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Underwater Wireless Sensor Networks: Architecture, Communication Challenges, Localization Techniques, Security Issues, and Future Research Directions – A Comprehensive Survey

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***Abstract*: Dependable underwater monitoring technologies are of great importance to the marine environment evaluation, offshore infrastructure surveillance, oceanographic sensing, disaster prediction, and defense applications. Underwater Wireless Sensor Networks (UWSN) constitute the basis of such operations. Contrary to the radio-frequency dominated terrestrial communication, UWSN is inherently challenged by the nature of underwater physical medium. Acoustic signals are generally used in UWSNs, which have limited bandwidth, long propagation delay, high bit error rates, multipath distortions, Doppler shifts, and extremely low power. The positioning of nodes emerges as a critical requirement in UWSNs because of the insufficiency of physical measurements. GPS signals are inaccessible underwater, and alternative techniques should be used for underwater vehicle localization. Positioning can be achieved through acoustic ranges, anchor nodes, utilizing Autonomous Underwater Vehicles (AUV), cooperative localization methods, numerical optimization, and machine learning techniques. In this article, we present a comprehensive survey of the key aspects of UWSN. Specifically, we highlight the importance of localization in UWSNs, and give an in-depth overview of physical layer considerations, networking solutions, and advanced localization algorithms. We classify the localization algorithms based on range-based, range-free, mobile anchor utilization, optimization, and machine learning approaches. Additionally, we discuss the critical system-level impediments such as sound speed profiles, synchronization errors, sparse deployments, and possible security threats. Finally, we provide the insights on the topics of IoUT, edge intelligence, and federated learning, along with considerations on digital twins and energy autonomy.**

***Keywords*: Underwater Wireless Sensor Networks, Underwater Localization, Acoustic Communication, Internet of Underwater Things, IoUT, Swarm Optimization, Edge Intelligence.**

1. Introduction

Oceanic water bodies occupy around 71% of the Earth's surface and help control global climate, support marine life, facilitate sea transport, and contain natural resources. However, the underwater ecosystem is mostly unobserved owing to the physical limitations for signal transmission and high costs involved in underwater operations. The traditional approach to observation through oceanographic ships, diving activities, wired networks of instruments, and Remotely Operated Vehicles (ROVs) faces a limitation of high costs, poor geographical coverage, and temporal observation.

UWSN helps mitigate the above problems as the system enables uninterrupted multi-hop subsea sensing. Generally, an UWSN includes free-floating sensors, gateway nodes, buoy sensors, AUVs, and onshore base stations that work collectively to gather, process, and communicate physical data.

WSN extensively uses the radio frequency mode of communication that features high data rate and lower latency in air. When the same method is used in underwater environment, it faces high attenuation due to high conductivity of seawater and is restricted to a few meters' range unless the low-frequency spectrum (<100 Hz) with large aperture antennas is employed. Optical communication can achieve gigabit per second data rates but it suffers from beam spreading, turbidity scattering, and line-of-sight alignment restrictions. The acoustic wave will still be the physical medium of choice for transmitting information across tens to hundreds of meters beneath the ocean surface. Yet underwater acoustic channels are marked by slow propagation speed (approximately 1500m/s), limited bandwidth, multipath effects, Doppler shift, and high bit error rate (BER).

It is crucial to take into account spatial context while performing any sub-sea information processing: the readings on water temperature or some chemicals make no sense without knowing the geographical position of the node. The GPS radio signals do not reach underwater, so the nodes need to localize themselves with special acoustic localization algorithms based on the metrics like TOA, TDOA, RSSI, AOA, connectivity matrix, AUV path estimation, optimization techniques, or

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machine learning.

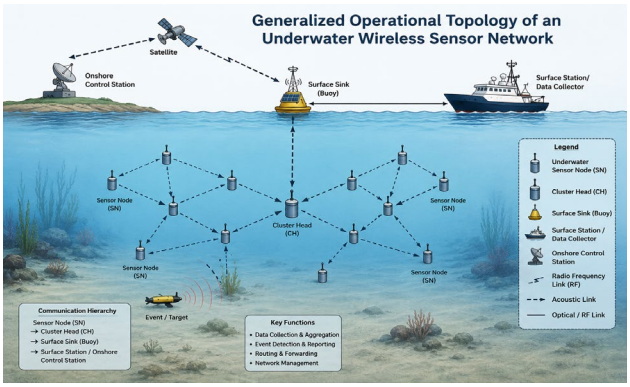

Fig. 1. Generalized operational topology of an underwater wireless sensor network

A. Motivation and Survey Contributions

Unlike existing surveys that concentrate on fragmented sub-topics like routing protocols, optical transceivers, or localization, this paper is intended to give an architectural and operational overview. The physical communication aspects, localization models, security threats, and intelligent control models have been considered in this paper.

The key contributions of this survey paper include:

- *Systemic Architecture Analysis:* An analysis of 2D, 3D, and hybrid UWSN deployment architectures along with physical layer communication challenges.
- *Localization Classification:* A classification of underwater localization protocols into range-based, range-free, optimization-based, and artificial intelligence-based schemes with analysis of their computational complexity and accuracy.
- *Analysis of Bottlenecks:* Analysis of the environment-related bottlenecks such as SSPs, node mobility, low density of anchors, and cross-layer power drainage.
- *Security Analysis:* An analysis of the attacks on the subsea routing and localization schemes.
- *Future Research Directions:* An analysis of IoUT, subsea edge intelligence, federated learning, and digital twins.

2. Background and Comparative Fundamentals

A. Technical Evolution of Subsea Sensing

Data collection for early oceanography was performed using boats, mooring lines, scuba divers, and ROVs tethered by cables. There was no continuous spatio-temporal sensing with this methodology because it was not scalable due to its high cost of implementation. The ad hoc sensor networks were adopted to perform water-based data sensing in an effective manner. This made use of nodes that sensed the environment and communicated the data through acoustic links. Modern low power processors, acoustic modems, and AUVs have led to IoUT, which is a network model for connecting underwater devices to cloud computing.

3. UWSN Architecture and Deployment Paradigms

A. Network Components

Four key layers of core UWSN systems include:

1. *Underwater Sensor Nodes:* Key components featuring sensing capabilities, low power microcontrollers, acoustic transducers, and battery packs housed within pressure-proof casings.
2. *Gateway/Cluster Head Nodes:* Unique subsea nodes featuring enhanced processing capabilities, greater memory and multi-frequency acoustic modems for collecting data from nearby sensors.
3. *Surface Buoys:* Floating platform equipped with two types of communication equipment, namely sub-sea acoustic modems and RF/cellular/satellite equipment for land-based connectivity.
4. *Autonomous Underwater Vehicles (AUVs):* Propelled mobile nodes capable of collecting data and conducting adaptive sampling operations, as well as serving as mobile localization nodes.

B. Topological Deployment Configurations

1. *Two-Dimensional (2D) Seabed Deployments:* The sensor nodes are tied to the sea bed in two-dimensional layout. They communicate through multi-hop acoustic channels with benthic gateway nodes that are connected to surface buoys through vertical cables. Such layout is good for pipeline surveillance, benthic mapping, and seismographic activity.
2. *Three-Dimensional (3D) Volume Deployments:* The sensor nodes are held at different depths using anchor-and-buoy tether system. Dynamic control over depth is possible by using motorized winches and buoyancy engines. It allows for monitoring of whole water column which is necessary for thermal gradient, salinity variations, and pollution monitoring.
3. *Mobile-Static Hybrid:* Static benthic and floating sensor nodes are combined with AUVs and surface vessels. The AUVs travel between the static node groups, collect cached information, and perform node localization. This helps reduce acoustic

Table 1
Subsea vs. Terrestrial WSN comparison

Parameter	Terrestrial WSN	Underwater WSN (UWSN)
Primary Transmission Medium	Electromagnetic / Radio Frequency (RF)	Acoustic Waves (Secondary: Optical, MI, RF)
Signal Propagation Velocity	$\approx 3 \times 10^8$ m/s	$\approx$ 1500 m/s (Environmentally variable)
Operational Bandwidth	Wide (MHz to GHz range)	Very Narrow (kHz range)
Propagation Latency	Negligible (µs scale)	High ($\approx$ 0.67 s/km)
Geographic Positioning	Direct GPS signal reception	GPS unavailable subsea; acoustic positioning
Node Mobility Model	Typically stationary or land-mobility	Passive drift caused by ocean currents and tides
Power Replenishment	Solar, wind, or easy battery replacement	Battery-constrained; high cost of subsea retrieval
Bit Error Rate (BER)	Low (10^{-9} to 10^{-6})	High (10^{-5} to 10^{-2}) due to multipath and fading

communication distances and save energy for stationary nodes.

4. Underwater Physical-Layer Communication Technologies

A. Acoustic Communication

Acoustic transmission still prevails in subsea communication applications due to its capability of propagating in liquid environments at a high speed of several kilometers. But acoustic transmission velocity is about 1500 m/s, which is five times slower than light. The transmission loss TL(d, f) depending on distance d and frequency f is defined by:

$$TL(d, f) = k \cdot 10 \log_{10}(d) + d \cdot \alpha(f) \cdot 10^{-3}$$

where k is the geometric spreading factor (k=1 for spherical and k=2 for cylindrical). The absorption coefficient α(f) can be found from Thorp's empirical equation for frequencies above 1 kHz:

$$\alpha(f) = (0.11\, f^2) / (1 + f^2) + (44\, f^2) / (4100 + f^2) + 2.75 \times 10^{-4} f^2 + 0.003$$

This equation limits high frequency acoustic signals to only short ranges, thus making long range acoustic systems use low frequency with narrow band width.

B. Optical Wireless Communication

UOWC relies on blue-green wavelength optical spectra ($\lambda \approx$ 400nm – 550nm) that suffer minimal attenuation in pure water. UOWC offers high data rates (up to Mbps to Gbps) and low latency, making it a good fit for subsea live video streams and AUV docking maneuvers. Nevertheless, UOWC suffers significantly from optical signals attenuation caused by absorption, scattering due to impurities and ambient lighting at surface layer level. Moreover, UOWC relies heavily on maintaining line-of-sight channel between transmitter and receiver.

C. Radio-Frequency and Magnetic Induction

RF signals attenuate rapidly (28 dB/m at 100 MHz) in conductive seawater. ELF RF can propagate farther, although it requires a large transmitter loop size and enormous amount of energy, making it non-applicable for small sensor nodes. RF technology is mainly limited to short underwater links (<5m) and cross boundary communication between surface buoys and land receivers.

Magnetic Induction (MI) technology relies on quasi-static magnetic fields generated by magnetic field loops. Magnetic induction allows for deterministic signal propagation without any multipath delay, sound speed profile fluctuations and water flow influence. Nevertheless, magnetic fields decrease rapidly with distance ($1/r^3$), thus communication distances are limited unless several hop relay coils are used.

5. Network-Layer Challenges in Subsea Environments

A subsea communication network is faced with various interrelated physical and network layer constraints:

1. Narrow Bandwidth and High Latency: The bandwidth available in subsea acoustic channel is low, hence slow speed of transmission of data. Signal propagation time is five orders of magnitude larger than terrestrial RF channels, thus making standard MAC protocols like CSMA/CD very inefficient due to longer idle times and collision of packets.
2. High Power Consumption: The power consumption by acoustic modems is high during transmission. Since it is not easy and expensive to replace sensor batteries, power consumption is an important factor to consider.
3. Dynamic Network Topology and Node Drift: The movement of subsea currents causes continuous shifting of the topology of the network due to movement of non-anchor nodes.
4. Channel Distortion: Reflection of multipath signals from the sea surface and seabed leads to channel interference. Doppler shift in frequencies is introduced by currents and drift of nodes leading to poor decoding of signals.

6. Comprehensive Analysis of Subsea Localization Techniques

Subsea localization techniques are generally divided into four types: range-based, range-free, optimization-based, and artificial intelligence-based algorithms.

A. Range-Based Localization Algorithms

Range-based techniques estimate distance and angle information from signal characteristics and perform trilateration or multilateration to find target coordinates.

- *Time of Arrival (TOA):* Estimate the distance from the one-way signal propagation delay Δt as d = v_sound · Δt. Requires synchronized clocks at the nodes within nanoseconds precision.
- *Time Difference of Arrival (TDOA):* Measure time differences of arrival of signals from multiple reference nodes. Form hyperbolic distance curves for localization. No need for clock synchronization at the target node.
- *Received Signal Strength Indicator (RSSI):* Calculate distance from transmitted acoustic power and received signal strength according to a log-distance path loss model. Very susceptible to fading and path loss.
- *Angle of Arrival (AOA):* Determine the arrival angle of an incoming signal with the help of hydrophone arrays.

B. Range-Free Localization Algorithms

Range-free approaches make position estimates based on connectivity matrices in the network, hop counts of anchors, or topological boundaries without any distance calculation. They include DV-Hop (Distance Vector-Hop) algorithm and Centroid Localization. Range-free algorithms use very little energy but have lower accuracy.

Table 2
Comparative analysis of subsea localization algorithms

Category	Representative Schemes	Accuracy	Complexity	Clock Sync Req.	Mobility Resilience
Range-Based	TOA, TDOA, AOA	High (0.5–2 m)	Moderate O(N)	High (Nanosecond)	Poor
Range-Free	DV-Hop, Centroid	Low–Mod (5–20 m)	Low O(1)	None	Moderate
Optimization	PSO, GWO, WOA	High (0.2–1 m)	High O(K·I·P)	Metric dependent	High
AI-Driven	DNN, RL, LSTM	Very High (< 0.5 m)	High train/Low infer	Low	Very High

C. Optimization-Based Localization Algorithms

Optimization approaches pose node localization as an optimization problem that requires finding the minimum distance error between measurement and computation:

$$f(x_u, y_u, z_u) = \sum w_i \mid \sqrt{((x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2)} - \hat{d}_i \mid^2$$

Heuristic Optimization Algorithms such as Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), and Whale Optimization Algorithm (WOA) solve this optimization function without falling into the trap of local minima.

D. Artificial Intelligence and Machine Learning Localization

Supervised regression models (SVM, KNN) use RSSI and TOA features in a one-to-one mapping manner to estimate positions. Deep Neural Networks (CNN, LSTM) work on spatio-temporal CSI to find the locations, and Reinforcement learning approach allows AUVs to intelligently modify flight paths in favor of covering space completely.

7. Critical Bottlenecks in Subsea Localization and Security

A. Environmental Constraints & Sound Speed Profile (SSP)

The speed of sound in water depends on temperature, salinity, and pressure, which is formulated by Medwin in his equation as follows:

$$v = 1449.2 + 4.6\,T - 0.055\,T^2 + 0.029\,T^3 + (1.34 - 0.01\,T)(S - 35) + 0.016\,Z$$

This results in refraction of acoustic waves through a non-straight path due to the dependence of sound speed in seawater, resulting in estimation error for ranges.

B. Cyber-Physical Security Threats

- *Wormhole attacks:* Attack nodes collect acoustic packets at one place and transfer these packets to other areas using an out-of-band high-speed communication channel.
- *Sybil attacks:* One malicious node plays the role of several anchor nodes and broadcasts false coordinates.
- *Phantom anchor attacks:* Attackers delay the ranging packets, resulting in incorrect positioning calculations.

8. Future Research Directions

1) *Internet of Underwater Things (IoUT):* Connecting underwater sensor networks to the global IP network via autonomous surface gateways that allow real-time monitoring and tracking of oceans.
2) *Subsea Edge and Fog Computing:* Performing filtering, anomaly detection, and localization optimization on edge buoys and AUVs instead of land-based servers to decrease latency and conserve bandwidth.
3) *Digital Twin for Marine Sensor Networks:* Building a real-time digital twin of an underwater network to predict node drifting and link failure and improve network performance.
4) *Federated Learning on Power-Constrained Sensor Arrays:* Training the localization models on all nodes in the subsea network locally by exchanging only the model weights.
5) *Subsea Energy Harvesting:* Building a hybrid energy harvesting node by harnessing the energy of waves, tides, and thermal gradients in the ocean.

9. Conclusion

Underwater Wireless Sensor Networks (UWSNs) offer indispensable infrastructure for ocean surveillance, resource exploration, resource management, and security applications. Acoustic operation in underwater networks imposes challenges in the form of physical limitations such as low speeds of propagation, low bandwidth, high levels of signal attenuation, node drift, and limited energy. This survey analyzed the architectures of UWSNs, the challenges at the physical layer in terms of communication, the problems that can occur at the network layer and localization protocols.

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