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A Survey on Underwater Wireless Sensor Networks and Applications

A. Gkikopouli, G. Nikolakopoulos and S. Manesis

Abstract— **In this article a survey on the different technologies in the area of Underwater Wireless Sensor Networks (UWSN) will be presented. The characteristics of these networks are different from those found in the terrestrial ones, while their architecture is vulnerable to various issues such as large propagation delays, mobility of floating sensor nodes, limited link capacity and multiple messages receptions due to reflections on the sea ground and sea surface. This article will present an overview of the underlying technologies in UWSN and will focus in presenting the most important research approaches towards UWSNs' architecture, routing, MAC and localization protocols, energy consumption and security, while highlighting their most illustrative real-life applications.**

I. Introduction

Wireless Sensor Networks (WSN) have become a dominant technology in our days, while their applications are creating a huge impact in the way that many processes are being interconnected and share valuable information. Due to the recent developments in the WSN's communication capabilities and in the improvements of the networks' infrastructure, this technology could be applied in numerous applications, where characteristic examples could be extracted from: a) environmental monitoring and forecasting, b) infrastructure structural health monitoring, c) localization and tracking, d) distributed health monitoring, and d) decentralized actuation and control.

Recently, there has been an extended interest regarding the deployment and fine tuning of underwater wireless sensor networks that would be able to support multiple ocean applications such as: oceanographic data collection, seismic waves monitoring, sea water pollution measurement, assessment of water quality, supporting unmanned underwater robotic missions, biological monitoring, and security. In the industrial world, the use of UWSNs is limited and met until now in large-scale wastewater treatment plants where the large tanks or lagoons may contain sludge and wastewater simultaneously. In such cases we need to know the varying level of the sludge below the treated water or to perform concentration measurements of the various chemical and biological contaminants through underwater sensors.

For many years, the traditional approach for ocean monitoring has been the deployment of underwater smart sensors that were able to record on board data and afterwards recover them on the surface after their collection. This approach posed a lot of limitations as: a) it had the drawbacks of not allowing the online processing of the acquired information, b) closed loop/bi-directional communication and mission reconfiguration was impossible, and c) failures and malfunctions could not been identified at the moment that were taking place [18].

Nowadays the extension of WSNs to the UWSNs have emerged new possibilities as these networks are allowing the deployment of smart, reconfigurable and fault tolerant sensing nodes that have the same merits as the terrestrial WSNs. Despite this great achievement, the UWSNs are still vulnerable to various issues stemming from the need to exchange data underwater. Due to the fact that the water is a worse communication medium than the air, the UWSN communications are characterized by large propagation delays, limited link capacity, low bandwidths, greater number of packet losses, limited battery life, and packet re-ordering/multiple message receptions mainly due to the reflections of the data packets on the sea ground and the surface [2]. The aim of this article is to present the most representative current research efforts and the technological advances that aim in increasing the UWSN performance and allowing their vast utilization, while acting as a base start for those that would like to emphasize in this area.

This article is structured as it follows. In Section II the technology and the characteristics of the UWSN are being presented, while in Section III an overview on the current research efforts in this area are being presented, where the focus is in: a) routing, b) localization, c) energy consumption, and d) security. In Section IV illustrative applications from real-life deployments of UWSN will be reported and in the last Section V the conclusions are drawn.

II. The Underwater Wireless Sensor Networks

Underwater wireless sensor networks consist of a variable number of nodes, deployed both at underwater and at the surface, and are aiming in performing collaborative tasks over a prescribed area. To achieve this purpose, the nodes should exchange and share information among themselves and base stations, while at the same time should self-organize the characteristics of the communication channel to adapt to the current application needs, as posed by the surrounding environment. Most of the applications usually being found in the area of UWSN can be classified into three

A. Gkikopouli and S. Manesis are with the Department of Electrical and Computer Engineering, University of Patras, Rio 26500, Greece.
(e-mails: ece6730@upnet.gr{stam.manesis}@ece.upatras.gr.
G. Nikolakopoulos is with the Department of Computer, Electrical and Space Engineering, Luleå University of Technology, Luleå 97187, Sweden (e-mail: geonik@ltu.se).

categories which are: a) monitoring, b) tracking, and c) actuating applications, while all these applications are directly affected by the induced time delays.

A generic UWSN configuration is the one depicted in Fig. 1, where the multiple types of UWS-nodes depending on the node's mobility and level of operation could also be observed. In general the nodes could be anchor, ballast or floating nodes and also could act as a simple measuring and actuating node or a base station. This approach could also be extended to the case of having Autonomous Underwater Vehicles (AUVs) as the last could also considered as ballast nodes.

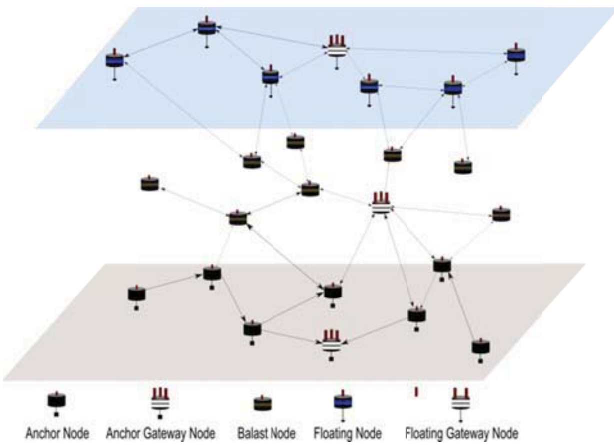

Figure 1. Generic Layered UWSN Deployment and Different Types of Nodes

In UWSN there are three types of transmission medium, which are the acoustic communication, the radio wave communication and the optical communication [23]. Each one of these mediums has the merits and the drawbacks that should be considered before selecting the appropriate one. In the sequence, these mediums will be presented.

A. Acoustic Medium

Acoustic communications are the typical physical layer technology in underwater networks. In deep waters, acoustic channels propagate very well through conductive sea water at long distances only very low frequencies (30-300Hz) [26],[39], while many applications in UWSN prefer to use sonic transducers due to the high attenuation of electromagnetic signals in water [24]. However, the speed of the sound in water depends significantly on salinity, temperature and pressure. The authors in [30] have taken into consideration the aforementioned variation and proposed an algorithm to generate an estimate the speed of sound using signal propagation characteristics. In spite of the common preference of acoustic channels in deep waters, the good performance reduces the signal bandwidth (~KHz) and transmission rates. As a consequence, the communication time extends, which means very large propagation latency and more energy consuming [28]. In shallow waters, acoustic propagation is a rather unfortunate choice, since it attenuates and it is prone to noise and turbidity.

B. Electromagnetic Medium

The most valuable characteristic of the Electro Magnetic (EM) communication is the utilization of higher carrier frequencies, which leads to larger bandwidths (~MHz) at the cost of very close ranges. The speed of the EM wave exceeds by 4 orders of magnitude the speed of acoustic waves, which reduces the delays evidently [39]. Furthermore, EM waves are immune to acoustic noise and quite tolerant to turbulence caused by tidal waves or human activity [9]. Among optical and radio waves, the latter is not influenced by the clarity of the water, which gives an important precedence over shallow water communication. However, it is expected that submarine EM propagation will experience very high signal attenuation due to the fact that saline water is conductive [38]. The final restriction in the use of EM is that it suffers from Electro Magnetic Interference (EMI).

C. Light Medium

The nature of light is the main cause for the limited exploitation of the optical waves, since light is abruptly absorbed and the intensity of light decreases exponentially with water depth [9]. Therefore, it requires tight alignment of nodes and operation only in very clear waters. Comparing to EM waves, the optical ones succeed in higher bandwidths, reaching even gigabits per second, but lack in insensibility to turbidity and function well in short ranges. However, it is being investigated whether it is possible to use relatively low-power components and circuits equipped with LEDS and photodiodes, so the cost of the communication system will decrease significantly. Applications, such as performing pollution monitoring and frequent data collection (water temperature, specific conductivity, pH, turbidity, and possibly oxygen concentration) could use a high-data rate optical link to periodically deliver data. Ongoing research efforts appeared in [24],[3],[4] focus on building the best-fitting PHY(Physical) and MAC Layer for both optical and electromagnetic communication.

Regarding the architecture of UWSNs, this could be classified in the following three types [2]:

1. Static two-dimensional underwater acoustic sensor networks (UW-ASNs) for ocean bottom monitoring. These networks are constituted by sensor nodes that are anchored to the bottom of the ocean. However, they lack of real time applications and the interaction between control center and monitoring instruments is impossible. Applications, using this kind of architecture could be environmental monitoring or monitoring of underwater plates in tectonics [18].
2. Static three-dimensional UW-ASNs for ocean-column monitoring. This category includes networks of sensors that float anchored at different depths and could be used for surveillance applications or monitoring of ocean phenomena (ocean bio-geochemical processes, water streams, pollution).
1. Three dimensional networks of autonomous underwater

vehicles (AUVs). These networks include fixed portions composed of anchored sensors and mobile portions constituted by autonomous vehicles. Typical applications may be oceanography, environmental monitoring an underwater resource study [15].

In order to overcome the shortcomings of two-dimensional and three-dimensional underwater sensor networks, [49] proposed a new concept: flexible loading platform. Its function is to load the different sensors for different tasks and detect data, while going up and down by inflating or shrinking it's cubage through a bladder equipped pump.

III. Research Approaches Overview

A. Routing Protocols

A detailed list of the existing routing protocols can be found in [7], and a synopsis of them is being depicted in Table I.

TABLE I. **EXISTING ROUTING PROTOCOLS**

I.	Vector-Based Forwarding Protocol (VBF)
II.	Robustness Improved Location-Based Routing for Underwater Sensor Networks (H-VBF)
III.	Depth-Based Routing for Underwater Sensor Networks (DBR)
IV.	Hop-by-Hop Dynamic Addressing Based (H2-DAB)
V.	Focused Beam Routing Protocol for Underwater Acoustic Networks (FBR)
VI.	Path Unaware Layered Routing Protocol (PULRP)
VII.	Adaptive Routing
VIII.	GPS-free Routing Protocol for Deep Water (DUCS)
IX.	A Low Propagation Delay Multi-Path Routing (MPR)
X.	Pressure Routing for Underwater Sensor Networks (HydroCast)

NIR [44] is a UWSN routing protocol based on node neighbor information, which chooses the next step via the Greedy Strategy where the nodes with more neighbors are provided with a higher communication rate. Adopting the single-path Greedy Forwarding (GF) in NIR can be a great energy saver, but it limits its applications only to 2D underwater circumstances.

The challenge of an adaptive scheme for setting data propagation range, always weighing up the consequences in the energy consumption throughout the network, has caused the evolvement of a Reliable and Energy Balanced Routing Algorithm (REBAR) [10]. The aim of this algorithm is to reduce the energy consumption of the nodes near the sink, by letting the nodes broadcast in a specific domain, between source and sink, by utilizing geographic information, since network-wide broadcast causes high energy expenditure. Taking into consideration that the presence of underwater obstacles or even node malfunction restrain the network coverage and leave regions unsecured, an extended REBAR with a mechanism to bypass the uncovered areas (voids) in the network has been utilized. In terms of network lifetime and packet delivery ratio, the simulations have indicated that REBAR performs well enough to top the VBF-based (Vector Based Forwarding) algorithms. However, when there is no node mobility, the sink fails to receive new packets, because the nodes close to sink consume their energy very quickly.

In [12], a mobile geocast (or mobicast) routing protocol has been introduced to maximize the data collection and minimize the energy consumption problem, while the proposed scheme is being applied into two stages. In the first one, the AUV collects data from sensor nodes within a 3D ZOR (Zone of Reference), while in the second phase it wakes up the sensor nodes in the next 3D ZOR to be queried, while trying to avoid topology holes. The drawback of this protocol it that as the velocity of water flows is getting higher, the data delivery rate is being decreased and the power consumption is being increased.

The network reliability can be increased by the utilization of two hop acknowledgments (2H-ACK) [6], where two copies of the same data packet are maintained in the network without extra burden on the available resources. This approach reduces significantly the possibility for a sensor node to die from energy soon, a result that would cause a large number of packet losses.

Lately, a different aspect of LEACH [28], named HMR-LEACH (Hierarchical Multi-path Routing – Low Energy Adaptive Clustering Hierarchy) has been proposed. Simulation results have been presented that indicated that this protocol satisfies better the needs of network lifetime, energy consumption and network lifetime, if compared to the LEACH and LEACH-M (multi-hop algorithm, also based on LEACH). According to HMR-LEACH, the cluster head nodes, transfer data to base station by the multi-hop mechanism, while the choice of the transmission path is carried out by the assignment of a probability to each transmitting path based on specific weights. The utilization of this algorithm avoids long-distance transmissions, a property that makes it also suitable for relatively large-scale networks.

ERP^{2}R (Energy-efficient Routing Protocol based on Physical distance and Residual energy) [1] is a routing protocol that uses physical distance for reducing unnecessary retransmissions and the residual energy for energy balancing. With these special characteristics, this algorithm manages to improve end-to-end delay and as well to minimize the consumed energy amount, which consequently extends the lifetime of the network.

EADA-RAT [30] (Energy Aware Data Aggregation via Reconfiguration of Aggregation Tree) is a protocol, which aims to overcome the obstacle of energy dissipation and high delay, by minimizing the number of data transmissions and moving the aggregation point respectively. It reconfigures the aggregation tree via a dynamic pruning and grafting function to operate a temporal path from the underwater sources to the underwater sink.

Another energy-efficient algorithm is SEANAR [42] that assigns weights to nodes with higher connectivity to the sink and adopts a simple yet more effective than Greedy Forwarding and VBF-based in route selection.

The creators of the Energy optimized Path Unaware Layered Routing Protocol (PULRP) [19] routing protocol, in an effort to improve the protocol from a networking energy-balanced view and to discover the best routing path, they proposed the E-PULRP algorithm. The energy imbalance has been fought off by selecting the layer width of various layers and considering the probability of successful packet transmissions and minimum overall energy expenditure. The nature of this protocol is resistive against node mobility and underwater currents and doesn't require localization, time-synchronization or routing-table maintenance, while the serious drawbacks of this approach are that dependence on the application, the golden mean between the energy consumption and the throughput, while the average delay performance is different every time.

B. MAC Protocols

The characteristics of an underwater acoustic channel, such as the especially limited bandwidth and the high propagation delays, pose unique challenges for Media Access Control (MAC) that enables multiple devices to share a common wireless medium in an efficient and fair way.

The authors in [46] provided a summary of the MAC protocols used in underwater acoustic networks and suggested also a R-MAC protocol combined with periodic sleep and listen scheme, that would be able to serve underwater sensor networks in shallow waters with RF electromagnetic links. In the sequel this survey will be extended with the latest proposed approaches.

By utilizing lightweight synchronization, the TDMA-based (Time Division Multiple Access) MAC protocol proposed in [29] has presented an insensibility to the network density and it is able to operate as well. A super frame has been utilized in order to solve the synchronization problems of underwater nodes and a guard time has been proposed after every node's communication time to avoid collision. When compared to other TDMA approaches, simulations have depicted that this prospect of TDMA performs better. The major disadvantage of this protocol is that nodes must periodically perform expensive scheduling operations, which significantly reduces the battery life.

ERMAC (Efficiency Reservation MAC protocol) [31] is suitable for energy preservation, mainly due to the scheduling of transmissions: changing to sleep mode after transmission mode. It has a better ratio of utilizing energy consumption in the narrow bandwidth of the acoustic channel when compared to the legacy centralized topology MAC protocol TDMA, while it can also completely avoid data packet transmission collisions. All the aforementioned characteristics contribute in improving the network transmission accuracy.

C. Localization Protocols

The nature of the water limits the number of effective localization schemes. In terrestrial wireless sensor networks, the GPS system is widely utilized, because of its simplicity and intuitive fundamental concepts and most of all because of the precision it offers in localization. A GPS receiver's job is to locate four or more satellites, calculate the distance to each other and utilize this information to derive its own location, while it should be noted that the transmitted signal is reaching the earth with a very low strength, that it can't penetrate water. Furthermore, from an economic perspective, it is not a feasible solution, since sensors are often deployed in large numbers and manual configuration is unmanageable [35].

Instead of GPS, four kinds of localization methods have been developed, that make the location discovery process autonomous and function independently of GPS. These methods are: a) RSSI, b) TDoA, c) AoA, and d) ToA that will be analyzed in the sequel.

The idea behind RSSI (Received Signal Strength Indicator) is that the configured transmission power at the transmitting device (P_T) affects directly the receiving power at the receiving device (P_R). Ideal distribution of P_R is not applicable, as the propagation of the radio signal is interfered with a lot of influencing acoustic interferences, such as near-shore tide noise, near-surface ship noise, multi-path and Doppler frequency spread, etc. [34], [45].

AoA (Angle of Arrival) measurement is a method for determining the direction of propagation of a radio-frequency wave incident on an antenna array. The addition of antennas to an extant sensor network increases significantly the cost and size of the network, and this is the reason why AoA is not preferred in comparison to the other localization algorithms.

TDoA (Time Difference of Arrival) is based on: a) the difference in the times at which a single signal from a node arrives at three or more nodes, and b) the difference in the times at which multiple signals from a single node arrive at another node. Unfortunately, TDoA is no longer feasible. The first disadvantage in the utilization of this algorithm is the need for extra hardware for transmitting the second signal, which increases the node cost. Also, it utilizes RF and acoustic signals and RF signals have limited range in underwater communication.

The most prevalent and simple algorithm is **ToA** (Time of Arrival). With this algorithm, the distance between nodes is being estimated by measuring the propagation time of the transmitted signal. This type of estimation requires precisely synchronized nodes and time stamped packet transmissions.

Trilateration is a method of determining the relative positions of objects using the geometry of triangles similar to triangulation. Unlike triangulation, which uses AoA measurements to calculate a subject's location, trilateration involves gathering a number of reference tuples of the form (x, y, d). In this tuple, d represents an estimated distance between the source providing the location reference from (x, y) and the sensor node. To accurately and uniquely determine the relative location of a point on a 2D plane using trilateration, a minimum of 3 reference points are needed.

Multilateration is the process of localization by solving the mathematical intersection of multiple hyperbolas based on the TDoA). In multilateration, the TDoA of a signal emitted from transmitter to three or more receivers is being measured accurately with tightly synchronized clocks. When N receivers are being utilized, it results in $N-1$ hyperbolas, the intersection of which uniquely positions the object in a 3D space. In case that a large number of receivers are being utilized ($N > 4$), the localization problem can be posed as an optimization problem that can be solved using, among others, a least squares method [35].

A detailed survey in [17] has been made over the localization protocols and we are going to add the latest updates in their works on the Table II.

TABLE II. **LOCALIZATION TECHNIQUES**

A. CENTRALIZED LOCALIZATION TECHNIQUES
1) Estimation-based Schemes:
a) *Motion-Aware Self Localization (MASL) Technique*
b) *Hyperbola-based Localization (HL):*
c) Area-based Localization Scheme (ALS)
d) Three Dimensional Multi-power Area Localization Scheme (3D-MALS)
e) Silent Localization using Magnetometers (SLM)
2) Prediction-based Schemes:
a) Collaborative Localization (CL)
B. DISTRIBUTED LOCALIZATION TECHNIQUES
***1)* Estimation-based Schemes:**
a) AUV-Aided Localization (AAL)
b) b) Localization with Directional Beacons (LDB)
c) Dive and Rise Localization (DNRL) Protocol
d) Multi-Stage Localization (MSL)
e) Large-Scale Hierarchical Localization (LSHL) Protocol
f) Detachable Elevator Transceiver Localization (DETL) Protocol
g) Three-Dimensional Underwater Localization (3DUL)
h) Anchor-Free Localization (AFL)
i) Underwater Positioning Scheme (UPS)
j) Wide Coverage Positioning (WPS)
k) Large-Scale Localization Scheme (LSLS)
l) Underwater Sensor Positioning (USP)
2) Prediction-based Schemes:
a) Scalable Localization with Mobility Prediction (SLMP)

In [39], the network is being formed by a subset of nodes such that every node in the original set is covered by four nodes, belonging to this special subset. The performance of this algorithm is highly energy efficient, but as the density of the sensors lowers, the localization error increases. Based on the SemiDefinite Programming (SDP) [16], two novel localization schemes, namely position-fixed and magnified-range have been proposed. Both of them offer highly accurate estimations, when the perfect, according to the application, combination of the number of anchors, connectivity and background noise has been found.

In deep water, more complex problems must be handled and therefore a balance needs to be found between energy efficiency, cost and accuracy. A scalable algorithm, able to meet the above challenges has been presented in [50], where the localization scheme consists of four types of nodes. Those are surface buoys, Detachable Elevator Transceivers (DETs), anchor nodes and ordinary nodes. The surface buoy is assumed to be equipped with GPS on the water surface. A DET is attached to a surface buoy able to rise and broadcast its position. The anchor nodes can compute their positions based on the position information from the DETs and the measurements of distance to the DETs. For the computation of node positions, lateration is being preferred based on the min-max method.

Another distributed localization technique is the Multi-Stage AUV-aided Localization [40] that has been developed in order to minimize the serious energy expenses and the high localization delays due to the slow speed of the AUVs. The UWSN comprises an AUV and ordinary nodes that dive to a known depth (provided by pressure sensors) and remain static (by fixing with anchors) during the localization process. Moreover, all nodes can communicate (omni-directionally) with the AUV and other nodes by sending or receiving acoustic signals. The AUV can surface to obtain its coordinates using GPS signals, and can be pre-programmed to dive to a given depth (provided by pressure sensors) and traverse a given path. As with the ordinary nodes, the AUV is equipped with an omni-directional antenna and communicate with nodes via acoustic signals. It is being assumed that the AUV as well as the ordinary nodes are all time synchronized. Instead of the three-stage message (wakeup, request and response), silent positioning is being proposed. This method performs well when k=1 (k-stage of coverage), whereas when k>1, high localization error occurs and the communication cost is quite bigger.

Using an ideal spreading-model, 3D-MALS (3D Multi-power Area Localization Scheme) has been extended for large sale UWSN in [51], using the same philosophy as in [20]. The simulation results have presented improved performance than 2D-ALS, but the selection of the power level needs to be done with caution, as the transmission power is related to spreading distance directly, when the power level increases.

D. Energy Consumption

Energy saving among long propagation delays, node mobility and high error probability, is a major concern in UWSNs. To succeed in minimizing the energy consumption and maximizing the network lifetime, robust, scalable and energy-efficient routing protocols should be designed.

Existing multi-hop ad hoc routing protocols are not adequate, since they apply a continuous exchange of overhead messages which is quite energy-consumptive [11]. Furthermore, a centralized routing protocol is not an adequate solution, because it is concentrating all the routing information about traffic in one single point and thus increases the probability of protocol's failure. In flooding based protocols, even if one node has lost the packet, other nodes can transmit the data packet, which needs a lot of broadcasting activities for the same packets, which consequently results in unnecessary energy consumption [1], [25][43]. According to [15], the best method in routing protocols is based on clustering scheme, which offers better scalability with respect to the number of nodes, performs better in shallow water and most important it saves energy and expands the system lifetime [22],[14],[27]. The conduct of the simulations showed also, that direct transmission despite to its simplicity has the worst results, reducing the network throughput, because of the increased acoustic interference in the deep water.

E. Security

Security is a major challenge in UWSN, mainly because the number of possible attacks in each layer of the communication model is quite big and the corresponding consequences on the performance of the network can be quite harmful. The security requirements in WSNs include availability, authorization, authentication, confidentiality, integrity, nonrepudiation and freshness. In [41], it is proposed to add forward and backward secrecy, as new sensors are being deployed and old sensors fail. The threats and attacks, to which UWSN are susceptible, can be classified as data threats security attacks, DoS (Denial of Service) attacks, impersonation attacks, replication attacks and physical attacks. CDMA (Code Division Multiple Access) is a promising scheme for underwater acoustic networks, because it enables multiple devices to share a common wireless medium in an efficient and fair way. It has been widely utilized against jamming, exhaustion and flooding [13]. Nevertheless, more sophisticated solutions should be found in order to deal efficiently with DoS attacks, which can compromise a sensor node, alter the integrity of the data, hack the messages, inject fake messages and waste network resource. In [48], the authors have proposed four protocols: B-NDP, MA-NDP, DV-NDP and SDV-NDP that can competently prevent establishing false neighboring relationships. The two first ones are suitable for applications where network connectivity and end-to-end delay are of primary concerns, whereas the latter ones are ideal for applications with relatively high node density and extremely high requirements for wormhole looseness. Summarizing, to achieve a secure system, security must be integrated into every component, since components designed without security can be a point of attack [36].

IV. UWSN Applications

There is a quite wide range of applications for underwater acoustic sensor networks [37], while these could classified as:

- **Ocean Sampling Networks.** Networks of sensors and AUVs, such as the Odyssey-class AUVs [5], can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment. Experiments such as the Monterey Bay field experiment [33] in August 2003 demonstrated the advantages of bringing together sophisticated new robotic vehicles with advanced ocean models to improve our ability to observe and predict the characteristics of the oceanic environment.
- **Environmental Monitoring** such as pollution monitoring (chemical, biological, etc.), monitoring of ocean currents and winds, improved weather forecast, detecting climate change, understanding and predicting the effect of human activities on marine ecosystems, biological monitoring such as tracking of fishes or micro-organisms, are other possible applications. For example, in [47], the design and construction of a simple underwater sensor network is described to detect extreme temperature gradients (thermoclines), which are considered to be a breeding ground for certain marine micro-organisms.
- **Disaster Prevention.** Sensor networks that measure seismic activity from remote locations provide tsunami warnings to coastal areas and keep under surveillance submarine volcanoes. Specifically in July and August 2011 while exploring Axial Seamount, a three-month-old volcanic eruption off the Oregon coast, MBARI’s seafloor mapping robot documented a huge lava flow covering large areas of the seafloor [32]. Also, frequent seismic monitoring is of great importance in oil extraction, because of its challenging nature. In particular, seismic sensors are not currently permanently deployed in underwater fields, which cover areas of 8kmx8km or less. The authors of [21] with the current knowledge of the situation proposed a tiered communication network, where some supernodes are connected to users via non-acoustic communications channels, on condition that all nodes are within two hops of a supernode and the time of retrieving all the data is about one hour.
- **Assisted Navigation.** Sensors can be used to locate dangerous rocks or shoals in shallow waters, mooring positions, and submerged wrecks.
- **Distributed Tactical Surveillance.** AUVs and fixed underwater sensors can collaboratively monitor areas for surveillance, reconnaissance, targeting and intrusion detection systems. For example, in [8], a 3D underwater sensor network is designed for a tactical surveillance system that is able to detect and classify submarines, small delivery vehicles (SDVs) and divers based on the sensed data from mechanical, radiation, magnetic and acoustic microsensors. With respect to traditional radar/sonar systems, underwater sensor networks can reach a higher accuracy, and enable detection and classification of low signature targets by also combining measures from different types of sensors.
- **Mine Reconnaissance.** The simultaneous operation of multiple AUVs with acoustic and optical sensors can be used to perform rapid environmental assessment and detect mine like objects.
- **Military purposes.** Given the typical mobility speed of a submarine (e.g. 10-15 knots) and the delay in dispatching anti-submarine task forces, the submarine hunting task force has to locate the target in an area of hundreds of square nautical miles due to the coarse granularity [26].

V. Conclusion

In this article a survey on Wireless Sensor Networks and applications has been presented. The most important approaches have highlighted towards UWSNs’ architecture, routing, MAC and localization protocols, energy consumption and security, while their most illustrative real-life applications has been depicted in short.

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