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A Systematic Overview of Underwater Wireless Sensor Networks: Applications, Challenge and Research Perspectives

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ABSTRACT

Underwater Wireless Sensor Networks (UWSNs) are becoming increasingly popular in marine applications due to advances in wireless and microelectronics technology. However, UWSNs present challenges in processing, energy, and memory storage due to the use of acoustic waves for communication, which results in long delays, significant power consumption, limited bandwidth, and packet loss. This paper provides a comprehensive review of the latest advancements in UWSNs, including essential services, common platforms, critical elements, and components such as localization algorithms, communication, synchronization, security, mobility, and applications. Despite significant progress, reliable and flexible solutions are needed to meet the evolving requirements of UWSNs. The purpose of this paper is to provide a framework for future research in the field of UWSNs by examining recent advancements, establishing a standard platform and service criteria, using a taxonomy to determine critical elements, and emphasizing important unresolved issues.

Keywords: Wireless sensor networks; Ad-hoc networks; Internet of Things; Localization algorithms; Node mobility; Security mechanisms; Energy-efficient communication

1. Introduction

Wireless Sensor Networks (WSNs) are used to monitor aquatic environments via data collection and wireless transfer. Underwater Sensor Networks

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(UWSNs) have great potential in environmental monitoring, oceanographic research, and defense applications. Interconnected sensors form UWSNs, collecting and transmitting data wirelessly in underwater environments, facing unique communication and deployment challenges. Acoustic waves are primarily used for transmitting information underwater, resulting in high latency, power consumption, packet loss, and limited bandwidth. This paper covers key concepts of WSNs and underwater networks, as well as challenges associated with UWSNs. Additionally, it highlights various localization algorithms developed to mitigate these challenges. UWSNs are cost-effective for monitoring large bodies of water and providing real-time, accurate data about the underwater environment, allowing researchers to explore underwater areas that were previously uncharted. Several researchers [1,2] have worked on developing and implementing advanced techniques for achieving high-rate communication using underwater acoustic technology. Recent technological advances have enabled subsea exploration through the use of UWSN. These networks consist of aquatic sensors that collect data on water characteristics such as temperature, quality, and pressure. Sensor nodes are spread across the underwater environment and work together to detect and communicate potential threats. Deploying UWSNs requires a platform that can adapt to forced wireless communication resources. Adapting terrestrial WSNs to UWSNs is challenging due to the unique characteristics of the underwater environment. Designing and deploying UWSNs is further complicated by limited energy and storage capacity, harsh environmental conditions, and underwater object mobility. Nonetheless, the potential benefits make UWSNs an attractive research area. Several approaches have been proposed to address the challenges of UWSNs, including the use of acoustic communication [3], adaptive routing protocols [4], energy-efficient algorithms [5], and deployment strategies [6]. The Internet of Things (IoT) has also played a role in advancing UWSNs [7].

However, protecting this type of network remains a challenge and is a current area of research [8]. Autonomous UWSNs consist of nodes that can gather and communicate environmental data on their own, with their locations not always predetermined [9]. These networks are used in various applications, including military and maritime ones. The nodes can be stationary or mobile, and they are connected via wireless links [5]. The major use of these networks is to locate and identify targets or barriers. Centralized and decentralized architectures are the foundation for most data fusion systems seen in the literature [10]. Efficient routing protocols are also important for UWSNs [11]. In this study, various filtering methods used in the distributed architecture, including Extended Kalman Filter (EKF), Non-Hinty Filter (NH∞), and Smooth Variable Structure Filter (SVSF), are covered [12-17]. The study aims to conduct a comparative review of the literature based on UWSNs. Distributed fault detection filter design for UWSNs is explored by Chen Y. [18], while Feng Y. [19] focuses on distributed filtering for multiple target tracking in cluttered underwater sensor networks. Ez-Zaidi A. [20] provides a comparative study of distributed filtering algorithms for underwater target tracking in multi-sensor networks, and Shu H. [21] proposes a distributed multi-target tracking algorithm based on an optimal joint probabilistic data association filter in underwater sensor networks.

In this article, we aim to provide a systematic overview of UWSNs, including their applications, challenges, and research perspectives. Specifically, we will define the key concepts related to UWSNs, explain the potential benefits of using these networks, and highlight the challenges that need to be overcome for their successful deployment. Our objective is to provide a comprehensive understanding of UWSNs to researchers, practitioners, and anyone interested in this emerging field.

This paper provides an overview of UWSNs in Section 2, discussing their importance and potential to transform underwater sensing. Section 3 covers the various underwater wireless communication systems and challenges associated with UWSNs such as energy efficiency, node placement, and communication protocols. Section 4 presents the restrictions of undersea wireless sensor networks and current research and development efforts to improve their performance. Sections 5 and 6 discuss the research methodology and security requirements and difficulties for UWSNs, respectively. Section 7 presents UWSN applications, while Section 8 covers their architectures. Sections 9 and 10 discuss open research issues and localization algorithms, including range-free and range-based algorithms. Finally, Section 11 concludes the paper and suggests future research directions.

2. Definitions and key concepts of UWSNs

A wireless underwater sensor network can be constructed by connecting many nodes via bidirectional acoustic links [5]. Until it reaches the base station, a network node can exchange information with nearby nodes and communicate with them (see **Figure 1**). Each node may have one or more sensors that capture environmental data for transmission, usually to platforms or buoys on the surface [22]. Localization algorithms for UWSNs are discussed by Han G. [23], while Pranitha B. [24] provides an overview of propagation models and statistical characterization of underwater acoustic communication channels. Liu J. [25] proposes a distributed data compression method for underwater wireless sensor networks.

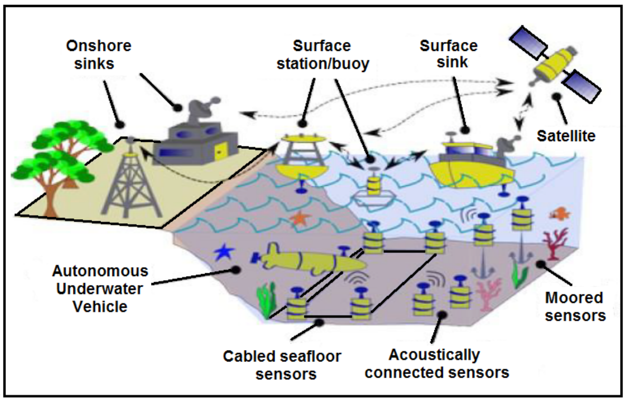


Figure 1. Underwater sensor networks [6].

UWSNs are networks of interconnected underwater sensor nodes that use acoustic and optical communication to transmit data to the base station. The design and deployment of these networks require consideration of factors like propagation delay, network lifetime, and routing protocols. In a study by Partan J. [26], the challenges of underwater communication and the need for reliable routing protocols are discussed. The proposed routing protocol, called “GloMoSim”, uses geographic and network topology information to determine the optimal path for data transmission in UWSNs.

2.1 Components of a UWSN and their functions

- **Sensor Nodes**: These nodes are responsible for sensing the environment and collecting data. They use various types of sensors, such as temperature, pressure, and pH sensors, to measure the physical and chemical properties of water. Alsulami M. [27] discusses the design and implementation of sensor nodes in UWSNs, focusing on the challenges of sensor placement and power management.
- **Communication Modules**: These modules allow the nodes to communicate with each other wirelessly. Acoustic and optical communication modules are commonly used in UWSNs. Heidemann J. [28] presents a comprehensive survey of communication technologies used in UWSNs, including acoustic and optical communication. The authors review the advantages and disadvantages of each technology and discuss their applicability in different scenarios.
- **Power Modules**: These modules provide power to the nodes, which can be in the form of batteries or energy harvesting systems. They are responsible for ensuring that the network lifetime is maximized. Ali M. [29] discusses the use of energy harvesting systems in UWSNs to extend the duration of network operation. The authors propose a novel energy harvesting system that uses piezoelectric transducers to generate energy from water flow.
- **Base Station**: The base station is responsible for collecting data from the nodes and processing it. It also serves as a gateway for data transmission to the outside world. Khalid M. [30]

presents a review of base station architectures and their impact on network performance in UWSNs. The authors compare centralized and distributed base station architectures and discuss their trade-offs in terms of data processing, energy consumption, and reliability.

2.2 UWSNs design overview

The UWSN architecture comprises sensor nodes, communication modules, and a base station that gathers data from the underwater environment and transmits it wirelessly. Data can be transmitted to external systems via satellite or terrestrial networks. The routing protocol plays a crucial role in data transmission. Ismail A.S. [31] identified several challenges in underwater acoustic sensor networks, including node localization, channel modeling, and network topology control. Various routing protocols have been proposed for UWSNs, and they can be classified based on different criteria such as data delivery, energy consumption, and network lifetime. UWSN network lifetime depends on factors such as energy consumption, transmission range, and data rate, and ensuring network longevity is essential for efficient underwater data collection and transmission.

3. Underwater wireless communication techniques

In this article, the construction of a UWSN using bidirectional acoustic links for underwater communication is discussed. The advantages of acoustic wave communication over other types of waves are highlighted, along with the challenges of attenuation and limited range, as presented by Goh J.H. [32] and Yan H. [33] The article also introduces Magneto-Inductive Communication (MIC) as a potential replacement for wireless networks in UWSNs. The unique features and challenges of UWSNs are also explained in this work, and key concepts related to the technology, such as energy efficiency, routing protocols, and network lifetime, are defined by Goyal N. [34] and Kashif Manzoor M. [35]

3.1 Underwater acoustic communication

Unlike traditional wireless networks that use electromagnetic waves for communication, UWSNs rely on underwater acoustic communication. Acoustic waves travel much slower in water than electromagnetic waves, and their signals are affected by various factors such as water temperature, pressure, and salinity.

3.2 Energy constraints

UWSNs are typically powered by batteries, which have limited energy capacity. Thus, energy efficiency is a critical design consideration for UWSNs, and various techniques such as duty cycling and node clustering have been proposed to reduce energy consumption.

3.3 Localization

In UWSNs, localization refers to the process of determining the position of nodes in the network. Due to the unique challenges of underwater communication, localization in UWSNs is a complex task and requires specialized techniques such as range-based or range-free localization.

3.4 Mobility

Some UWSNs may involve mobile sensors, such as underwater robots or autonomous vehicles, that can move around in the water environment to collect data from different locations.

The Internet of Underground Objects (IoUT) could also be referred to by the acronym IoUT, and it deploys sensor nodes and transceivers underground for real-time monitoring [36-40]. There are several aquatic wireless communication techniques (see **Figure 2**), including:

- **Acoustic communication**: It uses sound waves for underwater communication, which has advantages such as long-distance transmission, but also faces challenges like interference and attenuation. However, this method is limited by its bandwidth, propagation delay, noise susceptibility, and reverberation [35,39].

- **Optical communication**: It uses light to transmit data in water, providing high data rates but is vulnerable to absorption and scattering. Its advantages include high bandwidth, immunity to electromagnetic interference, and low propagation delays. However, limitations such as attenuation and absorption leading to limited range, signal distortion, and the need for specialized equipment and expertise make it challenging for underwater applications [35,38].
- **Radio communication**: It uses radio waves to transmit data through water. Radio signals can penetrate the water's surface, but they are subject to high attenuation and interference in water [35].
- **Magnetic communication**: It uses magnetic fields to communicate through the water. Magnetic signals can achieve moderate data rates and can penetrate obstacles, but they are subject to interference from the Earth's magnetic field [35].

It is worth noting that communication protocols are essential for efficient data transmission in UWSNs [41-43]. They are responsible for managing the network topology, routing data, and ensuring reliable communication. Some of the commonly used communication protocols in UWSNs are:

- **Medium Access Control (MAC)**: The MAC protocol is responsible for managing access to the communication medium, such as Time-Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA) [5].
- **Routing Protocols**: Routing protocols are responsible for determining the optimal path for data transmission from the source node to the destination node. Examples include Ad-hoc On-Demand Distance Vector (AODV), and Destination Sequenced Distance Vector (DSDV) [5,41].
- **Transport Layer Protocols**: These protocols provide end-to-end communication services for applications. Some examples of transport layer protocols are Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) [42,43]. Other transport layer protocols include Stream Control Transmission Protocol (SCTP), Datagram Congestion Control Protocol (DCCP), and Multipath TCP (MPTCP) [42,43].

4. Challenges of UWSNs

Designing UWSNs is challenging due to the unique characteristics of acoustic waves in marine environments. Highly variable underwater conditions, such as temperature, salinity, and currents, can impact sensor performance and lead to data inaccuracies. UWSNs face challenges such as high attenuation and multipath propagation, high energy consumption, interference, limited storage and processing power, and security threats. These challenges can significantly impact their performance, leading to communication failures, reduced transmission range, data loss, and potential security breaches. Studies [5,44,45] highlight specific design difficulties and challenges faced by UWSNs.

4.1 Limited bandwidth

The bandwidth of the underwater acoustic channel is small and highly dependent on the trans-

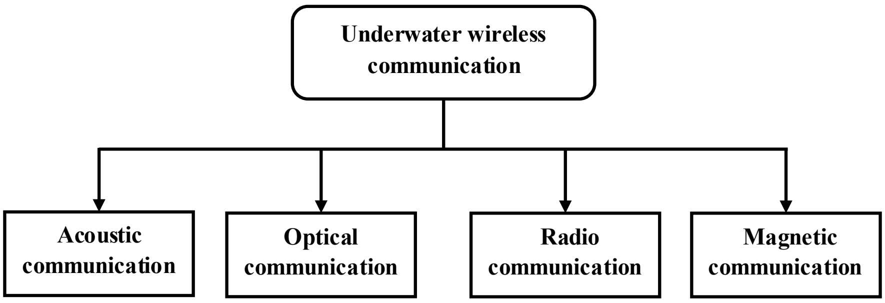


Figure 2. Underwater wireless communication techniques.

mission's range and frequency, as mentioned by Li N. [46]. Due to the high attenuation of radio signals in the water, underwater wireless communication channels have limited bandwidth, making it difficult to transmit large amounts of data, thus affecting the sensor network's performance.

4.2 Limited power resources

Designing underwater sensor nodes is challenging due to limited hardware resources and energy supply, particularly for long-range acoustic communication. Battery power is limited, leading to restricted data collection and computation capabilities, and a shortened lifespan of underwater sensor networks. Current research [5] focuses on energy-saving techniques, which can result in a short lifespan, requiring frequent maintenance and replacement.

4.3 Unreliable communication channel

Acoustic systems operate at 30 kHz, and the bandwidth of acoustic channels decreases with distance. Hydrological factors such as temperature, density, noise, and multipath and Doppler effects greatly affect underwater acoustic channels, leading to bit errors, delays, packet loss, and node failure. The studies [47,48] provide more insights into these factors and their impacts.

4.4 Vulnerability

UWSNs are subject to a number of active and passive limitations that leave them open to various dangers and malicious attacks. Nodes deployed in hostile environments are particularly vulnerable to physical damage due to hydrological topology. Ali M.F. [47] highlights these challenges and suggests that UWSNs are difficult to secure and monitor in deep-water conditions.

4.5 Interference

Interference from other underwater devices, marine mammals, and human activities can affect the performance of underwater wireless sensor networks. Developing communication protocols that can mitigate the effects of interference is a significant challenge [49].

4.6 Deployment and maintenance

Deploying and maintaining UWSNs in harsh and remote ocean environments is challenging. Researchers must develop efficient strategies for the deployment, anchoring, retrieval, and repair of sensor nodes. Jiang P. [48] highlights the need for effective methods to address these challenges.

4.7 Data management

Researchers face challenges in managing and processing the vast amounts of data generated by UWSNs due to high data rates and intermittent connectivity. They need to develop efficient data routing, storage, and processing techniques to handle these challenges (see **Figure 3**). These are just some of the many obstacles researchers and engineers face in developing and deploying effective UWSNs [5].

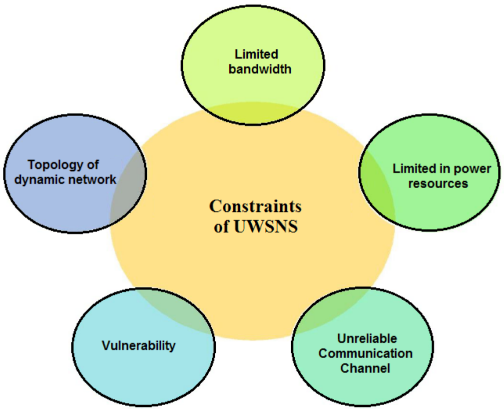


Figure 3. Challenges of UWSNs.

4.8 Topology of dynamic network

The deployment and mobility of wireless underwater sensors are challenging due to their high cost and the difficulties of real-time operations. Underwater objects' mobility creates a dynamic network structure that can affect the data flow and accuracy rate of data transfer. Researchers [50,51] have addressed this issue in the sensor network's architecture.

5. Research methodology

There are different research methodologies used to study UWSNs, depending on the research questions and objectives. Some of the common research methodologies used in UWSNs research include:

5.1 Experimental research methodology

This methodology involves conducting experiments on UWSNs to measure their performance, efficiency, and reliability. For instance, researchers can test the communication range, data transmission rate, and power consumption of UWSNs.

5.2 Simulation research methodology

This methodology involves simulating UWSNs using software tools to study their behavior and performance in a virtual environment. This method is cost-effective and allows researchers to test different scenarios, network topologies, and algorithms without the need for physical deployment.

5.3 Analytical research methodology

This methodology involves developing mathematical models to analyze the performance of UWSNs. For instance, researchers can use queuing theory, optimization theory, and probability theory to analyze the delay, throughput, and energy consumption of UWSNs.

5.4 Case study research methodology

The methodology involves studying UWSNs deployed in real-world applications to identify their challenges, limitations, and success factors. UWSNs are a type of wireless sensor network used in various applications, including oceanography, environmental monitoring, underwater surveillance, and offshore exploration. Different platforms exist in UWSNs, as shown in **Figure 4**:

- **AQUA**: It is a UWSN platform developed by the University of California, Santa Barbara. It supports high data rates and low-latency communication between underwater nodes through hardware and software components such as acoustic modems and routing protocols. Research on AQUA has been presented in studies by Ayaz M. [52] and Ma Y. [53].
- **UWMAC**: An Under Water Medium Access Control protocol (UWMAC) developed by the University of Manitoba. It is designed to provide efficient and fair sharing of the communication medium among underwater nodes and to support multiple access techniques, including time division multiple access (TDMA), Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA) [54,55].
- **DOLPHIN**: It is a platform for underwater optical wireless communication developed by the University of California, San Diego. It is designed to support high data rates and low-power consumption and to enable real-time video and audio streaming between underwater nodes [56].
- **WSNLab**: It is a simulation platform for UWSNs developed by the University of Rome. It is designed to enable the evaluation of different protocols and algorithms in a controlled environment and to provide a realistic simulation of underwater conditions, including water depth, temperature, and salinity [57,58].

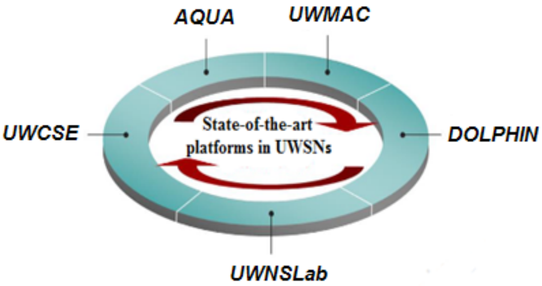


Figure 4. The UWSN platforms.

- **UWCSE**: It is a platform for underwater cognitive sensor networks to enable intelligent decision-making among nodes. It supports distributed sensing and actuation with cognitive radios and machine learning algorithms. The platform is developed by the University of Virginia [42].

6. Security requirements

6.1 Passive attacks

Detecting passive attacks in wireless sensor networks is difficult as they don't impact network functionality. Encryption can make it harder for intruders to gain access to data. Passive attacks involve nodes trying to obtain data without disrupting normal operations, and jamming can interfere with radio transmissions [58-62]. Packet captures enable packet decryption, eavesdropping, and secret communication delivery and can help to predict natural communication, as can be seen in **Figure 5**.

6.2 Active attack

Wireless sensor networks face vulnerabilities due to technical limitations like low energy consumption, radio waves, and low computational capacity. Active attacks by insiders or outsiders can modify or destroy data, while internal attacks can cause significant damage [63]. Attackers can be external to the network, making it challenging to isolate them, causing severe damage [58,64]. Encryption and authentication are critical security tools to address these challenges:

Node compromise attacks

Submarine sensor nodes in hostile sea environments face security challenges requiring specialized equipment. Nodes can be compromised and used for monitoring or interruption, causing significant damage [65-67]. Memory-based data access makes these nodes vulnerable to cracking and collection.

Repudiation attacks

In repudiation attacks, malicious nodes decline to participate in a certain communication action with other nodes. Whether the communication is malicious or not, a node involved in such a communication action will refuse. A subset of the features that can be anticipated from a security protocol, secret or authentication properties, is the subject of the verification of non-repudiation properties [54,67].

Routing attacks

To prevent malicious routing protocol attacks, cryptographic techniques are proposed, despite their higher power consumption. This approach is often used to protect against attacks, in addition to traditional computer security measures involving access control, authentication systems, and cryptographic protocols [54,68].

Flooding attacks

Flooding attacks can be carried out in two ways, one where an attacker sends common packets intensively to a single destination, making it difficult to distinguish between malicious and legitimate traffic, and another where an attacker asks for connection establishment until resources are depleted, causing valid requests to be rejected [69-71].

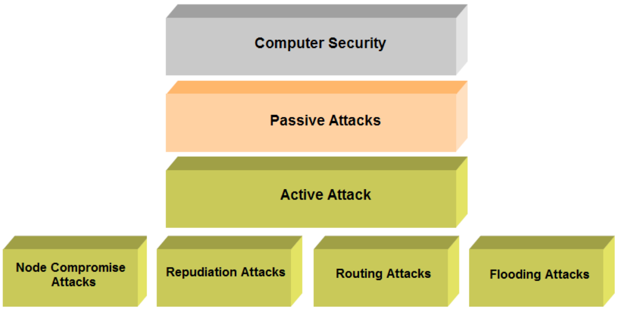


Figure 5. Emerging research direction and challenges.

6.3 Security criteria

Authentication

UWSNs require encryption to secure the acoustic channel and prevent attackers from intercepting and manipulating packet content. Proper identification of nodes can also enhance security. Intrusion Detection Mechanisms are effective in detecting anomalies and removing malicious nodes [70].

Confidentiality and survivability

Confidentiality is crucial to safeguard wireless networks from unauthorized access. Low-power encryption can prevent malware from stealing sensitive information. Ensuring the networks' survivability is important for maintaining essential services in real-time during attacks. The overall security of the network depends on the survivability of the Message Authentication Code (MAC) and the confidentiality of routing information [66].

Innovativeness

Lee J. [72] emphasizes that to achieve freshness in data transmission in real-time through the routing process, it is essential to ensure that the delay in messages does not reflect the wrong state of the network and leads to a large loss of information. This requires the strong application of technologies prioritizing the telecommunications, signal processing, and computer science sectors.

Integrity

UWSNs require measures to ensure data integrity and availability while protecting against unauthorized access and malicious attacks. This is important due to the unique challenges of operating in an underwater environment. The field of UWSNs is evolving, and its security measures must adapt accordingly. Ensuring the integrity of data is essential to prevent unauthorized alteration, corruption or loss of data [70,72].

Isolation

The use of isolation techniques and cryptographic algorithms can help identify and isolate malicious nodes in WSNs. Acoustic modems are also important for resource sharing and dependable underwater wireless transmission. Lower-layer protocols can be exploited to achieve better control of information transfer in the marine environment. This approach is independent of the protocol architecture used in different sensor networks [73,74].

Availability

To ensure the availability of UWSNs, a self-adaptive redundancy technique can be introduced to maintain communication services, even in the case of node failures or attacks. Achieving robustness against attacks requires risk modeling, intrusion detection, and node protection, as stated by Akyildiz I.F. [5]. Securing emerging systems, such as acoustic modems, is also essential and can be done through cryptography processes.

Self-stabilization

Self-stabilization consists in making the nodes recover in real time from attacks independently and without human intervention. If a node is self-stabilized in the face of malicious attacks in the network, it can recover that node by itself, even if the attacker is still trying to penetrate or remain in the network [59,74,75].

6.4 Security solutions

Encryption

Encryption is an effective solution for ensuring confidentiality and integrity. It encodes the data to prevent unauthorized access and ensures that the data are not tampered with during transmission [59].

Intrusion detection systems

Intrusion Detection Systems (IDS) can detect and prevent node compromise and data tampering. IDS can monitor the network and alert the authorities if any suspicious activity is detected [59].

Key management

Key management is crucial for secure communication in UWSNs. It ensures that the keys used for encryption and decryption are secure and not compromised [75].

Watermarking

Watermarking is a technique used for detecting data tampering. It embeds a unique digital signature in the data, which can detect any modifications made to the data during transmission [59].

Physical security

Physical security is the practice of protecting people, property, and assets from physical threats like theft, vandalism, or unauthorized access. It involves using physical barriers, locks, alarms, and surveillance systems to deter, detect, and respond to potential security breaches. Physical security is crucial for an effective overall security strategy and can help prevent or reduce the impact of security incidents [75].

7. UWSN applications

UWSNs have numerous potential applications in various fields such as environmental monitoring, maritime security, oceanic exploration, pipeline surveillance, etc. These technologies offer high precision and extensive coverage, which can help solve complex issues in the oceans and better understand the marine environment [40,76]:

7.1 Environmental monitoring

UWSNs can be used for monitoring environmental conditions in the oceans, such as temperature, salinity, water quality, presence of pollutants, etc. This information can help in better understanding climate change and preventing natural disasters.

7.2 Oil and gas industry

UWSNs can be used in the oil and gas industry for monitoring underwater pipelines, offshore drilling, and offshore platforms. They can help in detecting leaks, measuring pressure, and monitoring equipment performance.

7.3 Marine biology

UWSNs can be used for marine biology research, such as monitoring and tracking marine species, studying their behavior, and studying the underwater ecosystem.

7.4 Oceanographic data collection

UWSNs can be used for collecting oceanographic data such as temperature, salinity, and pressure. The collected data can be used for climate modeling, weather forecasting, and oceanography research.

7.5 Military and defense

UWSNs can be used for military and defense applications, such as underwater surveillance and monitoring of enemy activity. They can also be used for underwater communication and navigation.

7.6 Underwater infrastructure monitoring

UWSNs can be used for monitoring underwater infrastructure such as bridges, dams, and underwater tunnels. They can help in detecting structural damage, measuring water levels, and monitoring traffic.

8. UWSN architectures

8.1 Static two-dimensional (2D) architectures

Sensor nodes anchored to the ocean floor transmit data through a transmit-receive process to an underwater base station which transmits the information to a surface station via a transceiver. The communication between the surface station and surface and ground base stations is facilitated through a Radio Frequency (RF) signal, as illustrated in **Figure 6(a)**. Direct transmission of data from each sensor to the receiver is less energy-efficient and multi-hop transmission through intermediate sensors saves energy and expands network capacity. However, this method also poses challenges in routing the data [75].

8.2 Static three-dimensional (3D) architecture

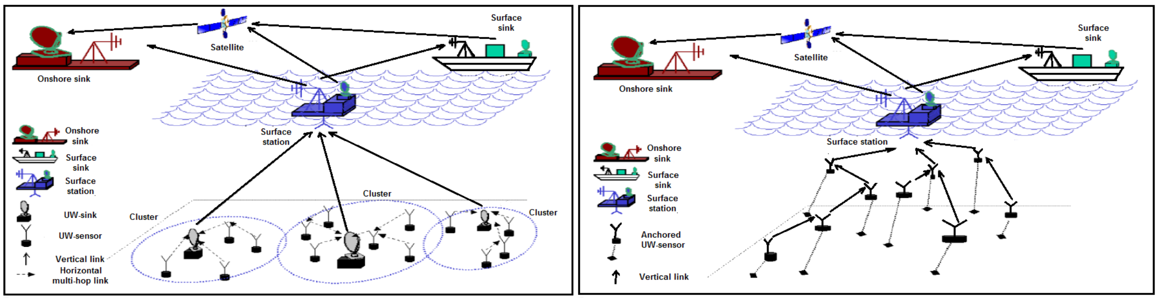
In this architecture, each sensor is anchored to the ocean floor and equipped with a floating buoy that fixes the sensor to the ocean surface [75-79] shown in **Figure 6(b)**. This architecture poses many problems that need to be solved to allow 3D tracking:

Detection coverage

The sensors in an underwater network need to collaborate to adjust their depths and obtain a 3D coverage of the ocean column based on their detection ranges. This enables them to sample the desired phenomenon at all depths and achieve global coverage [78].

Communication coverage

Isbitiren G. [79] and Cui J. [81] and have pointed out that 3D submarine networks require multiple relay points rather than a single base station for communication between sensors and the surface station as shown in **Figure 6(b)**. These multi-hop paths ensure



(a) (b)

Figure 6. UWSN architectures [76]: (a) Two-dimensional (2*D*) static underwater sensor arrays, (b) Static three-dimensional (3*D*) underwater sensor networks.

the reliable transmission of data. Coordination of depth levels is also important for maintaining a connected network topology. A minimum of one path between each sensor and the surface station is necessary for effective communication, making designing and operating such networks particularly challenging.

8.3 Autonomous sensor networks with underwater vehicles (4D)

Autonomous Underwater Vehicles (AUVs) have diverse applications in oceanography and seafloor exploration, using wireless or wired controls [25,38]. They are cost-effective and can navigate at different depths via sensors. Integrating AUVs with static sensor networks can improve UWSNs, and innovative methods are needed to achieve this objective [77], such as:

Adaptive sampling

Adaptive sampling, also known as control strategies, can be used to command mobile vehicles in hostile locations to ensure the usefulness of the data collected. Felemban E. [56] has proposed these strategies for surveillance missions. An example of this is increasing node density in an area when a high sampling frequency is required for a given monitoring phenomenon.

Self-configuration

AUVs can set up and maintain sensor networks by detecting connectivity devices and responding to node failure or data channel attenuation. They can deploy new sensors, establish network infrastructure, and act as temporary relay nodes. Solar-powered AUVs are an ideal choice, as they can continuously collect data for several months without needing to be recharged. Bian T. [75], Cui J. [77] and Blidberg D.R. [80] present this concept, which is illustrated in **Figure 7**.

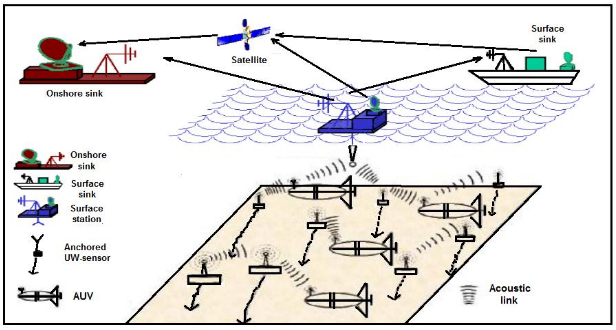


Figure 7. Three-dimensional underwater sensor networks with AUVs (4*D*) [75].

9. UWSNs based localization algorithms

9.1 Centralized localization algorithm

Localization in UWSNs is based on estimation, with sensor nodes lacking initial knowledge of their location. The control center calculates node positions during the post-processing stage through data gathering. Centralized systems involve a control center that gathers data on estimated distances between nodes and anchor nodes to determine node placement, as discussed by Jiang S.M. [51] and Ameer P.M. [81]. After identifying the positions of the sensor nodes, it sends location data back to the appropriate nodes, as described by Mirza D. [82] and depicted in **Figure**

8(a). The Centralized Localization Algorithm (CLA) for UWSNs is shown in **Figure 9**.

Hyperbola based localization scheme

The parabolic curve localization method, which utilizes hydrophones, is an effective approach to locating a mammal target. Felemban E. [56] presented a centralized sensor node that calculates the position, normalizes and calculates the error model, and transmits long-range signals to an anchoring node located at approximately 1 km distance. This method uses normal distribution for modeling and calibrating estimating errors and hyperboles for localization-based Schemes (HLS). Ayaz M. [52] noted that the HLS method is more reliable in finding unidentified nodes and reducing the risk of distance measurement inaccuracy compared to the circle approach.

Motion aware self-localization scheme

The Motion-Aware Self-Localization (MASL) system is proposed by Mirza D. [82] to address the difficulty of quickly collecting telemetry data in mobile UWSNs due to node mobility. The MASL system aims to identify errors in distance estimations and provide an accurate positioning scheme, but the longer signal propagation delay in the underwater environment may lead to outdated data due to the longer time required to gather distance estimations for localization.

Three-D multi-power area localization scheme

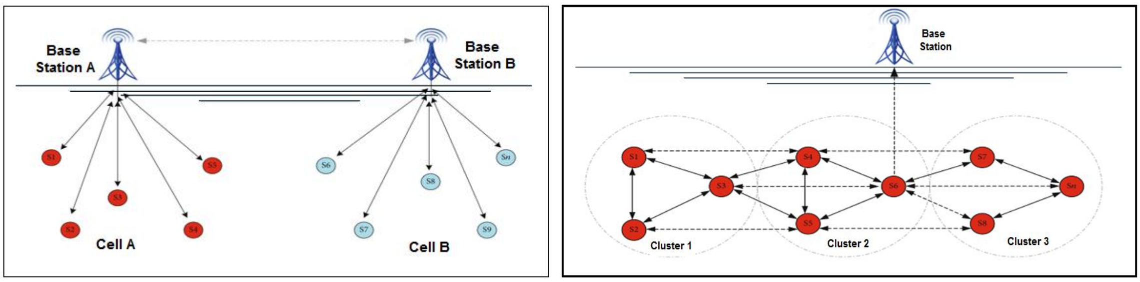
The 3D-Multi-power Area Localization Scheme (3D-MALS) is an advanced method proposed by Chandrasekhar V. [83], which uses a variable rate of transmission energy and vertical buoy mobility with a mechanical device called Detachable Elevator Transceiver (DET) to localize nodes. DET broadcasts its GPS coordinates at different energy concentrations and then descends underwater. Each surface buoy in a hybrid UWSN is equipped with a multi-powered acoustic transceiver and DET, which communicates with unknown nodes and then descends to broadcast position information at pre-configured depths. The DET broadcasts beacon signals at different powers from each broadcast site. This scheme offers high accuracy and robustness in a variety of underwater environments [84].

Area localization scheme

The Area Location Scheme (ALS) is a localization method for estimating the position of unknown nodes in large-scale underwater environments. It works by transmitting signals at different power levels and dividing the working region into non-overlapping areas using anchor nodes [85]. The ALS provides an estimate of the node's placement rather than precise coordinates, making it suitable for situations where accuracy is not crucial. The transmission power can be adjusted by anchor nodes, as demonstrated by Cheng W. [78] and the method does not require synchronization while having a low received signal strength. For more detailed information, Othman A.K. [86] offers a comprehensive description of ALS.

Collaborative localization scheme

The Collaborative Localization Scheme (CLS) is a technique for determining the position of underwater sensors without relying on long-range transponders. It utilizes two types of underwater nodes, including profilers that can dive deeper than other



(a) (b)

Figure 8. UWSN algorithms [82]: (a) Centralized network topology, (b) Distributed network topology.

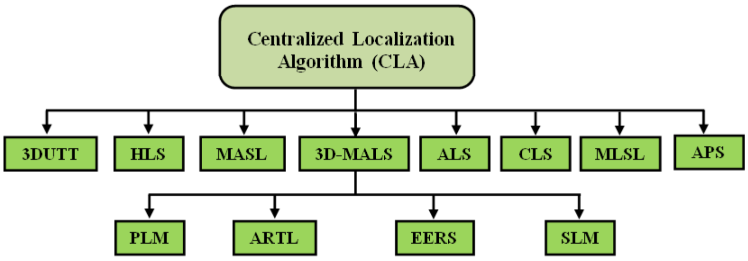


Figure 9. Centralized network algorithm.

nodes. To assign profilers to successor nodes, ToA is utilized based on the distance between them. This approach facilitates the collection and transfer of deep ocean data from underwater sensors to the surface. In this case, Bian T. [87] provides a description of the CLS.

Sensor arrays-based localization approach

The Maximum-Likelihood Source Localization (MLSL) method, proposed by Ma Y. [53] is commonly used in UWSNs that use sensor arrays to locate targets emitting narrowband acoustic signals. MLSL estimates the target position by analyzing the amplitudes of the received signals, utilizing the negative log-likelihood function. The global likelihood function is obtained by summing the local likelihood functions. MLSL does not require time synchronization or distance measurement, making it ideal for UWSNs. MLSL is connected to the Sensor Arrays based Localization Approach (SALA) via wired connections.

Probabilistic localization method

The multi-iteration approach used in terrestrial applications to reduce distance measurement error is not practical for underwater localization due to high communication costs. However, the probability distribution of distance measurement error in underwater environments follows a distinct pattern that can be leveraged to improve accuracy. Han G. [23], Bian T. [75], and Ameer P.M. [81] consider both uniform and normal error distributions and propose a Probabilistic Localization Method (PLM) to increase accuracy. Compared to other statistical approaches like Minimal Mean Squared Error (MMSE) and Minimum Mean Absolute Error (MMAE), PLM requires less information transmission [88].

Asymmetrical round-trip based localization

The Asymmetrical Round Trip based Localization (ARTL) algorithm proposed by Liu, B. [88] assumes that unknown nodes cannot receive their own packets, but anchor nodes can. The ranking scheme is used to determine distances between anchor nodes and unknown nodes based on the difference in arrival time. The base station uses this data and previously collected information to initiate the localization process. ARTL is a simple and efficient solution for UWSNs that does not require time synchronization, complex computations, or immediate replies from unknown nodes.

Absolute positioning scheme

AUVs provide researchers with new methods of ocean access, but accurate positioning data is crucial for their effective use. To address this issue, Liu B. [88] proposes an Absolute Positioning Scheme (APS) for locating AUVs. However, the acoustic interrogation pulse limits the localization coverage to only one AUV, and the timing difference of the signal arrivals is imprecise due to the motion of both the AUV and the ship. Using the ship's GPS-located hydrophone for AUV localization, as described by Isbitiren G. [79] is not practical due to high energy requirements and hardware costs.

Energy-efficient ranging scheme

Isbitiren G. [79] proposes an Energy-Efficient Ranging Scheme (EERS) for localizing sensor-equipped drifters in mobile UWSNs. EERS addresses the challenge of unpredictable mobility by using Sufficient Distance Map Estimation (SDME) to measure range through a one-way time of exchange message arrival. SDME includes synchronization-data collection (SDME-S) for time synchronization and distance estimation (SDME-D) using a two-step process. This method is more energy-efficient since not all nodes need to broadcast localization messages during the distance estimation process [22].

Three-dimensional underwater target tracking

The Three-Dimensional Underwater Target Tracking (3DUTT) algorithm is proposed for tracking underwater targets in two phases [79]. First, sensor nodes passively listen to the environment to detect targets, and then a projector node periodically sends pings to localize the target in the active ranging phase. The target's location and velocity are tracked by the sink node using trilateration for localization. The algorithm uses an adaptive approach to identify and activate new boundary nodes to prevent energy depletion. The sink node selects a new projector node based on the calculation results. The 3DUTT scheme is described by Isbitiren G. [79].

Silent localization using magnetometers

The traditional method of localizing nodes in UWSNs is limited due to sound scattering, but Silent Localization using Magnetometers (SLM) is suggested as a solution, replacing acoustics with magnetometers. The technique involves a friendly ship with a known magnetic dipole to locate unknown nodes with triaxial magnetometers. Each unknown node has a pressure sensor and an accelerometer for estimating depth and sensor orientation. An Extended Kalman Filter (EKF) is used to predict the vessel's trajectory and unknown node locations simultaneously. SLM is beneficial in shallow water environments where sound scattering is significant [89].

9.2 Distributed localization algorithm

The Distributed Localization based Algorithm (DLA) is a decentralized solution proposed by Chandrasekhar V. [83] for nodes in underwater sensor networks to locate themselves using neighborhood distance and anchor position information, and transmit data to a super node. Randomly distributed anchor nodes are used for position reference using distributed positioning techniques. Unlike terrestrial networks, GPS-equipped nodes cannot serve as anchor nodes in underwater networks, as cited by Mirza D. [82]. Nodes communicate through point-to-point leaves in a distributed network, as shown in **Figure 8(b)**, and the algorithm is presented below in **Figure 10**.

AUV assisted localization technique

The AUV Assisted Localization Technique (AUV-ALT) proposed by Erol M. [90] is designed for a hybrid 3D UWSN system comprising underwater sensor nodes and moving AUVs. The AUV determines its position using the "dead reckoning" method and receives GPS coordinates periodically when it travels to the water's surface. The locating process begins when an underwater sensor node sends a request signal to the AUV, which triggers the locating process, and the AUV responds with a signal. During the AUV cycle, a wake-up signal may be transmitted from a different location along its course to improve the accuracy of localization.

Dive and rise localization scheme

The Dive and Rise Localization Scheme (DNRLS) is a distributed location algorithm that uses mobile anchoring for underwater sensor node localization [91]. Dive 'N' Rise (DNR) beacons are mobile anchoring nodes that use GPS receivers to obtain their sea surface coordinates. The underwater sensors use the ToA method to measure distances from DNR beacons and calculate their location based on range estimations and anchor node coordinates. DNRLS has several benefits such as being silent, requiring low communication, and being energy efficient.

Three-dimensional underwater localization

The Three-dimensional Underwater Localization (3DUL) procedure involves three buoys floating on the surface and numerous underwater sensors at various depths, and has the drawback of requiring a long localization time and no time synchronization [91,92]. The procedure is carried out in two algorithmic phases, with ranging used to gather depth data in the first phase and dynamic trilateration used as a reference node to project buoy positions in the second phase.

Range-free scheme-based mobile beacons

The Range-Free Scheme based Mobile Beacons (RFSMB) technique is a range-free localization scheme that employs a mobile anchor node moving across the sea surface to random destinations to obtain depth information from pressure sensor installations on unidentified nodes [91]. This allows the unknown nodes to estimate their own localization independently by selecting three beacons that have been received. The RFSMB technique adheres to the Random destination point model [92].

Localization scheme using directional beacons

Luo, H. [93] introduced a novel Localization Scheme using Directional Beacons (LSDB) for two-dimensional localization in a sparse underwater environment. It utilizes a low-cost pressure sensor to detect the depth of a node and estimate its 2D position at the fixed depth. The nodes receive a series of beacons from an AUV while it moves in a straight line at a constant depth to enable localization.

Ray bending-based localization

The Ray Bending based Localization (RBL) approach addresses the issue of sound rays bending in water due to the depth-dependent sound speed, which affects the performance of traditional localization techniques that assume straight-line sound propagation. The RBL approach, presented by Ameer P.M. [94] and Porter M.B. [95] considers the spherical shape of constant range interval surfaces, which results from the assumption of constant velocity and a straight line trajectory.

Node discovery and localization protocol

The Node Discovery and Localization Protocol (NDLP) is a GPS and anchor-free algorithm for subsea localization [27]. It involves a primary seed node with a known position that identifies the relative placements of nearby nodes and selects a secondary seed node. NDLP allows for large-scale localization of unknown nodes by repeatedly selecting seed nodes, making it an effective solution for sub-sea localization.

Reactive localization algorithm

The Reactive Localization Algorithm (RLA) is an event-based localization algorithm presented by Toky A. [96]. It involves a sensor node detecting an event and broadcasting a message with its ID and energy level to its neighbors. At least four non-coplanar anchor nodes are discovered by the K-Node Coverage Algorithm. In the reactive localization phase, the selected anchor nodes respond with their position data, and the sensor node uses quadrilateration to locate itself. RLA provides an efficient approach to event-based localization in wireless sensor networks.

Multi-stage AUV-assisted localization scheme

The Multi-Stage AUV-assisted Localization Scheme (MS-AUV-LS) is a hybrid approach that combines AUV-aided localization and Silent Localization techniques [83]. The algorithm uses passive listening of localization messages by unknown nodes to improve localization accuracy and reduce localization time. Simulation results show that the entire localization process can cover over 95% of the network in less than 10 minutes. However, MS-AUV-LS is prone to accumulate errors like other multi-stage algorithms.

Multi-frequency active localization method-based TDoA

Multi-Frequency Active Localization Method (MFALM) is a proposed localization method for mobile UWSNs based on TDoA and only localizes nodes detecting events, as their positions can change at any time. The network consists of three types of nodes: Buoy, relay, and standard nodes. Buoy nodes use GPS to locate themselves and broadcast their location via low-frequency acoustic signals periodically. Relay nodes use low-frequency signals to partition the network into different localization regions and determine the maximum hops for each area. Common nodes that detect events receive low-frequency signals from buoy nodes to locate themselves [83,97].

Underwater localization using directional beacons

The Underwater Localization using Directional

Beacons (ULDB) method is suitable for a hybrid 3D underwater sensor network, where stationary nodes are located using an AUV [93]. The AUV determines its self-location when it reaches the water's surface and receives GPS coordinates, then dives to a specific depth and moves across the area of interest during the localization process. It uses a directional acoustic transceiver to transmit its position and transceiver angle, resulting in lower energy consumption than the AAL method, which is a silent localization method [98-101].

Multi-stage DNR localization scheme

The Multi-Stage DNR Localization Scheme (MS-DNR-LS) aims to locate an unallocated node in a 3D underwater sensor network. The method adds coverage, delays the localization of a further stage, and uses effectively located submarine nodes as anchor nodes. Three distinct nodes are used to estimate the coordinates and distance of the unallocated node [98].

Underwater positioning scheme

The Underwater Positioning Scheme (UPS) uses auditory range and/or direction, followed by triangulation, to monitor and operate underwater divers or vehicles [98]. It is used for various purposes, including oil and gas exploration, marine science, rescue, and military needs. UPS is extended for UWSNs in a TDoA-based tracking system proposed by Luo J. [99], which uses four anchors to transfer messages from tags sequentially.

Large-scale hierarchical localization approach

The Large-Scale Hierarchical Localization (LSHLA) proposed by Zhou Z. [102] uses surface buoys with GPS for absolute positioning and anchor nodes for communication. Unknown nodes communicate with anchor nodes for localization, while anchor nodes can directly communicate with surface buoys for their absolute positions. The approach involves two sub-processes: Anchor node localization and unknown node localization.

Wide coverage positioning

Nodes near anchor knots need five anchors to solve the problem. In the case of Wide Coverage Positioning (WPS), four anchors are used whenever a distinctive location can be reached using four anchors called UPS (4); otherwise, WPS will use five anchors (UPS (5)). UPS (4) and UPS (5) are used together to solve the overhead and communication cost for sensor nodes with four anchors that can already be located [103,104]. These nodes consume the same energy as the initial location system.

Underwater sensor positioning

The Underwater Sensor Positioning (USP) method uses pressure sensors to map anchors and determine underwater node positions [93,98]. Neighboring nodes' messages are used to refine estimated positions, and non-localized nodes use bi-lateralization to localize using only two anchors.

Anchor-free localization

Underwater localization techniques often require specialized devices or a large number of anchor nodes. However, Anchor-Free Localization (AFL), as stated by Fu B. [101], uses data from neighboring nodes instead of anchor node information. Cheng X. [100] proposed another technique that enables the discovery of unlinked nodes on a Line-of-Sight and any rigid reference node, allowing for anchorless and surface-reflective location methods using a protocol without GPS to find nodes and their relative location.

Scalable localization with mobility prediction

The Scalable Localization with Mobility Prediction (SLMP) technique uses surface buoys, anchor nodes, and common nodes to estimate positions. This method utilizes mobility models to predict anchor node positions, and GPS coordinates received by buoys to estimate their positions. The anchor node then uses distance measurements to estimate its position, and the mobility model is checked periodically for validity. This approach is scalable and efficient for large underwater sensor networks [59,105].

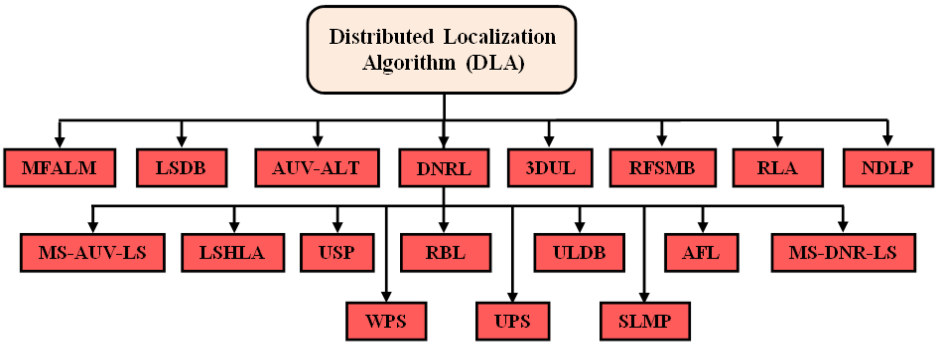


Figure 10. Distributed network algorithm.

10. Range-free and range based algorithms

10.1 Range-based algorithm

The Range-based Algorithm is a localization technique used in UWSNs to estimate the distance or angle between nodes using methods such as Time Difference of Arrival (TDoA), Time of Arrival (ToA), Angle of Arrival (AoA), and Received Signal Strength Indicator (RSSI). TDoA measures the time difference between signal transmission by different reference nodes to calculate distance, while ToA calculates the distance by measuring the ToA of signals. The latter is the most commonly used technique in UWSNs and is similar to the terrestrial sensor network. However, RSSI is not always practical in UWSNs due to certain constraints [106,107]. Zhou M. [108] and Luo J. [109] also proposed the use of ToA in UWSNs.

Time difference of arrival

A TDoA-based localization algorithm is proposed that does not require synchronization between base stations, which typically is necessary for improving accuracy. The method avoids using wideband signals or wire connections, which reduces operating costs. The proposed algorithm can locate a target even if the anchor nodes are asynchronous [97,110].

Time of arrival

Vaghefi R.M. [110] proposed a new method called ToA-Based Tracked Synchronization (ToA-TS) to address the need for balancing the target with anchor nodes in the ToA-based systems. This method uses GPS for time synchronization and identifies where beacon signals do not coincide. The receiver records the time of reception based on the submersible's local clock. Additionally, the author introduces a combined localization technique for Time of Flight (ToF) and Direction of Arrival (DoA).

Angle of arrival

An AoA algorithm estimates the location and orientation of underwater nodes by detecting signal angles from nearby nodes [97]. It uses a small antenna array to initialize the DoA as the azimuth direction of the vertex power and measures the phase derivative along the array axis to estimate the DoA. However, the range of arrivals may not always be precise. The algorithm provides close nodes around the node axis for each node in a network with zero attenuation [110].

Received signal strength indicator

In UWSNs, localization of sensors is a challenging task and commonly used methods are ToA and RSSI. RSSI-based localization relies on radio wave propagation path loss and has been implemented using acoustic signals [109]. Maximum likelihood estimation and frequency-dependent differential process are the proposed estimators. However, evaluating the distance between anchor nodes and unknown nodes is still a challenge, and ToA or RSS signals are commonly used for telemetry algorithms in UWSNs.

10.2 Range-free localization algorithm

The Range-free Localization Algorithms (RFLA) do not require bearing information and a hybrid localization algorithm for multi-platform mobile underwater acoustic networks was proposed by Guo

Y. [106]. The algorithm divides sensor nodes into multistage nodes, utilizing both range-based and range-free techniques to enhance localization accuracy and reduce communication costs. These techniques are valuable in underwater environments since they do not require prior knowledge of velocity.

Centroid algorithm

The 3D underwater location algorithm utilizes both mooring nodes and underwater sensor nodes to estimate positions. However, the Centroid Algorithm may not apply to 3D networks. Therefore, a joint and distributed establishment control of generic multi-agent robots is proposed for underwater applications like Autonomous Surface Vehicles (ASV). The algorithm aims to maintain a predefined geometrical shape with a leading agent whose dynamics are similar to those of its other supporters [75].

Hop count-based algorithms

The Hop Count-based Algorithm (HCA) utilizes anchor nodes placed along the boundaries or corners of a square grid. Several algorithms such as Distance Vector Hop (DV-Hop), Solid Positioning Algorithm (SPA), and DHL are presented to estimate the distance to anchor nodes. DV-Hop uses an average estimation of the spectrum of hops and the counted number of hops, while SPA adds an extra refinement step to improve accuracy. DHL dynamically estimates distance using density consciousness. These techniques are discussed in a study by Poursheikhali S. [97].

Area-based algorithm scheme

The Area-based Localization Scheme (ALS) is a range-free localization method that employs a synchronized sensor node clock, and is impervious to variations in sound speed underwater. 3D-MALS extends ALS to 3D, while Approximate Point in a Triangle (APIT) requires a heterogeneous network [78,97]. Anchors with high-power transmitters can use GPS coordinates for accurate location data. Zhou Z. [105] proposed a novel technique using MFCCs to extract underwater radiated noise characteristics.

11. Conclusions

The study highlights the need for further exploration and optimization of communication and localization techniques in UWSNs to improve accuracy and reliability. New communication protocols, algorithms, and hardware solutions need to be developed to address challenges such as low data rates, limited power supply, and unreliable information in UWSNs. Cost-effectiveness should also be considered in the design and deployment of UWSNs. To ensure a satisfactory future for UWSNs, it is essential to have a flexible architecture that enables wireless communication between different technologies. Future research should focus on improving node mobility, cooperative control, and high-level planning, with an emphasis on enhancing acoustic communication.

Challenges still exist in enhancing the capabilities and reliability of UWSNs for ocean monitoring and exploration. Research in this field could focus on developing hybrid energy harvesting strategies and exploring complex network scenarios. Another key area is developing data processing techniques to improve the accuracy of environmental measurements, including detecting and classifying underwater objects. Investigating the use of advanced sensors and actuators and integrating artificial intelligence and machine learning could further improve UWSN performance and enhance data analysis. Additionally, developing new approaches to energy harvesting and storage is critical for improving the endurance and reliability of UWSNs. Finally, integrating underwater robotics and autonomous vehicles could revolutionize the capabilities of UWSNs in ocean exploration and monitoring. By addressing these challenges, UWSNs can be fully realized, resulting in a better understanding and protection of the ocean environment.

Conflict of Interest

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