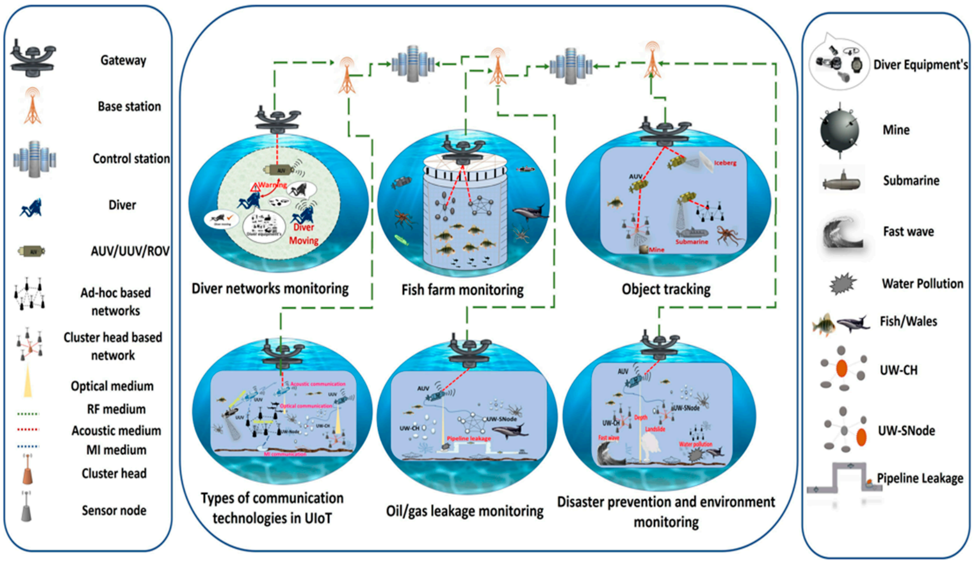

Figure 1. UIoT core applications, devices, and communication technologies.

UIoT communication technologies are the medium utilized by the UIoT networks for transmitting data through digitally connected UIoT devices to water bodies. However, the challenges and limitations of UIoT communication technologies are still a concern due to various factors, such as environmental characteristics, limited resources, application type, and medium type, etc. In the past few decades, many industries and scientists have proposed different communication technologies to build numerous UIoT applications. Communication technologies define the different types of medium used in UIoT networks, such as acoustic, radio frequency (RF), magnetic induction (MI), and optical communication (VLC: visible light communication/IR: infrared), and environmental characteristics signify the technical factors that affect the connectivity or communication in UIoT networks, such as node mobility, high energy consumption, turbulence, attenuation, and scattering [2].

1.1. Fundamentals and Motivations

UIoT devices and their types are discussed above in Section 1. In addition, the behavior of UIoT devices is smart sensing, highly mobile, heterogeneous functionality support, random selection in routing, etc. This causes, high energy consumption in UIoT environment. Moreover, the energy consumption in UIoT devices also depends on sensing, medium type, and depth, etc. Due to constrained underwater conditions, it is difficult to replace or recharge the battery of UIoT devices; this may reduce network lifetime or data loss in UIoT networks. Therefore, in order to increase the battery lifetime, network lifetime, and performance, etc., in UIoT networks, it is necessary to adopt various energy optimization techniques in UIoT devices.

Figure 2 shows the perceptions of energy optimization in UIoT networks. As demonstrated, the energy optimization in UIoT comprises of three phases: energy efficiency, energy procurement, and energy generation. Energy efficiency carries the procedure to provide efficient communication by supporting less energy consumption, eliminating energy wastage, reducing energy demand, and lowering cost; energy procurement delivers the quality of service to the customer by proving fixed price, timely delivery of UIoT services, and cost–reimburse, etc.; energy generation delivers the efficient methodology to generate energy in UIoT networks such as recharging with solar energy, recharge with underwater particles, recharging seawater spices, and recharging with fast waves, etc.

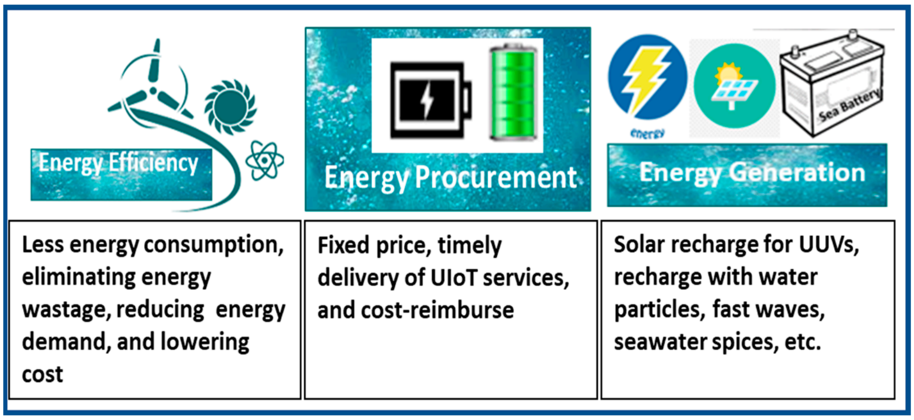

Figure 2. Energy optimization in UIoT.

In recent years, numerous routing and medium access control (MAC) protocols have been proposed to solve the energy optimization issues in UIoT. For example, Kamalika Bhattacharjya et al. proposed an energy-efficient routing protocol selection for cluster-based underwater wireless sensor network (CUWSN) [3], Ahmad Khasawneh et al. proposed reliable energy-efficient pressure-based routing protocol (RE-PBR) for underwater wireless sensor networks [4], Muhammad Faheem et al. proposed a novel dynamic firefly mating optimization inspired energy-efficient routing scheme called FFRP [5], Kuei-Ping Shih et al. proposed a multi-channel collision avoidance MAC protocol (MC-MAC) for underwater acoustic sensor networks [6], Ibtihal Ahmed Alablani at al. proposed a joint energy-efficient MAC and routing protocol termed EE-UWSNs for underwater wireless sensor networks [7], Jenifar Rahman et al. proposed energy-efficient MAC protocol termed bidirectional multi-flow MAC convention (BMF-MAC) [8], Kamrok Lee at al. proposed a novel energy-efficient contention-based MAC protocol for hybrid acoustic-optical networks in UIoT [9], etc. Despite the fact that several energy-efficient protocols have been developed, energy consumption is still a concern for UIoT due to the lack of developments, limitations, and behavior of each communication medium. Furthermore, most protocols are proposed only for acoustic-based communication technology with a simulation environment. Additionally, the technical limitation of UIoT networks, such as attenuation, channel noise, node mobility, and dynamic topology formation, etc., can reduce the battery life of UIoT devices. Therefore, energy optimization is still a concern for UIoT networks. Table 1 highlights the summary of the most recent routing and MAC protocols that deliver energy-efficient communication in UIoT.

Table 1. Summary of recent articles that delivers energy-efficient routing and MAC protocols for UIoT.

Category	Year	Author, Reference	Protocol Type	Application and Methodology	Advantages and Limitation
Energy-efficient routing protocols	2011	Huang, Chenn-Jung et al. [10]	Power-efficient routing protocol	• Proposed the simulation environment for underwater wireless sensor networks (UWSNs) • A forwarding node selection scheme method and forwarding tree trimming method are considered to prevent the spread of excess forwarding packets in UWSNs	• Excellent performance in the case of battery consumption, packet delivery ratio, and end-to-end delay. • Some features such as ocean current, turbulence, and salinity, etc., are not considered for the simulation environment
	2013	Awais Ahmad et al. [11]	AUV aided energy-efficient routing protocol (AEERP)	• Proposed the NS-2 based simulation environment for underwater acoustic sensor networks (UASNs) • Gateway nodes are selected based on RSSI values of the hello packet received from AUV, and higher energy nodes are considered as the gateway node after consuming a certain level of energy	• The simulation results have shown that AEERP has an 8% more delivery ratio, 4% less energy consumption, and 19% less end-to-end delay • Only simulated for acoustic-based communication • Other underwater devices, such as sensor nodes and cluster heads, etc., are not considered for the simulation environment
	2018	Mukhtiar Ahmed et al. [12]	Clustered-based energy-efficient routing protocol (CBE2R)	• Proposed the simulation environment using NS2.30 with AquaSim • CBE2R prolongs the battery power through powerful static courier nodes which are deployed from the sea surface to the seabed on different layers	
	2018	Ahmad Khasawneh et al. [13]	The reliable energy-efficient pressure-based routing protocol (RE-PBR)	• Proposed the NS-2 based aquarium for simulating underwater wireless sensor networks (UWSNs) • Link quality is estimated using the triangle metric method, a lightweight information acquisition algorithm is developed for efficient knowledge discovery of the network, and a multi-metric data forwarding algorithm is designed based on route cost calculation which utilizes residual energy and link quality	• Performance results provide good battery life, network lifetime, and packet delivery ratio • Only simulated for acoustic based communication, and the path length is also not considered for RE-PBR
	Others			Energy-efficient chain-based routing protocol (ECBCCP) [14], Energy-efficient routing protocol based on layers and unequal clusters (EERBLC) [15], multi-layer cluster-based energy efficient routing (MLCEE) [16], etc.	
Energy-efficient MAC protocols	2010	Nguyen et al. [17]	Efficiency Reservation MAC protocol (ERMAC)	• Proposed centralized underwater acoustic sensor networks • TDMA approach	• Requires strict time synchronization of nodes through broadcasts made from sink nodes which may consume high energy in large-scale networks.
	2013	Huifang Chen et al. [18]	Transmitter-oriented code assignment (TOCA)	• Proposed based on hierarchical CDMA approach • For multi-hop system	• Delivers better end-to-end delay, energy consumption, network throughput, and PDR compared to RMAC
	2019	Alfouzan et al. [19]	Graph Coloring MAC Protocol (GC-MAC)	• Proposed for distributed underwater acoustic sensor networks • FDMA approach	• Considers a fixed number of time-slots (colors) for each neighborhood which may cause low channel utilization.
	Others			Energy-conserving and collision-free depth-based layering MAC (DL-MAC) [20], Depth-based Layering MAC protocol (DL-MAC) [21], etc.	

As per Section 1.1 and Table 1, many researchers developed their research focusing on energy-efficient MAC and routing protocols of UIoT networks; for example, articles discussed routing protocols [3–5], and [10–16], articles discussed MAC protocols [6–9], and [17–21]. Furthermore, as per Table 2, several researchers provided surveys concerning the existing energy consumption and energy-saving issues of current UIoT system. Based on Section 1.1, most of the energy optimization techniques for UIoT networks are set up using a simulation environment, and also, the researchers and developers focused only on building energy-efficient MAC and routing protocols for UIoT networks, these techniques cannot be utilized as the best solution for energy-optimization in UIoT networks; due to the lack of field experiments, high cost, design issues, development, and management of devices in constrained UIoT networks. Therefore, since 2010, several researchers have been focused on building numerous energy optimization techniques for UIoT applications with field experiments [22–48], for example, underwater wireless power transfer for maritime applications [22], battery replacement approach for UIoT applications [23], automatic recharge techniques for UIoT networks [24], battery-free sensor nodes for UIoT networks [25], solar charging system for AUVs [26], artificial intelligence and machine learning-based energy optimization techniques for UIoT applications [27], etc. However, due to the technical limitations of UIoT networks, such as attenuation, channel noise, node mobility, and dynamic topology formation, etc., the battery life of UIoT devices can still be reduced. In effect, this can affect the network lifetime and damage the battery. Even though several researchers have provided their existing surveys concerning energy-efficient MAC and routing protocols of UIoT networks [3–21], and recent surveys based on Table 2 [49–56], it is necessary to include communication technologies, state-of-the-art articles based on real field experiments, and future research directions for delivering energy-optimized communication for UIoT networks.

Table 2. Summary of recent surveys concerning energy-optimization techniques in UIoT.

Author and Ref.	**Energy-Optimization Techniques**	**State-of-the-Art Review**	**Applications/Use Cases**	**Routing Protocols**	**MAC Protocols**	**Technical Challenges**	**Communication Technologies**	**Research Directions**	**Remarks**
Nusrat ZerinZenia et al. in 2016 [49]	🟠	🔴	🔴	🟢	🟢	🟢	🔴	🔴	Focused on the study of energy-efficient MAC and routing protocols of underwater wireless sensor networks
Mukhtiar Ahmed at al. in 2017 [50]	🟠	🔴	🔴	🟢	🔴	🔴	🔴	🔴	Focused on analyzing energy-efficient routing protocols of underwater communication
Nasarudin Ismail et al. in 2018 [51]	🟠	🔴	🔴	🟢	🔴	🔵	🟠	🔵	Focused on opportunistic routing for underwater acoustic communication technology
Sahana S et al. in 2018 [52]	🔵	🔴	🔴	🟢	🔴	🟠	🟠	🔴	Focused on the analysis of various routing protocols of underwater sensor networks, its research challenges, and provides the solutions to improve the performance on concerning issues such as propagation delay, limited battery, and node mobility, etc.
Yuvaraja Teekaraman et al. in 2019 [53]	🟠	🟠	🔴	🟢	🔴	🔵	🟠	🟠	Focused on the analysis of energy efficiency localization-free protocols in underwater communication

Table 2. *Cont.*

Author and Ref.	Energy-Optimization Techniques	State-of-the-Art Review	Applications/Use Cases	Routing Protocols	MAC Protocols	Technical Challenges	Communication Technologies	Research Directions	Remarks
Kalpna Guleria et al. in 2019 [54]	🔵	🟠	🔴	🟢	🔴	🟠	🔴	🟠	Focused on building a systematic review approach of energy-efficient routing protocols from 2012 to 2017
Kazi Yasin Islam et al. in 2021 [55]	🟠	🟠	🟠	🟢	🟢	🟠	🟢	🟠	Focused on the analysis of various communication technologies and power-saving techniques in physical, MAC, and routing layers of underwater wireless communication
Shreya Khisa et al. in 2021 [56]	🟠	🟠	🔴	🟢	🔴	🟠	🔴	🔴	Focused on analyzing numerous energy-efficient routing protocols that are presently available for underwater sensor networks, provides gap analysis, and categorizing its taxonomy
This paper	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	In this paper, energy optimization in UIoT is analyzed based on different communication technology such as acoustic, optical, IR, and MI and provides information on the state-of-the-art by showing numerous energy optimization approaches such as wireless power transfer, battery-less sensor nodes, AI and ML techniques, etc., along with its issues and future direction

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1.2. Research Contributions

This research aims at providing a survey on battery optimization issues in UIoT networks, state-of-the-art research concerning energy optimization techniques in UIoT, and provides the future direction to solve the energy optimization issues in UIoT networks. The main contributions of this paper are as follows:

- Section 2 identifies the various issues concerning energy optimization in the underwater internet of things
- Section 3 provides the state-of-the-art contributions relevant to inducement techniques of energy optimization in the underwater internet of things, i.e., it provides a systematic literature review (SLR) on various power-saving and optimization techniques of UIoT networks since 2010, along with core applications and research gaps, that include auto-recharging mechanism, wireless power transfer approach, battery-less design, AI and ML methods for power optimization, etc.
- Finally, based on the SLR conducted in Sections 3 and 4. Future directions are proposed to solve the energy optimization issues in UIoT networks.

2. Energy Optimization Challenges in UIoT Networks

This section describes the various energy optimization challenges in UIoT networks, which include environmental characteristics, technical challenges, design challenges, and other challenges as shown in Figure 3.

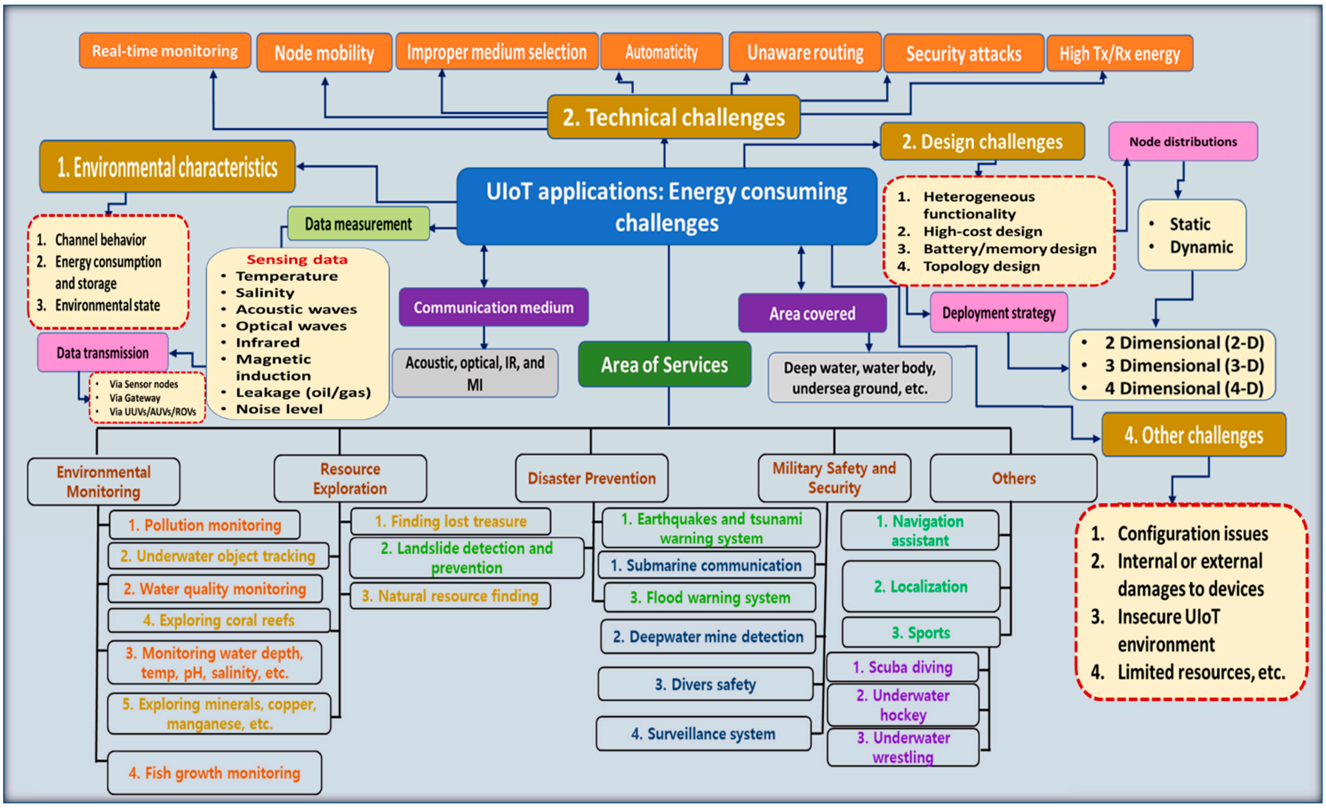

Figure 3. Taxonomy of energy optimization challenges in UIoT applications.

2.1. Environmental Characteristics

Delphin et al. pointed out that most of the characteristics of IoT systems are suitable for the UIoT environment since UIoT is the subclause of IoT [35]. However, most available energy-saving models are created for terrestrial IoT and acoustic-based UIoT networks. Additionally, due to the heterogeneous functionalities of UIoT devices, the existing energy-saving models cannot apply directly to UIoT networks. This statement highlights why the existing energy optimization techniques are not applicable to multi-medium-based communication technology in UIoT.

- Channel behavior: unlike terrestrial area networks, in UIoT networks, the devices are naturally interconnected through acoustic, visible light, infrared, radiofrequency, and magnetic induction mediums [57]. In effect, this causes high battery consumption, improper medium selection, unaware routing, data loss, and increased data error rate, etc. Likewise, the performance of each medium differs in the UIoT network. For example, the optical medium is high in bandwidth but compactable for a short-range communication scheme and the acoustic medium has a narrow bandwidth but is compactable for a long-range communication scheme. Other challenges such as absorption, turbulence, and scattering also affect the communication medium in UIoT networks [58]. Furthermore, due to the lack of energy management techniques in UIoT networks, the developers find it difficult to transmit data via a different medium and to solve energy-related issues in the underwater channel [36].
- Energy consumption and storage: in UIoT networks, the sensor nodes are designed with low battery capacity, less computational power, and limited memory [59]. Moreover, the nodes consume extra energy for sensing, gathering, processing, and transmitting information. The terrestrial area networks are designed with high battery capacity and huge memory size, and also, the batteries are replaceable and rechargeable. However, in the case of UIoT networks, it is hard to replace or recharge device batteries, and also memory management becomes complex due to the constrained behavior of natural behavior. This may cause power constraints in UIoT networks.

- Environmental state: in UIoT environments, internal activities such as mammal behavior, fast waves, and external noises, etc., lead to the formation of frequent changes in UIoT network topology [60]. In effect, this may cause node damage, connectivity issues, data accuracy issues, and unaware rerouting, etc. [61]. In addition, compared with terrestrial area networks, the UIoT devices are sparsely installed in UIoT environments, and they consume high amounts of energy for data sensing and transmission.

2.2. Technical Challenges

- Node mobility: the UIoT networks are deployed with static and dynamic nodes. Most UIoT nodes move from place to place to transmit information. Due to auto-mobility settings or autonomic operation, the UIoT nodes consume high amounts of energy. This causes the easy draining of energy in UIoT nodes [62].
- Improper medium selection: in general, the UIoT devices can transmit information via different communication mediums such as acoustic, infrared (IR), visible light, radiofrequency (RF), and magnet induction (MI). Even though the UIoT networks can use a different medium for communication, the unsuitable medium selection in UIoT networks can consume more energy. This can reduce the battery lifetime of UIoT devices [35].
- Unaware routing: due to internal waves, mammals' activity and other objects' behaviors lead to high mobility, path loss, and routing errors, etc. [60]. The frequent changes in the position of nodes can cause rerouting. In effect, it consumes high amounts of energy for routing in UIoT networks.
- Automaticity: in UIoT networks, the sensor nodes and other devices, such as UWSNodes, UUVs, and ROVs, etc., are programmed to perform their operations by themselves. This includes automatic behavior such as sensing, transmitting, moving, and rerouting, etc., which can affect the battery life of UIoT devices.
- Real-time monitoring: the UIoT applications, such as diver networks monitoring, early warning system, and object tracking, etc., are the real-time applications developed for preventing the disasters that occur in UIoT networks. Due to real-time sensing and transmission, energy consumption is very high, which reduces the battery life of UIoT devices.
- High transmitting (Tx)/receiving (Rx) energy: in UIoT networks, the transmission and receiving of the energy of acoustic and optical mediums are high. In addition, the optical medium consumes a high amount of energy even for short-range data transmission [63].
- Security attacks: the UIoT networks consist of numerous attacks, such as black-hole attacks, routing attacks, battery attacks, and Sybil attacks, etc., among which battery-oriented attacks can directly attack the battery of UIoT devices [58]. This causes energy down in UIoT nodes and reduces network lifetime.

2.3. Design Challenges

- Heterogeneous functionality: different vendors design the devices in the UIoT networks. Therefore, the behavior of each device differs in UIoT environment [64]. This causes high battery consumption.
- High-cost design: due to the complex behavior of UIoT environment, it is necessary to protect UIoT devices by designing their housing cases and fouling cleaners, etc. Therefore, the design of UIoT devices is quite expensive compared to terrestrial IoT [65].
- Battery/memory design: UIoT networks are equipped with automatically operated UIoT devices. Additionally, the particular area of UIoT network is covered with thousands of nodes. In this case, the nodes are designed with limited memory and with limited battery capacity. Therefore, the possibility of battery failure is high in UIoT networks [59].

- Topology design: as discussed in Section 2.1, the sensor nodes are sparsely deployed in UIoT networks. Additionally, as discussed in Section 2.2, auto-mobility can frequently change the position of UIoT nodes [66]. This led to difficulty in designing the topology for UIoT applications.

2.4. Other Challenges

Other challenges include the environmental characteristics, technical challenges, and design challenges that are discussed in Sections 2.2 and 2.3. Many researchers provide a survey on additional challenges that aided UIoT networks and provided some of the solutions to overcome the challenges in UIoT networks, such as network configuration issues [59,67–69], internal or external damages to devices [59,70–76], noise issues [77–88], high-cost issues [89–104], insecure UIoT environment [105–119], limited resources [120–130], environmental limitation [131–140], and transmission loss [141–157], etc. Figure 4 shows the comparison of techniques that have been proposed to solve various UIoT issues vs. battery issues in UIoT networks. Additionally, the result identifies that 14.9% of research focused on solving battery issues in UIoT devices [58].

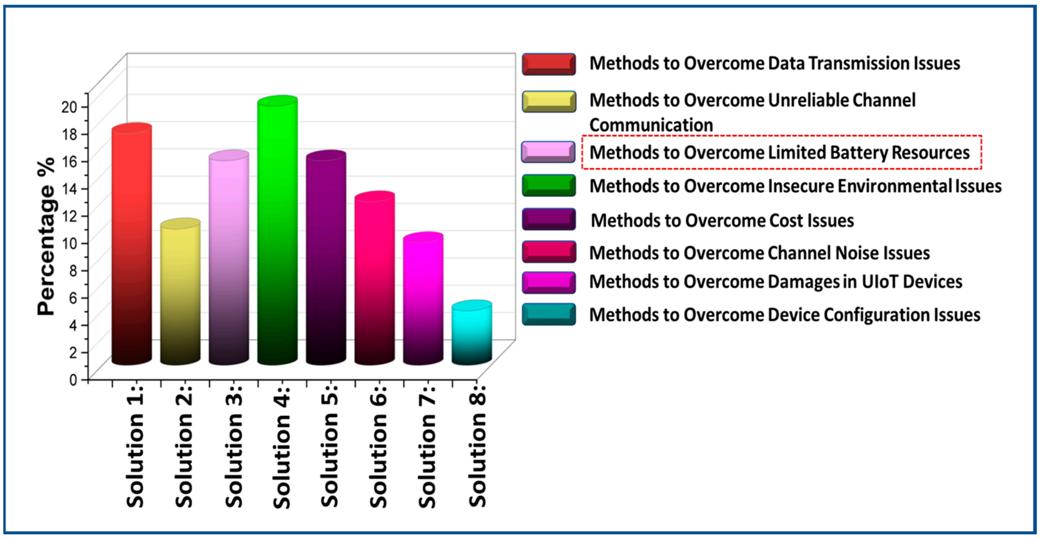

Figure 4. Analysis of techniques developed for battery challenges vs. other challenges in UIoT networks [58].

3. State-of-the-Art Review on Energy Optimization Techniques in UIoT

This section describes the state-of-the-art concerning various energy optimization techniques of UIoT networks such as underwater wireless power transfer, auto-recharge or battery-free systems, solar charging systems, and battery swapping approaches, etc. The description of each energy optimization technique is described underneath:

3.1. Wireless Power Transfer Techniques for UIoT

R. Guida et al. [24] designed and developed the first battery-less technology for underwater wireless communication that can be recharged through acoustic waves from a long distance. In B. Sai Srujana et al. [28], the authors present a reliable and energy-efficient power supply system for UIoT system based on multi-source energy harvesting methods which manage energies from piezoelectric harvesting and microbial fuel cell. Kesler et al. [29] proposed a highly resonant wireless power transfer (HR-WPT) technique to wirelessly transfer several kilowatts of energy to a remotely operated underwater vehicle. K. Shizuno et al. [30] demonstrated a long-distance and efficient charging system for underwater sensor networks. The antenna was designed with a size of 24 cm × 24 cm × 1.5 cm. With this charging antenna, the power is transferred over 10 cm underwater with more than 60% efficiency. L. M. Pessoa et al. [31] developed wireless power transfer in seawater by considering two different magnetic inductors. The system was designed and enhanced using electromagnetic 3D simulation. T. Kojiya et al. [32] proposed a contactless power supply system (CLPS) for transferring 500 W power to underwater vehicles, with 96% efficiency using 48 mm of the coil. The performance can be improved by expanding the coil size. J.-G. Shi et al. [33] proposed underwater inductive coupling power transfer (ICPT) techniques to evaluate the wireless power transfer system for AUV docking applications. Ze-song Li et al. [34] designed and developed a contactless power transmission (CLPT) system for deep-sea underwater application; using this, they achieved 400 W of power with a 2 mm gap in the electromagnetic coupler, with an efficiency of 90% in salt water. Zhengchao Yan et al. [45] designed and developed a rotational free wireless energy transfer system for the unmanned underwater vehicle (UUV), and the result shows that the system can deliver 664 watts at an efficiency of approximately 92%. In [121], due to the constrained environment and the unstructured, dynamic behavior of UIoT networks, the surface water docking system encounters limitations when installed in the underwater environment. These limitations include high cost, biofouling, less sensing capacity, and difficulty to move, etc. Furthermore, the design of the underwater docking system allows for pollutants, dirt, and biological waste to be collected and settle in the charging repository, which can damage the functions of the underwater docking system. One of the most promising technologies concerning underwater docking systems was proposed by the US Navy for wireless power transmission in underwater networks. The design of a self-charging AUV station and different underwater power transfer mechanisms are shown in Figure 5. Types of underwater wireless power transfer techniques (U-WPT) are discussed below. A summary of recent underwater wireless power transfer techniques since 2015 is presented in Table 3.

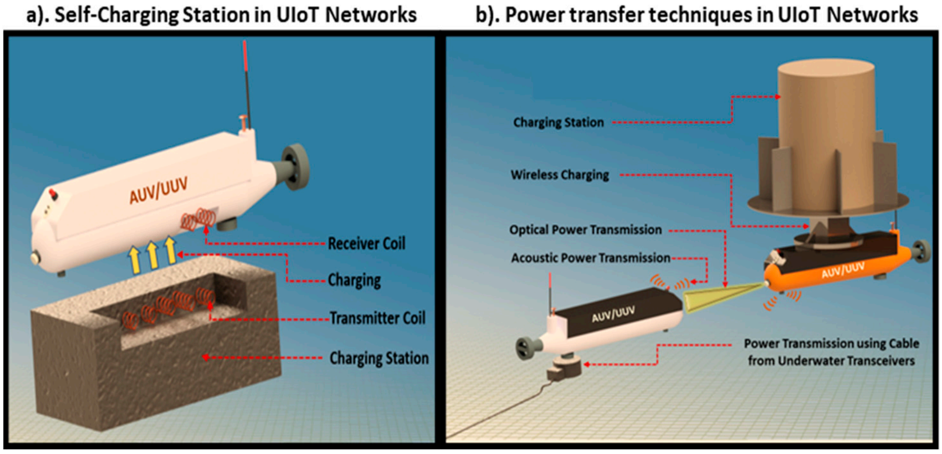

Figure 5. (**a**) Design of AUV self-charging station. (**b**) Types of power transfer methods in UIoT networks.

3.1.1. Underwater Acoustic Wireless Power Transfer (UA-WPT)

The existing UA-WPT techniques are discussed in [158–161]. For example, Yang et al. [55] describe the core techniques of ultrasonic wireless power based on piezoelectric transducers. R. Guida et al. [24,159] developed an ultrasonic wireless power transfer approach for UIoT, and Z. Liu [161] proposed a novel underwater wireless high power transmission methodology based on an acoustic transducer array.

3.1.2. Underwater Optical Wireless Power Transfer (UO-WPT)

The existing UO-WPT techniques are discussed in [162–172]. The UO-WPT is the subclause that originated from optical power transfer, it was first proposed for solar-based communication for satellites [162]. The concept of UO-WPT is similar to the idea of microwaves in the terrestrial environment. In addition, optical power transmission in a terrestrial environment deals with high-power transmission and long-distance communication. However, due to attenuation and scattering in UIoT environments, the energy consumption is high and transmission coverage is low. In the case of UO-WPT, the optical power transmitter can be installed in UIoT devices that are capable of absorbing and transferring light waves to low-powered UIoT devices. Furthermore, compared to other underwater power transfer technologies, the UO-WPT can transfer high-power light waves to nearby sensor nodes. This can help to recharge the batteries of sensor nodes in UIoT networks.

3.1.3. Underwater Inductive Wireless Power Transfer (UI-WPT)

The concept of UI-WPT technologies was discussed in [34,173–184]. The UI-WPT has begun to receive attention in UIoT networks for recharging AUVs, UUVs, ROVs, and UW-SNodes. The UI-WPT system comprises of components such as a transmitter, receiver, and coupler, through which the UIoT devices can transmit and receive energy. The UI-WPT comprises of two coils, the primary and secondary coil; the primary coil acts as the transmitter end with a high-power source, and the secondary coil acts as the receiver, and it uses magnetic field induction as the medium to transfer energy between two coils in underwater communication. Recently many researchers have enclosed dynamic wireless power transfer technology for supporting multiple power transmissions in terrestrial area networks [174], these methods can be adapted to UIoT networks.

Table 3. Analysis on recent wireless power transfer techniques of UIoT networks since 2015.

Year	Reference	Type	Application	Frequency [kHz]	Analysis and Performance Level
2016	Wangqiang Niu et al. [185]	Two-coiled U-WPT	Sea water and fresh water	78 kHz and 114 kHz	Good performance in both sea and saltwater
2016	M. Urano et al. [186]	Electric Coupling	Study on electric coupling in U-WPT	10 kHz to 1 MHz	U-WPT system needs high-speed and high-voltage switching devices.
2017	Duarte et al. [187]	Load modulation	Analysis of the voltage-mode power driver with magnetic resonance in U-WPT	104 kHz and 111 kHz	Utilized for understanding resistive load modulation in U-WPT.
2018	Yan et al. [188]	Eddy current loss	Analysis of eddy current loss in U-WPT using different frequencies	215.5 kHz to 248.4 kHz	Efficiency depends on an increase and decrease in misalignment.
2018	Orekan et al. [189]	Power efficiency tracking	Maximizing U-WPT system efficiency	178 kHz	Tracking efficiency is above 85%
2018	Masaya Tamura et al. [190]	A capacitive wireless power transfer system	U-WPT system for freshwater	≈200 kHz	Achieved efficiency of 91.3%
2018	T. Kan et al. [174]	Wireless charging system	Three-phase charging system for lightweight AUV	465 kHz	Achieved efficiency of 92.41%
2019	Zhengchao Yan et al. [191]	A curly coil structure is used to adapt the cylindrical symmetric hull	U-WPT system for AUVs	85 kHz	Achieved efficiency of ≈95%

Table 3. *Cont.*

Year	Reference	Type	Application	Frequency [kHz]	Analysis and Performance Level
2019	Canjun Yang et al. [192]	Docking system for U-WPT	Omnidirectional charging system for AUVs	≈90 kHz	Reducing 95% of eddy's current loss
2020	Chunwei Cai et al. [193]	Dipole-Coil magnetic coupler	Wireless charging system for AUVs	50 kHz	Achieved efficiency of 89.7%
2020	Zhongjiu Zheng et al. [194]	Power efficiency tracking	U-WPT system for the marine vehicle	85 kHz	Achieved a system efficiency of 88%

3.2. Auto-Recharge/Battery-Free System for UIoT

In the past two decades, underwater piezoelectric particles and devices have played an essential role in energy generation and harvesting in UIoT applications, as they provide sophisticated energy density and are flexible for integration when compared to electromagnetic devices [195]. Numerous researchers have used piezoelectric components to harvest electrical energy from humans and animals [196], and this methodology can be utilized for UIoT networks. Judith Santana et al. [197] proposed a new charging mechanism for battery-less UIoT sensor nodes, for ocean fish farm monitoring applications. Guida et al. [24] provide an acoustically powered battery-less platform for UIoT; this is still considered the first battery-less design for UIoT. Raja Jurdak et al. [198] estimate the battery life of UIoT devices to provide efficient energy optimization for UWASN. Figure 6 shows the battery-free sensor node developed by the Massachusetts Institute of Technology for ocean exploration; this navigation system was powered by an acoustic signal [25]. They have built a battery-less indicative system named underwater backscatter localization (UBL). Rather than producing its sound signals, UBL replicates modulated signals from the UIoT environment. In this case, the developers can find the location information with zero energy. This technology is still under development, in the future, UBL technology will be considered the key technology for environmental monitoring applications in UIoT networks and US Navy.

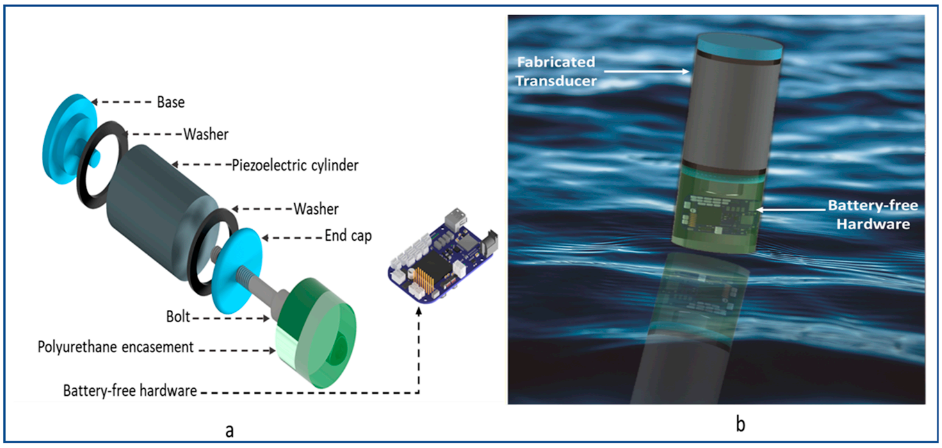

Figure 6. (**a**) Model of battery-free sensor nodes. (**b**) Design of piezoelectric sensor nodes invented by Massachusetts Institute of Technology (MIT), navigation system powered by sound [25].

T Kan et al. [174] proposed magnetic interface energy reconverting mechanism for underwater electric vehicles. In [199], the recharging model for AUVs was proposed based on ambient wave-induced motion. In this approach, a control moment gyroscope (CMG) ideology is considered, it utilizes the gyroscopic response of a flywheel that is equipped within AUVs to generate electric energy based on the rotation speed of AUVs. In [200], a novel method to harvest electrical energy from aquatic species was proposed. It can be denoted as a self-powered acoustic transmitter. In [158,195], a piezoelectric beam-based energy source was generated from sea species activities such as swimming, noise generation, etc., and stored as the battery backup for rechargeable and self-powered sensor nodes.

3.3. Solar Charging System for UIoT

Recently, in UIoT networks, mobile devices such as AUVs, UUVs, and ROVs have been equipped with solar charging systems; during the daytime, these vehicles can come to the surface water and harvest energy and store it as backup energy in their onboard batteries. The existing solar charging techniques are discussed in [26,201–210]. For example, the solar autonomous underwater vehicle I (SAUV I) [48] is the initial solar-based AUV developed with a lightweight technology of about 90 kg of weight. SAUV I is equipped with two panels of solar charging system with 30 Volts, a power controller, and 32 Ni-cad cells. Figure 7 shows the model of SAUV II [210], which was developed for monitoring and surveillance with an operating depth of 500 m, equipped with a solar panel of 1 m^2, a battery capacity of 2.4 KWh, and an air weight of 200 kg.

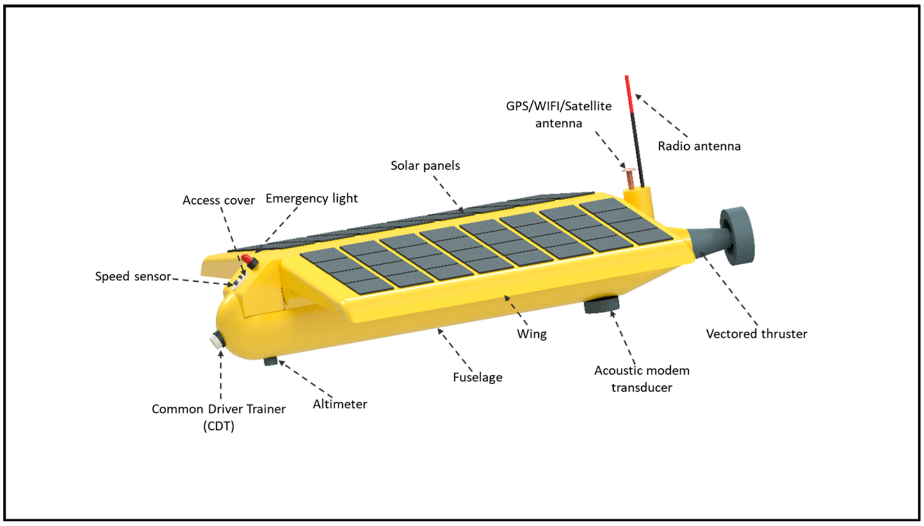

Figure 7. Model of solar-based autonomous underwater vehicle.

3.4. Battery Swapping Approaches in UIoT

In UIoT networks, battery swapping methods are generally used for underwater vehicles such as AUVs, UUVs, or ROVs to replace their batteries when they land on surface water. Although the processing time for battery replacement is fast, the downtime allied with resurfacing, swapping, and plunging into underwater vehicles is a huge process. In addition, the battery-swapping process needs supporting crew and vessels. Therefore, this process needs more manpower and, similarly, it is costly and difficult to manage. In one example, a battery replacement approach is adopted in Bluefin [23], a model shown in Figure 8. Bluefin is the AUV that is adapted with a battery replacement mechanism, the total processing time for battery replacement takes around 30 min, which includes resurfacing, battery swapping, and plugging into the vehicle.

3.5. Artificial Intelligence and Machine Learning Approaches in UIoT

Zhao et al. [27] proposed a battery-free-based machine learning technique for underwater environmental monitoring applications. In this technique, the underwater sensor node is designed to harvest energy by itself by utilizing the acoustic sound generated in the marine environment. The sensor node has a low-powered microcontroller onboard, it can charge up based on the acoustic power created by mammals or other objects in UIoT networks. This model emulates maritime bioacoustics applications, to recharge the nodes in UIoT networks based on the sound generated by underwater mammals. In addition, in the future, this device can be used as the sound recognizer of various animals in animal UIoT networks as shown in Figure 9. In [211], Seokhyeon Park et al. proposed the machine learning approach for handover in UIoT networks based on ocean currents. The handover priority is chosen based on the mobile node's current position and moving direction. This approach can reduce high battery consumption in UIoT networks.

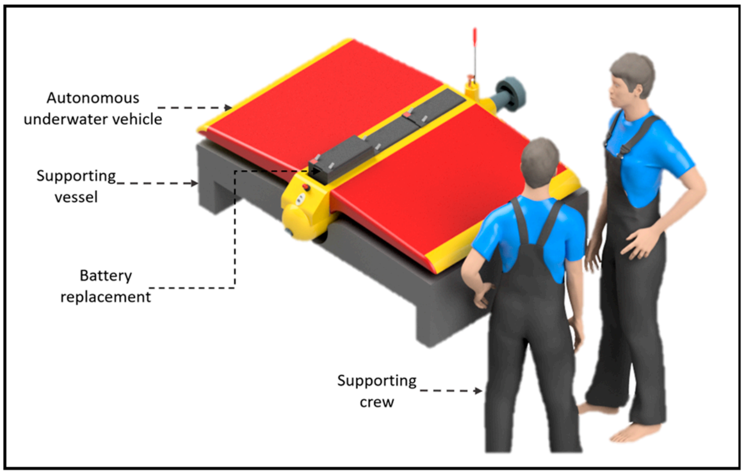

Figure 8. Model of battery replacement approach of Bluefin-AUV.

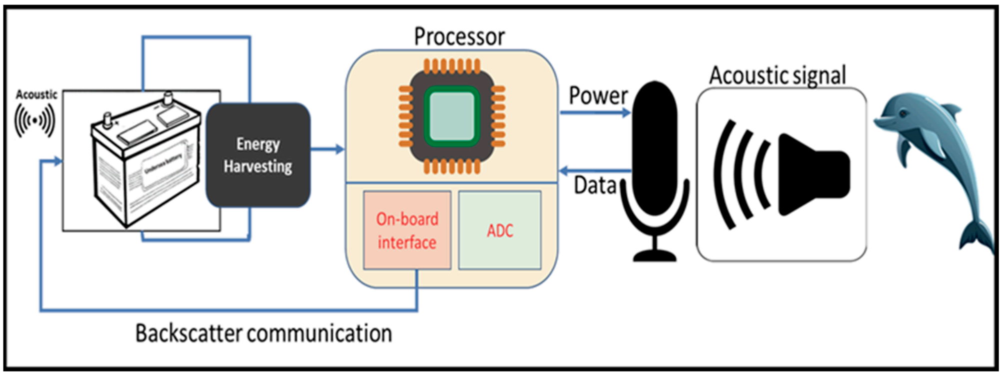

Figure 9. Battery-free sensor node approach for UIoT nodes.

Carlos et al. [212] proposed a novel approach to restore the energy of undersea sensor nodes to the extent of the battery life of UIoT devices. The research shows that the ocean waves can generate a frequency of 0.4 Hz in a second, this can supply energy to up to 48 sensor nodes. Daniel et al. [213] proposed a new approach utilizing plunked-driven piezoelectrics to harvest energy in UIoT networks. Wang et al. [214] proposed a reinforcement learning techniques-based power allocation model for full-duplex relay networks in UIoT environment. The simulation results show the proposed power allocation model performs well when the device has insufficient storage of energy. Mengqi Han et al. [215] proposed a sustainable energy harvesting approach for UIoT networks using reinforcement learning. The numerical result shows that the proposed approach improves the battery life and throughput during the transmission of data in UIoT networks.

3.6. Battery Management Approaches in UIoT

Harakare et al. [216] proposed a novel approach for battery management in AUVs. In this approach, lithium–polymer (LiPo) batteries are used by the authors to estimate the characteristics of batteries underwater, such as overheating, overcharging, quick battery loss, and damage, etc. This method can prevent damage to batteries in UIoT networks. Cheng Siong et al. [217] proposed a novel balanced battery management system by estimating the state of charge, and the test is successfully performed at the temperature of 4 °C in the water tank. Delphin et al. [59] proposed a network management system for underwater acoustic sensor networks. In this approach, the battery level of UIoT devices, such as available energy, consuming energy, and transmission energy, etc., are monitored to avoid future damage to the battery in UIoT networks. A summary is presented in Table 4 and the result is shown in Figure 10.

Table 4. Summary of various energy optimization techniques in UIoT.

Years	Main Clause	Subclause	Paper Count	Reference Number
2010–2022	Underwater wireless power transfer approach	Underwater acoustic wireless power transfer (UA-WPT)	4	[158–161]
		Consideration for underwater optical wireless power transfer (UO-WPT) based on the analysis of O-WPT	11	[162–172]
		Underwater inductive wireless power transfer (UI-WPT)	13	[173–185]
2010–2022	Surface water solar power transfer approach	Power transfer to AUVs/UUVs/ROVs	10	[202–211]
2010–2022	Auto-recharge/ battery-free system	Automatic recharge of sensor nodes using water particles, self-recharging, and battery-less sensor nodes	4	[21,36–38]
2010–2022	Battery swapping approach	Replacing the battery of AUVs with another battery	2	[23,24]
2010–2022	AI and ML approach	Deep learning, reinforcement learning, and lightweight AI mechanism	6	[27,211–215]
2010–2022	Battery management approach	To control and optimize the performance of battery modules	10	[120,216–224]

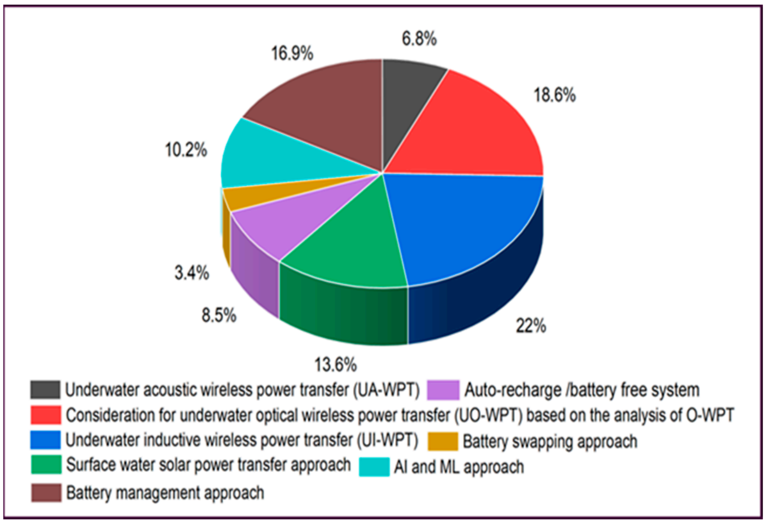

Figure 10. Analysis of various energy optimization techniques in UIoT networks.

4. Future Directions

Based on the results obtained from the current research study conducted in Sections 2 and 3, the future direction concerning the energy optimization issues in UIoT networks is discussed below.

4.1. Build a Multi-Medium-Based Smart Energy Consumption Model

Based on multi-media and multi-band-based adaptation layer techniques for UIoT by Delphin Raj et al. in [35], the battery consumption can be used efficiently using multi-medium communication technology. Eunbi Ko [36] proposed a selection mechanism for underwater multi-media communication to reduce the energy consumption in UIoT. Rakesh Kumar [71] proposed the novel method known as the hybrid communication model, which shows how to extend the network lifetime of underwater wireless sensor networks. The proposed approach was evaluated through a simulation environment and the performance was good in the case of battery life, throughput, and network life. Therefore, in the future, multi-medium communication technologies with a medium selection approach need to be adapted to UIoT devices to increase the battery life and to support fast and reliable data transmission in UIoT networks

4.2. Build Auto-Recharge Power Optimization Model

A seawater-based auto-recharging mechanism was developed in [13,14]. These are also known as sodium–seawater batteries (Na-SWB). Moon Son et al. [39] also proposed a battery model that can be recharged using seawater in UIoT devices, it is also known as the seawater battery (SWB). Finally, J Cho et al. [40] proposed a novel power optimization scheme for surface water buoys using seawater batteries. Therefore, it is necessary to apply an auto-recharging mechanism for underwater nodes in the future, or it is essential to build a power optimization model in the surface gateway and remotely operated underwater vehicle.

4.3. Build Battery-Free Sensor Nodes/Battery-Less Platforms for UIoT Networks

In [25], the Massachusetts Institute of Technology developed battery-free sensor nodes for UIoT applications. In [24], a battery-less platform using underwater wireless power transfer was developed for UIoT applications. These applications are still in the development stage and need further improvement in the future. In this case, in order to solve the energy optimization issues in underwater, it is necessary to adapt battery-free sensor nodes or battery-less platforms in UIoT networks.

4.4. Build a Smart Energy Harvesting Model Utilizing UIoT Environment

Energy harvesting and recharging from the UIoT environment is specifically necessary for solving the recharging issues in UIoT applications, wherever the placement of UW-SNodes is frequently hampered by limited in battery life, high network maintenance, and constrained underwater characteristics [28]. Though more researchers focused on energy harvesting using wild animals in terrestrial IoT applications, a few researchers tried to harvest energy from undersea animals and objects., such as energy harvesting using the piezoelectric beam generated from the fish moment, energy harvesting using the frequency band obtained from fast waves, energy harvesting using the ultrasonic sound wave generated from undersea mammals, and energy harvesting using the acoustic wave generated from ships. The explanation of each technique is explained below.

4.4.1. Recharge Using External Forces or Ultrasonic Waves Generated by Underwater Mammals

In UIoT environments, seawater mammals can generate external forces and produce ultrasonic sound naturally. For example, dolphins can produce a sound wave at the frequency of 0.2 to 150 kHz [225] under the sea to communicate with each other, and whales emit within the frequency range of 30 Hertz (Hz) to about 8000 Hz [226] in an undersea environment. In addition, the external forces generated by the sea mammals, such as tail moment, body moment, and swimming, can also generate energy in UIoT networks. In the future, the ultrasonic and external forces generated by the fish could be considered as one of the solutions for recharging low-power sensor nodes UIoT networks.

4.4.2. Recharge Using External Forces or Ultrasonic Waves Generated by Underwater Vehicles and Ships

In UIoT environments, the big-sized objects such as ships and underwater vehicles can produce acoustic noise as well as generating fast waves in an undersea environment. In the future, the ultrasonic and external forces generated by the ships and vehicles such as UUVs and AUVs, etc., can be considered as one of the solutions for recharging low-power sensor nodes UIoT networks.

4.4.3. Recharge Using Electric Power Generated by Seawater Species

Recent studies show that almost 350 species of fish in UIoT networks, such as electric eels, electric rays, electric stargazers, electric catfish, and skate, etc., can generate and detect electric signals [227]. For example, the electric eel can produce an electric current of up to 600 volts [228] and an electric ray can generate electricity ranging from 8 to 220 volts [229] in an undersea environment. Therefore, energy generated from seawater species can be considered as one of the solutions for recharging the low-power sensor nodes in UIoT networks.

4.4.4. Recharge Using Electric Power Generated or Transferred from UUVs/AUVS/ROVs

UIoT networks are equipped with smart sensing sensor nodes and high-power mobile devices such as UUVs/AUVs/ROVs. In addition, the sensor nodes are built with limited batteries. Therefore, in the future, the UIoT networks need the technology to find low-powered UIoT devices and produce the energy to recharge.

4.5. Build a Machine Learning (ML)-Based Battery Management System for UIoT Networks

In [42], a machine learning-based battery monitoring system was proposed to predict the battery lifespan in the terrestrial area network. In [43], a machine learning-based battery management system was proposed to detect the battery fault and find the remaining energy in terrestrial area networks. Hence, battery management is the major issue in UIoT networks. It is necessary to adapt the terrestrial IoT-based battery monitoring or management mechanism to UIoT networks. Therefore, energy optimization can be manageable for UIoT applications.

4.6. Build Artificial Intelligence (AI)-Enabled Energy Optimization Model to Reduce Battery Consumption in UIoT Networks

In [44], a smart AI-enabled energy management system was proposed for the internet of things (IoT). In [45], an algorithm for the energy efficiency maximization technique was proposed for UIoT. In the future, it will be necessary to build an AI-based energy-saving model to improve the efficiency of battery life in UIoT networks.

4.7. Build a Standard Security Model to Reduce Unwanted Energy Consumption in UIoT Networks

Delphin Raj et al. [58] provide the types of attacks in UIoT networks. A battery-oriented attack is considered an attack that targets particular devices in UIoT networks to drain the total energy of the device. In this case, it is necessary to develop a standard security model to protect the devices and save the battery life of UIoT devices.

4.8. Build Energy-Efficient MAC and Routing Protocols to Reduce Energy Consumption in UIoT Networks

Even though Table 1 describes the existing energy-efficient routing and MAC protocols of UIoT environment, energy efficiency is still a concern for UIoT networks due to the various factors discussed in Sections 2.1 and 2.2. Therefore, it is necessary to build a smart energy consumption module in UIoT devices by applying low energy consumption techniques or AI mechanisms such as auto device selection, less-mobility data transfer, and block/predict multi-transfers of data, etc.

4.8.1. Auto Device Selection in UIoT Routing Mechanism

UIoT devices are operated in a constrained UIoT environment, therefore it is necessary to adapt AI based selection module in UIoT devices, that can select appropriate devices and suitable mediums for routing based on the criteria such as distance, turbulence, temperature, etc. This approach can control excess energy consumption in UIoT networks.

4.8.2. Auto Mobility for Data Transfer in UIoT Routing Mechanism

UIoT devices are deployed in the deep-sea environment, however, some UIoT device mobility modules are not managed accurately due to the various factors that affect the device mobility, such as internal waves, mammal activities, water pollution, water density, etc. In this case, it is necessary to adapt the auto-mobility module in UIoT devices during the data transfer. This can avoid wastage of energy by selecting exact devices through routing in UIoT networks.

4.8.3. Block Multi-Data Transfer in UIoT Routing Mechanism

UIoT devices are sparsely deployed in UIoT environment, since it is difficult to avoid multiple repetitions of sending and receiving data of UIoT devices. In this case, it is necessary to adopt a multi-data transfer prediction and block mechanism to prevent the wastage of energy and data loss.

4.9. Build Smart Energy Harvesting and Transfer Modules in UIoT Networks

UIoT devices are adapted with limited battery capacity. Therefore, it is necessary to bring a smart-charging mechanism concerning wired and wireless communication in the underwater networks. One such important element is the undersea smart energy harvesting mechanism based on the cable power system. In this case, the energy can be stored from various sources in the charging station as shown in Figure 5, using the AI modules installed in each device, the low-powered devices are identified and the energy is transferred to those devices via wired or wireless communication technology. This mechanism can solve the limited energy issues of UIoT devices.

5. Conclusions

In the past two decades, energy optimization techniques are considered as one of the challenges of UIoT networks for long-term data transmission. Hence, this paper reviews the articles since 2010 and describes the various energy optimization issues, and state-of-the-art techniques concerning energy optimization in UIoT networks, and highlights the future solutions for energy optimization issues in UIoT networks. In this review, the fundamentals and motivations concerning energy optimization in UIoT networks are described in Section 1, and based on the discussion made in Section 1.1, the research contributions of this paper are pointed out in Section 1.2. Their descriptions is presented in Sections 2–4. Section 2 provides the taxonomy of energy optimization challenges in UIoT networks, including environmental characteristics, technical challenges, design challenges, and other challenges. Along with that, it provides the analysis of existing techniques developed for battery challenges vs. other UIoT challenges in Section 2.4. Section 3 provides state-of-the-art research on various energy optimization techniques in UIoT networks, including underwater wireless power transfer (U-WPT), auto-recharge systems, battery-free sensing approaches, solar charging systems, and battery swapping approaches, etc. In addition, from Section 3.1 to Section 3.6, the systematic review of numerous energy optimization techniques in UIoT networks is summarized in Table 4 and the results are displayed in Figure 10. In Section 4, the significant solutions concerning energy optimization in UIoT networks are highlighted as the future direction of this paper.

In the future, it will be necessary to adapt energy optimization or power-saving techniques to UIoT networks and devices, including the following: (1) building a multi-medium-based smart energy consumption model, (2) building an auto-recharge power optimization model, (3) building battery-free sensor nodes/battery-less platforms, (4) building a smart energy harvesting model utilizing UIoT environment, (5) building a machine learning (ML)-based battery management system, and (6) building a standard security model to reduce energy consumption for UIoT networks. In conclusion, to perform energy-efficient communication in UIoT networks and to solve the power optimization issues in UIoT networks, numerous techniques are discussed in Section 4, among which battery-free sensor nodes, automatic recharging using the water particles, and automatic recharging using sea mammal activities are considered as the best solutions for recharging the battery in UIoT environments. Other techniques such as multi-medium based medium selection mechanisms, standard security models for preventing battery attack, AI-enabled power saving models, and ML-based power-optimization techniques are considered as the best solutions for increasing the battery life of UIoT devices and network lifetime in UIoT environments.

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