Underwater Wireless Sensor Networks: A New Challenge for Topology Control–Based Systems

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Underwater wireless sensor networks (UWSNs) will pave the way for a new era of underwater monitoring and actuation applications. The envisioned landscape of UWSN applications will help us learn more about our oceans, as well as about what lies beneath them. They are expected to change the current reality where no more than 5% of the volume of the oceans has been observed by humans. However, to enable large deployments of UWSNs, networking solutions toward efficient and reliable underwater data collection need to be investigated and proposed. In this context, the use of topology control algorithms for a suitable, autonomous, and on-the-fly organization of the UWSN topology might mitigate the undesired effects of underwater wireless communications and consequently improve the performance of networking services and protocols designed for UWSNs. This article presents and discusses the intrinsic properties, potentials, and current research challenges of topology control in underwater sensor networks. We propose to classify topology control algorithms based on the principal methodology used to change the network topology. They can be categorized in three major groups: power control, wireless interface mode management, and mobility assisted–based techniques. Using the proposed classification, we survey the current state of the art and present an in-depth discussion of topology control solutions designed for UWSNs.

CCS Concepts: • **General and reference → Surveys and overviews**; • **Networks → Topology analysis and generation**; *Network dynamics*; *Ad hoc networks*; Network protocol design;

Additional Key Words and Phrases: Underwater sensor networks, topology control, architectures, models and algorithms

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1 INTRODUCTION

Underwater wireless sensor networks (UWSNs) have been attracting increasing attention from the scientific and industrial communities (Luo et al. 2017). This is due to its potential

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for (quasi)real-time data collection over traditional underwater monitoring systems relying on tethered instruments, cabled monitoring stations, or sensor nodes without communication capabilities. A UWSN is comprised of underwater sensor nodes, which are equipped with sensing, processing, storing, and underwater wireless communication capabilities that act collaboratively to monitor underwater regions and events of interest. The use of the underwater acoustic modem allows these devices to wirelessly communicate with each other to perform real-time underwater monitoring and actuation, online system reconfiguration, and the detection and report of operational failures and malfunctioning devices. The advancement of this technology is fundamental in filling the knowledge gap about our oceans, as well as about the life, resources, and events that lie beneath them. UWSNs are expected to revolutionize applications in the scientific, commercial, and military domains. A nonexhaustive list of UWSN applications include the monitoring of marine life, pollutant content, geological processes on the ocean floor, oilfields, climate, and tsunamis and seaquakes; oceanographic data collection; ocean and offshore sampling; navigation assistance; mine recognition; and tactical surveillance applications.

The development of large-scale deployments of UWSNs is designed to monitor wide areas in the ocean. However, the fulfillment of this vision will depend on the design of efficient and reliable underwater networking services and protocols. Unfavorably, the vast knowledge about the design of radio frequency–based wireless sensor networks (WSNs), acquired during decades of research, cannot be directly applied to the design of networking protocols for UWSNs. This is due to the particular characteristics of the underwater acoustic channel, such as long and variable propagation delay and low bandwidth, and the physical properties of the aquatic environment, such as water temperature and seabed sediments. In fact, the design of networking protocols for UWSNs faces many new challenges that are not even observed in traditional WSNs. The use of the underwater acoustic channel incurs limited bandwidth capacity, high and variable propagation delay, temporary path loss, high noise, multipath fading, shadow zones, Doppler spreading, and high communication energy costs. Moreover, underwater wireless communication suffers from severe time-varying link quality, as it is impaired by variations in water temperature that change the way the sound is refracted and the seabed sediments (i.e., the morphology of the sea bottom).

In this article, intrinsic properties, current research challenges, and the potential of topology control in underwater sensor networks are presented. We classify topology control algorithms, based on their principal methodology used to change the network topology, into three major groups: power control, wireless interface mode management, and mobility assisted–based techniques. In addition, we survey current state-of-the-art research in topology control solutions designed for these networks. We present an in-depth discussion of the challenges, advantages, and disadvantages of power control, wireless interface mode management, and mobility-assisted techniques used to design topology control algorithms for underwater acoustic sensor networks. To the best of our knowledge, this is the first work devoted to organizing, classifying, and presenting a thorough revision of the topology control in UWSNs.

The article is organized as follows. In Section 2, we underline two critical factors that make network topology of underwater sensor networks a highly dynamic process. In Section 3, we classify the topology control solutions designed for UWSNs in different categories. Within each category, we discuss the general pros and cons relating to the characteristics of UWSNs, and present the representative solutions. In Section 4, we discuss and survey transmission power–based topology control studies proposed for UWSNs. In Section 5, we discuss the proposed solutions that employ the management of the wireless interface of the underwater nodes for topology control. In Section 6, we survey proposals for topology control in UWSNs that use the mobility assisted of some nodes as the main technique for changing the topology. Some

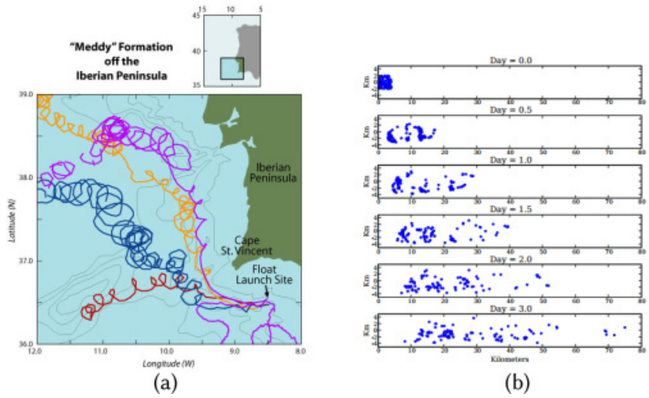


Fig. 1. (a) Trajectories of four different RAFOS floats released into the Mediterranean undercurrent south of the Iberian Peninsula from 1993 to 1994 (WHOI 2016). (b) Displacement of underwater nodes modeled according to the MCM model (Caruso et al. 2008).

future research directions in the field are presented in Section 7. We present our final remarks in Section 8.

2 THE WHYS AND WHEREFORES OF DYNAMIC TOPOLOGIES IN UWSNS

The topology of underwater sensor networks changes constantly with the passage of time. In this section, we discuss how the involuntary mobility of underwater nodes and the spatiotemporal variable quality of acoustic links can frequently change the topology of a UWSN.

2.1 Involuntary Mobility of Underwater Nodes

In untethered underwater sensor networks, underwater sensor nodes will freely move according to the currents of the ocean, performing spatiotemporal data collection. This involuntary mobility will spread underwater nodes as time passes. Consequently, some of the acoustic links between nodes that were present in the initial topology of the UWSN might not be present at a given point in the future. In fact, due to the involuntary mobility of underwater nodes, network partitions in a UWSN might take place after the deployment of the underwater nodes.

Mobility in the aqueous environment is very particular. It relates to several environmental factors, such as water temperature, currents, boundary conditions, atmospheric forces, and bottom topography (Zhou et al. 2011). Figure 1 illustrates two involuntary mobility patterns. Figure 1(a) shows the trajectories of four different RAFOS floats. Figure 1(b) depicts an instantiation of the meandering current mobility (MCM) model (Caruso et al. 2008). In the MCM model, the mobility of underwater floats and drifters is impacted by meandering sub-surface currents and vortices. From the analysis of the mobility traces of 46 floats, Rienzo et al. (2016) observed that, similar to the results in Figure 1, some underwater sensor nodes move following a straight trajectory, whereas others might become trapped in flows and stay moving in loops.

2.2 Spatiotemporal Variable Quality of Underwater Acoustic Links

The topology of an underwater network will also change on a recurrent basis due to the spatiotemporal variability of the quality of acoustic links. Their quality depends on several factors, such as the depth of communicating nodes, water temperature, the seabed sediments (i.e., the morphology of the sea bottom) of the considered area, and the ambient noise (thermal, wind, turbulence, and

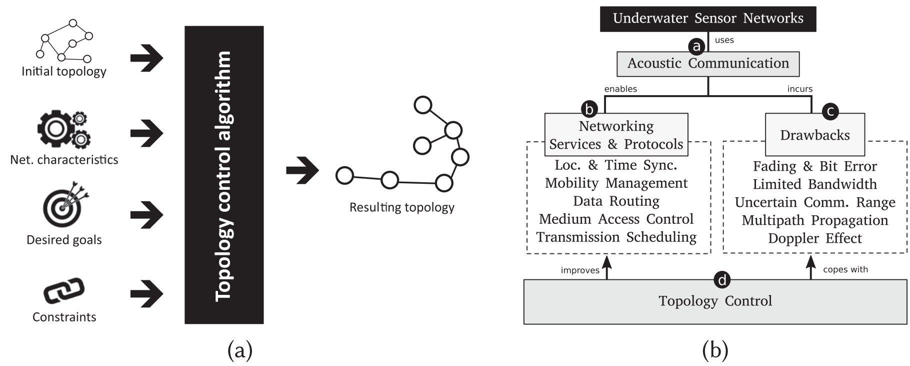


Fig. 2. (a) Framework of topology control. (b) Big picture of topology control in underwater networks.

shipping activities). Therefore, if acoustic links have the same configuration (e.g., transmission power level), they might perform differently or even be down at some moments.

The preceding fact is discussed in Guerra et al. (2009a). The authors present the signal attenuation of acoustic waves transmitted in the northeastern coast of the Italian region of Calabria during two different seasons of the year (summer and winter). Whereas a high signal absorption was noticed closer to the surface in transmissions performed in August, it is considerably less for transmissions at the same location and configuration, but performed in January. In this scenario, therefore, an acoustic link between the transmitter and a closer node located in a depth above 100 m exists in January but is absent in August.

Pu et al. (2015) conducted a sea experiment where they observed a spatial and temporal communication range uncertainty effect in underwater acoustic links. This uncertainty effect was explained based on the time-varying nature of wind, current, marine mammal noise, and human-made activities. Moreover, they perceived a heterogeneous packet loss ratio that varied significantly among different acoustic links with the same configuration. This can be attributed to the geometry of the sea surface and seabed sediments that leads to multipath signal propagation.

In addition, Qarabaqi and Stojanovic (2011) observed in experimental measurements that the received signal power of an acoustic transmission in shallow water varies over time, as the channel experiences fading. At some moments, the received signal power might be so weak that the transmitted messages cannot be decoded. During those moments, the link is nonexistent, as no data communication can occur.

3 TOPOLOGY CONTROL ALGORITHMS IN UNDERWATER SENSOR NETWORKS

Topology control has the potential to mitigate undesired effects of the underwater wireless communication and, consequently, to improve the performance of networking services and protocols in underwater sensor networks. Figure 2(a) depicts the overall framework of topology control. Accordingly, a topology control algorithm should consider the initial network topology and characteristics, desired goals, and constraints to determine a novel topology. Figure 2(b) shows the big picture of the relationship between topology control and underwater sensor networks, which is summarized as follows:

(1) UWSNs use the underwater acoustic channel for providing wireless communication capabilities for underwater sensor nodes.
(2) Underwater wireless communication through acoustic channels enables networking services for distributed underwater applications.

Table 1. Challenging Tasks in UWSNs and Their Relationship With Topology Control

Task	Challenges	Topology Control
Localization and time synchronization	GPS is not possible; clock synchronization is challenging; distance, angle, and time-of-arrival estimations are difficult due to variable signal propagation speed; highly unpredictable mobility (Liu et al. 2016).	Topology control, based on different transmission power levels, can be used to improve localization; AUVs with controlled mobility and/or depth adjustment of some nodes can be used to improve trilateration-based localization (Ferreira et al. 2016).
Mobility management	High mobility and peculiar mobility: nodes' movement follows oceans' currents (Caruso et al. 2008).	Topology control can be used to plan the trajectories of AUVs or the depth adjustment of some nodes, with the goal of keeping the network operational (Coutinho et al. 2013a).
Data reduction	Traditional data aggregation is infeasible; high overhead and message collisions around the fusion center (Fazel et al. 2011).	Topology control can reduce interference, and improve spatial reuse and data routing; Topology control can also deal with poor link quality to improve compressed sensing (Shashaj et al. 2014).
Routing	Loss of connectivity; high bit error rate; mobility; high overhead to maintain routing paths (Lee et al. 2010).	Topology control can increase bandwidth and deal with the communication void region problem that diminishes the performance of geographic routing (Coutinho et al. 2017a; Ghoreyshi et al. 2017).
Medium access control (MAC)	Long propagation speed and distances; long message preambles and low data rates (Zhu et al. 2013).	Topology control can confine interference, increase spatial reuse, scheduling efficiency, and data rate; Topology control can also deal with the classical hidden and exposed terminal problems (Su et al. 2015).
Energy-efficient network operation	High energy cost for transmitting (order of watts); high overhead and message collisions; time-varying and poor channel quality that demands message retransmissions (Stojanovic and Preisig 2009).	Topology control through power control can deal with time-varying link quality; Topology control can also reduce interference and eliminate the needs for message retransmission (Qarabaqi and Stojanovic 2011).

(3) However, the underwater acoustic channel has peculiar characteristics that impair underwater wireless communication and challenges the design of efficient networking protocols.
(4) In this regard, topology control can be employed to mitigate most of the shortcomings of the acoustic channel and improve the performance of UWSNs.

Indeed, the conscious and purposeful control of the network topology stabilizes and smooths the undesirable changes in the network caused by the variable link quality, involuntary mobility, and node failures, which avoid frequent data exchange for the localization of nodes, neighborhood discovery, and data route recalculation. Table 1 summarizes some of the main networking-related tasks and their challenges in UWSNs. It also shows how topology control can deal with the presented challenges.

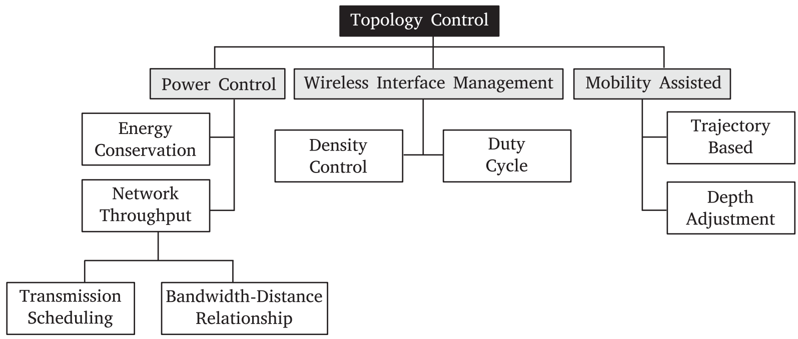


Fig. 3. Taxonomy of topology control in UWSNs.

Different perspectives have been adopted to classify algorithms and protocols designed for topology control in wireless ad hoc and sensor networks. According to the literature, they have been classified in different ways as follows:

(1) *Global* or *local* (Wattenhofer et al. 2001), based on the needed topological information to perform the control. In the former case, the information of the entire network topology is employed for topology control. In the latter, the local information of the topology—that is, a k-hop neighborhood information ($k = 1$ or $k = 2$)—is enough for topology control.
(2) *Centralized* or *distributed* (Ramanathan and Rosales-Hain 2000), according to the nature of the solution. In the former case, a unique node is responsible for computing the new network topology. In the latter, a set or each node is responsible for making decisions to organize the network topology.
(3) *Proactive* or *reactive* (Zheng and Kravets 2005), whether it runs periodically or reactively because of some event in the network (e.g., nodes' failures).
(4) *Homogeneous* or *nonhomogenegous* (Santi 2005), based on the resulting communication range of nodes. In the former case, a unique value for the communication range is determined and used in all nodes. In the latter, the topology control algorithm assigns an appropriate communication range r_c to each node. This value is determined from the range between $r_{\min} \leq r_c \leq r_{\max}$.
(5) *Coverage*—, *connectivity*—, or *energy oriented* (Li et al. 2013a), according to the main goal to be accomplished by the use of the topology control algorithm. In fact, it can be observed in the literature that several of the topology control algorithms are strictly related to a desired goal.

In this survey, we propose to classify topology control protocols for UWSNs as follows: power control, wireless interface management, and mobility assisted. This classification is based on the main technique that each protocol employs to consciously control the network topology. This criteria is broad enough to cover the current algorithms, as well as future designs of topology control algorithms for envisioned UWSNs based on software-defined networking and heterogeneous UWSNs. The proposed taxonomy is depicted in Figure 3. Table 2 summarizes the challenges, advantages, and disadvantages of the proposed categories. A brief description of each category is provided next:

— *Power control–based topology control*: In this category, the topology control is performed by means of the proper assignment of the transmission power to each underwater

Table 2. Classification of Topology Control Algorithms for UWSNs

Approach	Main Idea	Advantage	Disadvantage
Power control based	The adequate transmission power is assigned to each node. Thus, communication links will be created and/or removed. Some algorithms aim to achieve a network-wide property, such as network connectivity.	Simple; scalable; conserves energy; does not change the sensing coverage; can overcome time-varying acoustic channel quality.	May diminish the network connectivity; increases the number of hops and end-to-end delay.
Wireless interface mode management based	The wireless interface of nodes alternates between active, sleeping, and powered-off modes. This changes the interconnections between nodes over time.	Simple; scalable; conserves energy relative channel polling; does not change sensing coverage.	Changes network density; changes routing paths from time to time; increases delay.
Mobility assisted based	Some mobile nodes are moved to new locations, creating new interconnections.	Improves network connectivity; deals with network partitions; improves data collection from hop spots.	Needs trajectory planning procedures; energy cost for mobility; may change sensing coverage.

sensor node. We classify and survey power control–based topology control algorithms according to the main goal that they are intended to achieve, as *energy conservation*, increased *network throughput* through transmission scheduling, or by the exploration of the distance-bandwidth relationship of the underwater acoustic channel.

— *Wireless interface management–based topology control*: In this category, the topology organization is performed by means of the management of the wireless interface, among the active and sleep states, of each node. We classify and survey wireless interface management–based topology control algorithms according to their main methodology. The categories include *density control*, in which a subset of the nodes is kept awake as a routing backbone to deliver data messages while the wireless interface of the remaining nodes is changed to the sleep mode, and *duty cycle*, where each node asynchronously and periodically alternates its wireless interface between active and sleep modes.

— *Mobility assisted–based topology control*: In this category, topology control is performed through the intentional movement of some nodes to new locations. In this survey, mobility assisted–based topology control is classified into two major groups as *depth adjustment based*, where underwater sensor nodes are moved to new depths to achieve a better topology, and *trajectory based*, where autonomous underwater vehicles (AUVs) move nodes according to predetermined trajectories.

Finally, the following statement needs to be made before we proceed further in the literature review. Some of the reviewed proposals in this survey did not claim that the designed algorithms were proposed for topology control. However, a critical analysis reveals that they consciously control the network topology during the proposed steps to accomplish their objectives (e.g., energy

Table 3. Power Control–Based Topology Control Approaches

Subcategory	Basic Solution	Challenges
Energy conservation	Assigns a minimum transmission power to each node to ensure network connectivity	Complex and impractical channel models; spatial and time-varying link quality; shadow zones; multipath propagation; uncertain communication range value
Network throughput	Assigns the optimal transmission power according to the distance, aiming to increase bandwidth or the proper communication range to increase spatial reuse	

conservation or reliable data delivery). To illustrate this fact, consider the studies of Casari and Harris (2007) and Coutinho et al. (2014a). Casari and Harris (2007) found that short-range communication links reduce energy consumption in UWSNs. The authors employed power control to reduce the communication range of underwater sensor nodes and thus, achieve energy-efficient message broadcasts in UWSNs. Indeed, the proposed protocols control the network topology whenever they decide to decrease the communication range of a node, since they are removing unnecessary long-range links. Coutinho et al. (2014a), in turn, proposed a geographic and opportunistic routing protocol to improve data delivery in UWSNs. The authors proposed a depth adjustment protocol developed to move underwater void nodes for new locations. In their work, an indirect topology control happens whenever a void node moves toward a new location, since new communication links are created with the new set of neighboring nodes.

4 TRANSMISSION POWER CONTROL–BASED TOPOLOGY CONTROL APPROACH

In this category, topology control occurs by means of the proper assignment of the transmission power level to each node. This is usually done with the objective of reducing the energy consumption and delay, or increasing the network throughput and data delivery reliability. The conscious organization of the topology results from the creation and removal of communication links whenever an increased or reduced transmission power is assigned, respectively.

In wireless ad hoc networks, power control–based topology control algorithms are mostly proposed to reduce the network energy consumption. However, in underwater acoustic sensor networks, this topology control approach has been additionally designed to mitigate the drawbacks of underwater acoustic communication (e.g., low achievable bandwidth and poor link quality). This is achieved by favoring short-range links, which allows for the use of increased frequencies, compared to long-range links. In addition, we must control the transmission power to deal with the spatiotemporal underwater acoustic link quality variability, with the intention of guaranteeing enough signal strength at the receiver that it can successfully receive and decode the transmitted message. In the remainder of this section, we survey power control–based topology control algorithms, whose main goals are energy conservation and network throughput. This subcategorization is summarized in Table 3. A qualitative comparison of the discussed protocols in this section is presented in Table 4.

4.1 Energy Conservation

In their vast majority, power control–based topology control algorithms are designed for energy conservation in battery-operated wireless systems. This also happens in UWSNs because underwater sensor nodes are energy constrained, and ship missions to replace batteries of underwater nodes are expensive, often lasting for several days. In the following, we discuss some representative studies proposing power control to prolong the UWSN lifetime.

Table 4. Power Control–Based Topology Control Algorithms

Category & Proposal	Task	Approach	Goal	Constraint	Potential Applications
Energy conservation: SBR, SBRB, FSBRB, and DBRB (Casari and Harris 2007)	Reliable broadcast	*SBR*: Every node rebroadcasts a message as it receives a broadcast message. *SBRB*: Long-range communication to notify all neighbors that a broadcast has started, whereas short-range communication is used to broadcast a message. *DBRB*: Operates similarly to the SBRB, but long-range transmissions send some FEC data to correct errors.	Energy conservation	Network connectivity	Long-term periodic sensing or event-driven underwater monitoring applications
Energy conservation (Casari et al. 2007)	Routing	Analytically investigate the impact of the bandwidth-distance relationship in the multihop short-range and single-hop long-range data delivery from underwater sensor nodes to sinks.	Delivery delay and energy conservation	Network connectivity	Long-term monitoring of oil/gas offshore exploration equipment where low delay for reporting equipment failures is fundamental
Energy conservation (Porto and Stojanovic 2007)	MAC	Optimize the transmission power to minimize the overall power consumption.	Energy conservation	Network connectivity	Long-term periodic sensing or event-driven underwater monitoring applications
Energy conservation: MTP (Zhou and Cui 2008)	Routing	Combine multipath and power control. The source node selects multiple paths toward the destination and calculates the optimal transmission power for each node along the paths. The data packet is transmitted among the selected paths, and multiple copies are then combined at the destination to recover the original packet.	Energy conservation	Desired data delivery reliability	Content pollution monitoring, target tracking, and underwater surveillance
Energy conservation: APRC (Al-Bzoor et al. 2012)	Routing	Iteratively decrement the transmission power of a node until it reaches the minimum level while still guaranteeing communication with a neighbor located in a layer closer to the sink.	Energy conservation	Network connectivity	Long-term periodic sensing or event-driven underwater monitoring applications
Energy conservation: LMPC (Xu et al. 2012)	Routing	Layered multipath routing is used for data delivery to sink nodes. Power control is performed on a hop-to-hop basis. Multiple copies of a received data packet are combined in the destination to error recovery.	Energy conservation	Desired data delivery reliability	Content pollution monitoring, target tracking, and underwater surveillance
Energy conservation (Kim et al. 2014)	Physical layer	Power control is based on the sea surface movement that affects the surface signal reflection and the strength of the received signal at a node.	Reliable data delivery	Channel quality	Content pollution monitoring, target tracking, and underwater surveillance
Energy conservation: iDTC and PADTC (Nasir et al. 2016)	Routing	Transmission power adjustment is used to tackle the communication void region problem of geographic and opportunistic routing protocols.	Improve data delivery; reduce energy consumption	Greedy forwarding toward the destination	Long-term underwater monitoring applications

(Continued)

Table 4. Continued

Category & Proposal	Task	Approach	Goal	Constraint	Potential Applications
Network throughput (Jornet and Stojanovic 2008)	Physical layer	Uses an increased number of transmission power levels to a finer tuning of the transmission power of the nodes.	Increased network throughput and energy conservation	Network connectivity	Long-term monitoring applications
Network throughput (Shashaj et al. 2014)	MAC and routing	A set of four transmission scheduling policies (FIFO, LOAD, LWS, and FAIR) for the selection of the node and time of the next transmission. Power control is used to assign to the nodes the lowest transmission power level while still guaranteeing a reliable connection with a relay node in the routing path toward the sink.	Reduced link interference; high throughput; low energy consumption	Reliable network connectivity	Long-term monitoring applications that require reliable data delivery
Network throughput (Su et al. 2015)	MAC	Dynamic transmission power adjustment and rate adaptation based on the achievable bandwidth to enhance spatial reuse. Game theory approach for the distributed transmission power adjustment among underwater sensor nodes.	Improve spatial reuse	Network connectivity	Applications relying on moderate-to-high–density network deployments
Network throughput (Anjangi and Chitre 2015)	MAC	Power control is used to limit the interference range of each node. From limited interference zones, transmission schedules are proposed to improve the network throughput.	Increase network throughput	Network connectivity	Applications relying on moderate- to high-density network deployments
Network throughput (Bai et al. 2016)	MAC	Correlation matrix is used to describe the source-destination relationship and conflict relationships among the links. Power control is used to achieve an SNR larger than the decoding threshold.	Reduce link interference; achieve high throughput; low delay	Requirements of real-time underwater monitoring applications, such as data delivery reliability and bounded delay	Monitoring of underwater equipment of offshore industrial activities; pollutant detection; underwater surveillance and target tracking

Casari and Harris (2007) and Casari et al. (2007) showed that short-range communication, based on multihop links in a UWSN, is preferable to long-range single-hop communication. Indeed, in terms of energy conservation, the optimal transmission power that should be assigned to each node in a UWSN is the minimum power level still guaranteeing connectivity between the nodes and the sink (Porto and Stojanovic 2007). However, a suitable transmission power might depend on several factors, and its proper assignment is not a trivial task. For instance, the use of long-range communication links improves network connectivity and reduces end-to-end delay, as messages require fewer hops to be delivered. However, long-range communication links will result in higher message collision rates. Another dichotomy is that short-range communication links increase throughput due to the increment of the spatial reuse but can lead to high end-to-end delay. Therefore, suitable transmission power selection is a challenging problem in a UWSN. In fact, various studies in the literature have proposed power control algorithms that change the network topology while considering different aspects of UWSNs and the acoustic channel.

A first group of protocols was designed for the transmission power adjustment aimed to conserve energy while maintaining network connectivity. As mentioned previously, Casari and Harris (2007), Casari et al. (2007), and Porto and Stojanovic (2007) proposed to use the minimum transmission power such that each node is still able to deliver its data to a sink node or broadcast a given message to all nodes. In a scenario of a concentric-layered UWSN architecture, Al-Bzoor et al. (2012) proposed the APCR routing protocol, which selects the appropriate transmission power at the nodes, by considering the trade-off between energy consumption and network connectivity. To do so, each node assigns the highest transmission power level, then starts reducing it until it reaches a power level that ensures communication with the closest neighboring node located at the next layer toward the sink. Recently, Nasir et al. (2016) proposed the PADTC algorithm, which uses power control to tackle the communication void region problem that severely diminishes the performance of geographic routing protocols.

Other protocols are devoted to selecting the minimum transmission power that still guarantees a required link reliability (i.e., a desired data delivery rate). Zhou and Cui (2008) and Xu et al. (2012) proposed the multipath power-control transmission (MTP) and layered multipath power control (LMPC). In both protocols, power control is performed not only for energy conservation but also for achieving a required packet delivery rate. In both solutions, the transmission power selection was formulated as an optimization problem, with the goal of minimizing energy consumption. The minimum transmission power level at each intermediate node is then determined, subject to a message error rate below an established threshold. The MTP and LMPC protocols differ in the procedures they use for determining multipaths and the layered network architecture considered in the LMPC protocol.

Moreover, the transmission power control has been considered in contention-based medium access control (MAC) protocols for UWSNs. Contention-based MAC protocols are preferable for UWSNs because of the spatiotemporal uncertainty problem that challenges the design of contention-free MAC protocols. More specifically, a handshaking contention-based MAC approach has the potential to reduce packet collisions encountered in widely used random access contention-based protocols. In this context, the transmission power control has been employed to improve the efficiency of the packet collision avoidance mechanism while reducing energy consumption. Accordingly, a node might select a high power level to transmit RTS/CTS packets, whereas the minimum transmission power still guarantees communication with the intended receiver to perform data transmission (Qian et al. 2016).

Finally, it is worth mentioning the study of Kim et al. (2014), which considered a different perspective for the use of power control. The authors proposed a transmission power assignment subject to the perceived channel quality. However, diverging from the solutions mentioned earlier, the developed solution in Kim et al. (2014) considered the height of waves during the transmission power adjustment. The reason for this is that the height of waves affects the surface signal reflection and the strength of the received signal at a node. Surface buoys, equipped with accelerometer and gyro sensors, record their elevation trajectory; from that, they compute the average of the water line. This computed value is used to estimate the root mean square (RMS) of the wave height. The transmission power of nodes and their appropriate frequencies are then adjusted proportionally to the RMS of the wave height. The proposed solution reduced the energy consumption by decreasing the transmission power of the nodes, as the wave height gradually decreased toward zero meters, which is the case where traditional approaches do not perceive variation of channel quality, and keep using excessive transmission power.

4.1.1 Critical Analysis and Open Issues. In the solutions described previously, the underwater acoustic channel model and network characteristics are often employed during the decision of topology control through power control. The underwater acoustic channel model is frequently used to estimate the strength of the received signal, according to the distance between the communicating nodes. Thus, a transmission power level can be assigned to a node if the estimated received signal strength is enough to ensure successful message delivery. However, a complete characterization of the unique features that affect underwater acoustic communication introduces significant complexity in analytical models.

Nevertheless, the adoption of more realistic models is fundamental for topology control. This fact introduces a greater challenge in the design of efficient power control–based topology control solutions. Depending on the scenario (shallow or deep waters), underwater acoustic communication will be more or less affected by environmental noise. Moreover, the received signal is determined by multi-path propagation, which has been neglected in most of the proposals. In addition, the signal propagation speed varies according to the characteristics of the environment: shallow versus deep water, warm versus cold seas, and flat versus rough sea bottom (Guerra et al. 2009b). Hence, it is preferable to have power control algorithms providing on-the-fly measured metrics of the network performance instead of estimating metrics from considered models.

Furthermore, having a periodic transmission power assignment would be desirable; this could operate on a per-message basis. This is due to the high spatiotemporal variability in the quality of the underwater acoustic channel. However, a periodic transmission power assignment increases network overhead and energy consumption due to the frequent channel probing or exchanges of control messages to update the neighborhood information and variables used to estimate the channel quality. Hence, power control–based topology control protocols should efficiently balance link quality and energy consumption when determining the frequency of updates in the assigned transmission power level.

In addition, as discussed previously, most of the solutions proposed for power control–based topology control relied on minimal transmission power assignment at intermediate nodes, ensuring connectivity and an acceptable message error rate. Therefore, as a node perceived a decrease in the channel quality, it would increase the transmission power, and therefore the energy consumption. However, not all message loss is occasioned by a weak received signal. Message loss can also occur due to temporary lack of connectivity occasioned by shadowing zones. In these situations of complete channel deterioration, it is better to suspend transmissions instead of wasting energy trying to deliver them using a higher transmission power.

4.2 Network Throughput

Power control–based topology control algorithms can also be proposed to improve the throughput of a UWSN. In UWSNs, an increased network throughput can be achieved either by confining interference or by increasing the achievable bandwidth. In the former approach, power control–based topology control algorithms assign a suitable communication range to increase spatial reuse (i.e., reduce interference) and, consequently, network throughput. In the latter approach, power control–based topology control algorithms determine the proper communication range and corresponding optimal frequency to increase the achievable bandwidth. Both approaches are discussed in detail in the following sections.

4.2.1 Transmission Scheduling. It is well known that the throughput of a network system is closely related to spatial reuse, which in turn represents the number of links that can simultaneously transmit data (Su et al. 2015). In wireless networks, the interference among nodes in close proximity to one another is a critical factor limiting the network capacity. In these networks, due to the broadcast nature of the communication medium, nodes located inside an interference zone of both the transmitter and receiver should be kept silent (i.e., without transmitting) when a transmission is happening. This silence is necessary to avoid message collisions and, consequently, wasting network resources (e.g., bandwidth and energy).

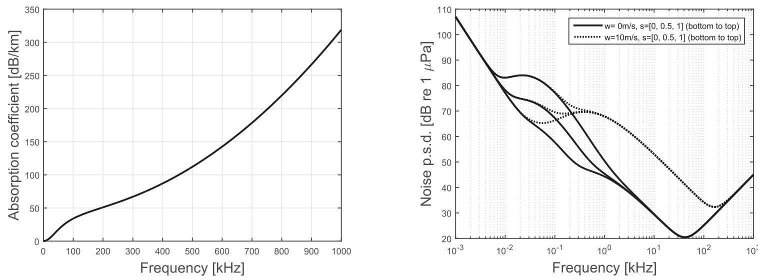
The design principle of power control–based topology control algorithms to improve network throughput is straightforward. First, a link-scheduling model is proposed or applied to detect links that will conflict with each other—that is, those links where packet collisions will occur when transmitting simultaneously. Second, a power control mechanism is generally proposed to decrease the communication range of underwater sensor nodes. The idea is to reduce the number of conflicting links, which will allow an increased number of underwater sensor nodes to transmit simultaneously without the risk of packet collisions.

The first step mentioned previously (i.e., modeling conflicting links) can be observed in the solutions described in the following. Bai et al. (2016) proposed an optimization formulation of the conflict-free link scheduling problem using correlation and conflict matrices. Su et al. (2015) devised a new metric to measure the spatial reuse, where a given transmission might successfully happen, if the signal to interference plus noise ratio (SINR) is larger than a decoding threshold. Shashaj et al. (2014) adopted a generalized approach to model communication conflicts, in which two types of conflicts might occur: (i) duplex conflict, where a node is not able to receive packets from more than one link simultaneously, nor capable of transmitting while it is receiving a packet, and (ii) interference conflict, where links are in conflict only if the generated interference is so powerful that the transmitted packet cannot be correctly received.

After modeling and detecting conflicting links, power control–based topology control might be used to reduce interference and improve spatial reuse. Bai et al. (2016) used power control to reduce interference zones, as well as to achieve a high throughput and a low end-to-end delay, which are frequent requirements of real-time underwater monitoring applications. Shashaj et al. (2014) proposed power control–based scheduling and routing policies to optimize network resources (e.g., bandwidth and energy) in periodic traffic applications of UWSNs. Su et al. (2015) proposed the UPC-MAC protocol, where power control is performed independently on the senders. To do so, the Nash equilibrium of a utility function is defined to maximize the network throughput and reduce energy consumption. In contrast, Anjangi and Chitre (2015) developed a transmission scheduling algorithm for randomly deployed underwater networks. The scheduling algorithm determines the time slots in which each node transmits and receives messages. In their work, power control was used to limit the interference range and, consequently, increase the achievable throughput.

From the aforementioned solutions, it can be observed that power control has been considered to either confine interference or guarantee an SNR larger than a decoding threshold. When a suitable transmission power is considered at each node, a conflict between the communication links can be reduced. Spatial reuse can thus be increased; consequently, so can the network throughput. In addition, when interference cannot be confined (i.e., the interference zone cannot be reduced), increased packet delivery rate can be reached by using a suitable transmission power that guarantees the right power strength at the receiver so that it can successfully decode the packet. However, the preceding proposals fail to consider power control to conserve energy (as described in Section 4.1).

4.2.2 Bandwidth-Distance Relationship. In UWSNs, in contrast to terrestrial wireless ad hoc and sensor networks, the design of topology control algorithms based on power control can be used to explore the bandwidth-distance relationship of the underwater acoustic channel. It is well known that in radio frequency–based wireless communication, the energy cost for transmitting is proportional to the distance between the communicating nodes. As the nodes are distant, a higher transmission power is necessary to ensure successful message reception (i.e., strong enough received signal). However, in the underwater acoustic channel, the distance between the communication nodes will also affect the useful bandwidth.



(a) (b)

Fig. 4. (a) Absorption coefficient. (b) Power spectral density of the ambient noise.

Stojanovic (2006) showed that for a given communication distance, there is a limit to the maximum usable frequency. This limit is due to signal absorption, which increases rapidly as the frequency increases, as shown in Figure 4(a). Moreover, the intensity of the ambient noise (e.g., turbulence, shipping, waves, and thermal noise), which impacts the underwater acoustic signal, varies according to the used frequency. Therefore, there is also a limitation of the useful acoustic bandwidth from below, as the noise is high for low frequencies and decays as soon as the frequency increases, as shown in Figure 4(b). This leads to the conclusion that, based on the attenuation-frequency product, there is an optimal frequency f_c for each communication distance in which impairments on the transmitted signal are minimized.

Several power control–based solutions, already discussed in the previous section, explored the bandwidth-distance relationship to further reduce energy consumption. This cost reduction is achieved by reducing the needed time for a packet transmissions, when an increased bandwidth and data transmission rate are possible. In this regard, Porto and Stojanovic (2007) showed that the optimal transmission range corresponds to the minimal value that guarantees network connectivity, while decreasing the energy consumption and increasing the network throughput, in the considered scenarios of high frequency of 35kHz.

Casari and Harris (2007) drew similar conclusions. They leveraged the bandwidth-distance relationship to reduce the number of transmissions to complete a network broadcast (e.g., applications of route dissemination, neighborhood discovery, and in-network reprogramming of nodes) and minimize energy consumption and delay. Thus, considerable energy savings were obtained when nodes could properly adjust their transmission power.

Casari et al. (2007) investigated the performance of multihop relaying-only and parallel transmission policies for data delivery from underwater nodes to a sink. The former solution employs short-range communication and forwards messages for all nodes upstream, until they reach the sink. In the latter, each node has the option of using long-range communication to forward part of its message directly to the sink, whereas the remaining messages are forwarded through multihop short-range communication. Again, results showed that multihop transmissions through short-range communication led to reduced energy consumption.

Jornet and Stojanovic (2008) investigated the effects of the number of available power levels that are allowed to be assigned to the nodes. Numerical results showed that there was a reduction in the total power consumption, based on an increase in the number of power levels. This was due to the fact that nodes could adjust their transmission power with greater accuracy. Results showed that four power levels were sufficient for achieving a good compromise between energy consumption and implementation complexity for the considered network.

In conclusion, the solutions discussed in this section highlighted the potentials for the use of power control–based topology control to explore the bandwidth-distance relationship of the underwater acoustic channel in UWSNs. In general, the obtained results in the mentioned studies showed that this approach improved network throughput and also reduced the energy cost. The exploration of this relationship is an important insight that must drive the future design of power control–based topology control protocols for UWSNs.

4.2.3 Critical Analysis and Open Issues. In the context of topology control, transmission scheduling, pairwise optimal communication range, and frequency assignment are promising techniques to increase throughput in the harsh environment of wireless acoustic communication. However, most of the proposed solutions have only addressed this problem from a theoretical point of view. Moreover, current proposals, especially regarding transmission scheduling, have been studied in limited scenarios of UWSNs with only a few links. In this way, there is a need to design local and distributed heuristic algorithms for transmission scheduling and assignment of an optimal communication range. A set of nodes in the proximity could efficiently exchange information and coordinate the use of transmission slots, range, and frequency to maximize the channel utilization and throughput. In this envisioned scenario, power control–based topology control will be fundamental for shortening the communication range of nodes, improving spatial reuse, and achieving high bandwidth. Moreover, transmission-scheduling proposals need to address practical aspects; thus, power control will be influential in coping with the high acoustic link quality variability.

Moreover, to the best of our knowledge, there is no study in this topic that considers scenarios of cooperative communication. Herein, we define a hard and soft cooperative communication as follows. Hard cooperative communication refers to those scenarios in which multiple nodes coordinately transmit the same message at the physical layer. The idea is to create a virtual antenna array to improve link quality and reliability by increasing spatial diversity, such as in Tan et al. (2013). However, we define soft cooperative communication as those scenarios where, at the network layer, multiple nodes coordinate to forward a message toward a destination. In this case, a set of next-hop forwarding candidate nodes is selected, and a transmission priority level is assigned to each candidate node. Thus, when the source node transmits, the candidates that have received the data message will forward it in a coordinated way such that a low-priority level node forwards the message only if it does not hear the message being forwarded by a high-priority node. This procedure, known as opportunistic routing (Coutinho et al. 2016a), is a possible efficient solution for improving link reliability in UWSNs.

In both scenarios, transmission scheduling and frequency selection will be challenging. Transmission scheduling algorithms must consider the nature of communications from many-to-one or one-to-many transmissions. The communication range assignment and the consequent optimal frequency usage at each node must consider and leverage its neighborhood to improve link reliability through cooperative communication. Topology control algorithms will be important for reducing the complexity of these algorithms, in the sense that they can be helpful for organizing network topology to reduce the complexity of communication.

Finally, it is worth mentioning that despite the conclusions of the benefits of short-range and optimal frequency usage for communication (Casari and Harris 2007; Casari et al. 2007; Porto and Stojanovic 2007; Stojanovic 2006), there is no extensive protocol design exploiting this potential using transmission power adjustment in UWSNs. In fact, most of the networking solutions for UWSNs have considered short-range multihop communication of the order of hundreds of meters instead of kilometers. For instance, some of the routing protocols proposed for UWSNs have considered a communication range of 250m or less (Coutinho et al. 2013b, 2016b; Noh et al. 2013).

Table 5. Power Consumption of the WHOI Micromodem-2

State	Energy Consumption	State	Energy Consumption
Transmitting	8–48 W	Idle (active)	300mW
Receiving	300mW	Hibernating (sleep)	165μW@5V or 455μW@12W

However, they do not exploit the on-the-fly transmission power adjustment capability already available in some acoustic modems. In fact, there is a lack of on-the-fly power control algorithms with the purpose of topology control in UWSNs despite the existence of acoustic modems allowing this. Interestingly, transmission power adjustment methodology is the most popular technique for controlling the topology of wireless ad hoc networks.

5 WIRELESS INTERFACE MODE MANAGEMENT–BASED TOPOLOGY CONTROL APPROACH

The management of the wireless interface of nodes is a well-investigated methodology for topology control in terrestrial WSNs. However, in underwater sensor networks, this research topic is still in its infancy. Indeed, discussion continues about whether the management of the wireless interface modes is a worthwhile approach for topology control aiming to reduce energy consumption of UWSNs. In the remainder of this section, we discuss representative proposals that have investigated the trade-offs of wireless interface mode management and energy conservation in UWSNs.

In wireless networks, the communication interface has different modes of operation: *transmitting*, *receiving*, *idle*, *sleep*, and, of course, totally *powered off*. Each operation mode has different unitary costs of energy consumption. Hence, the overall energy consumption of a node depends on the amount of time it spends with its wireless interface at each mode, as given by the following simplified equation of the energy consumption:

$$E = T_{\text{tx}} e_{\text{tx}} + T_{\text{rx}} e_{\text{rx}} + T_i e_i. \tag{1}$$

In Equation (1), the variables T_{tx}, T_{rx}, and T_i correspond to the amount of time that the wireless interface spent transmitting, receiving, and in the idle state, respectively. The terms e_{tx}, e_{rx}, and e_i are the energy consumption of transmitting, receiving, and idle states per time, respectively. In general, it is considered that a node does not spend energy when its wireless interface is powered off.

The WHOI Micromodem-2 (Gallimore et al. 2010), designed for underwater acoustic communication, presents the costs shown in Table 5. As seen in this acoustic modem, there is a significant difference between transmission and receiving/idle costs in acoustic modems. The receiving and idle energy costs, in fact, are very low and similar to the typical radio frequency–based wireless interfaces. In this regard, one might suggest that there is no reason to be concerned with receiving and idle energy costs in UWSNs, as they could be easily dominated by the transmission cost.

However, despite the significant difference between transmitting and receiving/idle costs, underwater sensor nodes spend most of their operational cycles in the idle listening mode, as data message transmissions in underwater monitoring applications are very infrequent. Therefore, the wireless interface mode management in UWSNs may also result in energy conservation, as observed in the work of Harris et al. (2009) and Coutinho et al. (2015b).

In the aforementioned context, topology control using wireless interface mode management can conserve energy during times of no communication. Topology control algorithms change the network topology, either by keeping a backbone of active nodes for communication purposes, where the remaining redundant nodes can go to sleep (density control), or by controlling the

Table 6. Summary of the Wireless Interface Mode Management Methodology

Subcategory	Basic Solution	Challenges
Density control	Keeps a set of nodes awake, at any time, to serve as a communication backbone for data delivery.	Low-density deployments; mobility; unreliable channels for determining and maintaining a communication backbone.
Duty cycle	Switches the radio of a node synchronously or asynchronously between active and sleep modes, periodically.	Time synchronization; overhead; high delay; long message preambles; low reliability of acoustic channel.

active periods of the nodes to make them available at the same time, for enabling communication (duty cycling operation). Both approaches lead to energy conservation, as they reduce the amount of unnecessary time a node spends listening to the channel.

Moreover, this topology control approach might reduce interference by means of the network density control, which decreases message collisions and the need for message retransmissions. Consequently, it will also improve the performance of slotted-based MAC protocols in UWSNs and decrease the overhead of neighboring discovery of routing protocols, as only a subset of the nodes will be awake.

However, the density control and duty cycling might diminish network connectivity and, consequently, the UWSN performance. In a UWSN, a set of nodes forming an active backbone might not be enough for data delivery. This is due to the variable quality of the underwater acoustic channel, as described in Section 2.2. Actually, the use of redundant nodes has been shown to improve data delivery reliability and balanced energy consumption in UWSNs (Coutinho et al. 2017b).

In this section, we discuss topology control solutions for UWSNs based on the management of the wireless interface modes. As already mentioned, the discussion follows two subcategories: density control and duty cycle. Table 6 shows a summary of these two categories. The proposals presented in the following are qualitatively compared in Table 7.

5.1 Density Control–Based Topology Control

In general, topology control algorithms in this category select a subset of the deployed nodes to be in active mode. The nodes that are kept in active mode form a communication backbone for multihop data delivery. To conserve energy, the unchosen nodes completely turn off their wireless interface. The density control–based topology control approach has been particularly employed in terrestrial WSNs, as they usually comprise high-density deployments.

At the present time, the density control–based topology control approach has been less explored in underwater sensor networks when compared to the other topology control approaches (power control based (Section 4) and mobility assisted based (Section 6)). The main reason for this is that underwater sensor networks, in contrast to terrestrial WSNs, typically involve sparse deployments. Moreover, the lack of redundant paths for data delivery might diminish the performance of UWSN applications. This is due to the high time-variable aspect of the quality of the underwater acoustic channel, as discussed in Section 2.2. Therefore, each node has a vital role for network connectivity in a UWSN.

However, as will be pointed out in the following, a few studies investigated the benefits and drawbacks of this topology control methodology in UWSNs. Further investigations might be

Table 7. Wireless Interface Mode Management–Based Topology Control Algorithms

Category & Proposal	Layer	Approach	Goal	Constraint	Potential Applications
Density control (Harris et al. 2009)	Physical layer	Compare sleep cycling, where nodes periodically alternate between active and sleep modes, and wake-up approaches, where an ultra-low-power radio is considered to wake the main radio, for energy conservation in UWSNs.	Reduce energy consumption	Network connectivity	Underwater monitoring applications requiring periodic data collection at low sample frequency
Density control (Wills et al. 2006)	Physical layer	Develop a low-cost and low-power acoustic modem to support short-range communication for dense underwater sensor networks.	Reduce energy consumption	Network connectivity	Underwater monitoring applications requiring high-density deployments, such as pollutant and marine biology monitoring
Density control (Sanchez et al. 2011)	Physical layer	Develop an acoustic triggered wake-up system that is not restricted to a specific acoustic modem.	Reduce energy consumption	–	General long-term underwater monitoring applications
Density control (Li et al. 2015)	Physical layer	Develop an on-duty circuit for power monitoring on the channel and acoustic modem wake-up system.	Reduce energy consumption and wake-up delay	–	General long-term underwater monitoring applications
Density control (Su et al. 2016)	Physical and MAC layers	Propose a cycle difference set-based protocol to determine the number and positions of active and sleep intervals in one cycle to guarantee that both the transmitter and receiver are awake for communication.	Reduce energy consumption and delivery delay	Network connectivity	Delay-constrained general long-term underwater monitoring applications, such as pollutant dispersion monitoring and underwater surveillance applications
Duty cycling (Zorzi et al. 2010)	Physical and network layers	Investigate how duty cycling affects the effective node density and energy consumption of UWSNs.	Keep network connectivity while reducing energy consumption	Network connectivity	Long-term underwater monitoring applications requiring highly reliable data delivery, such as target tracking and underwater surveillance applications
Duty cycling (Hong et al. 2013)	Physical layer	Study the sleeping–waking up frequency for duty cycling in UWSNs.	Reduce energy waste of frequent and unnecessary on/off radio switching operation	Network connectivity	General long-term underwater monitoring applications
Duty cycling (Coutinho et al. 2015b)	MAC and network layers	Develop an analytical framework for studying the control packet–based approaches used to guarantee that the transmitter and receiver will be awake at the same time for data transmission.	Reduce energy consumption and delay while maintaining network connectivity	Network connectivity	Long-term underwater monitoring applications requiring high-reliable data delivery, such as target tracking and underwater surveillance applications
Duty cycling (Coutinho et al. 2016c)	MAC layer	Propose an optimization model to investigate the performance of the on-the-fly adjustment of the sleep interval in duty-cycled UWSNs.	Achieve a balanced energy consumption	Network connectivity	Long-term underwater monitoring applications requiring high-reliable data delivery, such as target tracking and underwater surveillance applications

motivated by the facts that (i) the deployment of underwater sensor nodes usually occurs in the following manner: a group of underwater drift nodes are initially deployed in a small area and spread out with ocean currents as time goes by, creating high-density deployment in the beginning of the monitoring mission; (ii) underwater nodes might use a high communication range, which will result in redundancy.

Harris et al. (2009) studied the potentials of idle-time power management and wake-up modes in UWSNs. In the considered scenarios, simulations led to the conclusion that the ultra-low-power wake-up mode outperforms sleep cycling, and, of course, the approach of having all nodes always on, for UWSN applications of periodic data transmission at a frequency in the order of minutes to a few hours. This can be explained by the excessive transmission of control messages to ensure that the receiver node will be awake, and by the high energy cost for transmissions.

The conclusion in Harris et al. (2009) is important for motivating the design of low-power wake-up systems for underwater sensor networks. Basically, a low-power acoustic modem stays powered off when no communication is detected in the wireless broadcast channel. To wake up neighboring underwater nodes, an acoustic tone can be used as a stimulus wake-up signal propagated in the channel. Thus, whenever a sleeping node detects a given level of energy in the channel, its acoustic modem wakes up to receive a further data transmission. The challenge of this approach is the efficient design of acoustic modems having high sensitivity and fast reactivity to provide accurate awakenings.

In this context, Wills et al. (2006) developed a low-cost and low-power acoustic modem to enable high-density deployments of short-range communication-based UWSNs. In the designed acoustic modem, the wake-up receiver module is responsible for (i) monitoring the energy level existing in a narrow band of frequencies and (ii) waking up the receiver through an interruption, whenever the observed energy in the channel exceeds a threshold level.

Sanchez et al. (2011) designed an RFID-based wake-up system for a low-power acoustic modem. In the proposed solution, a wake-up signal is transmitted to inform the intended receiver about a new message transmission. On the receiver side, an interrupt signal is generated to wake up the microcontroller, whenever the intended receiver detects a wake-up signal matching its assigned recognition pattern. Li et al. (2015) designed an on-duty circuit for power monitoring and acoustic modem wake-up. To control the on-duty circuit, the authors implemented sleep, monitoring, and working operational modes in their modem. The wake-up circuit in the monitoring mode, triggered by an alarm time, wakes up and switches the modem to the working mode whenever it detects a wake-up signal received by the transducer.

In terms of protocols, a viable solution may lie in the asynchronous alignment of awake periods of pairs of underwater sensor nodes. This is a simple approach that can reduce the complexity and the requirement of an extra low-power acoustic modem used to wake up the main modem. In this approach, an overlap of awake periods among neighboring nodes can be determined based on the traffic load and their location in the routing path to sink nodes. Su et al. (2016) discussed how asynchronous wake-up can be used for energy conservation in UWSNs. The authors proposed a cyclic difference set (CDS)–based protocol, by utilizing combinatorial designs, to determine not only the number but also the positions of active and sleep intervals in one cycle to guarantee at least one overlapping slot where each pair of nodes will be awake. This approach seems to be very suitable for periodic data collection scenarios. However, it may be strictly dependent on the network topology and inadequate for nonstatic underwater sensor networks.

5.1.1 Critical Analysis and Open Issues. During the design of wireless interface management–based topology control protocols for UWSNs, the peculiar characteristics of the environment and underwater acoustic channel should be carefully considered. Regarding this topology control methodology, the conclusions and knowledge acquired in radio frequency–based WSNs cannot be directly applied to UWSNs, due to the high noise, limited bandwidth, shadowing zones, Doppler effects, and high energy consumption for transmission in the aquatic environment.

Ideally, each underwater sensor node should be kept sleeping as much as possible. It should only wake up when it has a data message to transmit. However, since the multihop is used for data delivery, each node must also adjust its operational cycle (alternating between idle and sleep modes) to contribute to the multihop routing task. Moreover, UWSNs are sparsely deployed due to the high cost of building and deployment, which makes each node vital to the network connectivity and limits the number of possible candidates to continue forwarding the data message. Therefore, the topology control, based on the network density management, will incur increased delay for the applications, since the sender node should wait until the next-hop node wakes up. The design of protocols for the management of the wireless interface modes in UWSN must also consider the overhead introduced to obtain the information used to decide which nodes should remain awake. This overhead might incur energy costs that could be higher than the expected energy savings. This happens because the energy cost to transmit is much higher than any other wireless interface mode.

As low-power and low-cost acoustic modems become more available, moderate-to-high UWSN density deployments become possible. In this future scenario, topology control through density control will be fundamental. Coutinho et al. (2016d) proposed the PCen centrality metric to identify central nodes in UWSNs, from the point of view of data forwarding. This information could be used to keep central nodes active. Moreover, density control can be locally performed around central nodes aiming to achieve a balanced energy consumption.

5.2 Duty Cycling–Based Topology Control

In this survey, we consider duty cycling as a methodology that can be explored for topology control. One might claim that the duty cycling operation does not change the network topology, since a pair of communicating nodes will be awake at the same time for data delivery. However, from the point of view of topology control, the proper selection and/or adjustment of the sleep interval of the nodes will force the absence or existence of some links during communication.

Duty cycling has been extensively investigated to achieve energy efficiency in energy-constrained radio frequency–based wireless ad hoc and sensor networks. In a duty-cycled network, each node periodically alternates the state of its radio between active and sleep modes. In this approach, energy conservation is achieved by avoiding keeping nodes idle listening to the channel, especially in scenarios of low traffic load in sensor networks.

In general, duty cycling protocols have been classified as *synchronous* and *asynchronous*, according to the mechanism used to ensure that the pairwise communicating nodes are awake at the same time (i.e., during message transmission). In synchronous duty cycling, the sleep/wake up schedule of the nodes is aligned by means of an explicit negotiation. Therefore, a sender node is always aware when its neighbors are awake and apt to receive data messages. Conversely, in asynchronous duty cycling, the duty cycle schedule of the nodes is completely decoupled. Therefore, at an arbitrary time, only a subset of nodes might be in the active mode—that is, awake and apt to receive data messages.

Either synchronous or asynchronous duty cycling protocols have peculiar characteristics that will affect the performance of UWSNs. The synchronous duty cycling protocols rely on periodic signaling to ensure an alignment between the duty cycling schedules of the nodes. Moreover, there is a need for synchronized clocks, which require extra computing and communication efforts. This approach does not seem to be appropriated for UWSNs because of the overhead for clock synchronization and schedule exchanging. Asynchronous duty cycling protocols, however, are simple and do not involve periodic beaconing for schedule alignments. These seem to be more suitable for the harsh environment of UWSN applications. However, these protocols lead to an increase in end-to-end delay, as there is no guarantee that a receiver node will be awake when a sender node has a data message to transmit.

In the following, we briefly discuss the three main methodologies used to design asynchronous duty cycling protocols:

— *Naive asynchronous duty cycling* (Coutinho et al. 2015b): In duty cycling protocols based on this methodology, a sender node transmits a data message whenever it is ready. The message is successfully received if there is a neighboring node awake during the transmission. This approach is efficient in terms of energy conservation and overhead. However, there is no guarantee that a data message will be successfully delivered to the destination, particularly in low-density UWSN scenarios.
— *Low-power listening (LPL) duty cycling* (Buettner et al. 2006): In duty cycling protocols based on this methodology, a sender node transmits preambles before transmitting a data message. The preamble phase is used to ensure that the intended receiver will be awake during the transmission of the data message. This phase lasts for a slightly longer period than the sleep interval of the receiver node. At the receiver side, whenever it wakes up and detects a preamble transmission, it remains awake to receive the data message transmitted after the preamble phase. It is important to mention that the classical LPL approach is infeasible for UWSNs, due to the long preamble transmissions and the high energy cost of acoustic modems for transmitting. For these networks, the strobed preamble variant is desired. In the strobed preamble LPL variant (Buettner et al. 2006; Li et al. 2014), short preamble transmissions are interleaved by silent times. Finally, it is worth mentioning that energy expenditure mostly happens in the sender nodes.
— *Low-power probing (LPP) or receiver-initiated duty cycling* (Rodríguez-Pérez et al. 2015; Sun et al. 2008): In duty cycling protocols based on this methodology, a receiver node transmits a beacon whenever it wakes up. This transmission is used to inform its awake situation for possible sender nodes in the neighborhood. Thus, whenever a sender node has a data message to transmit, it waits until the intended receiver wakes up and transmits the beacon.

In the literature, we can note an evolving path from the investigation of the basic principles of duty cycling in UWSNs to the effective development of algorithms. First, Zorzi et al. (2010) studied the effects of the effective node density on the energy consumption of a UWSN. In the considered scenario, nodes operating in a duty-cycled way were able to control their transmission power. The authors observed that one of the main drawbacks of the use of asynchronous duty cycling is the decrement of the instantaneous network density and, consequently, the network connectivity.

Hong et al. (2013) addressed the problem of sleeping-waking frequency in duty-cycled UWSNs. The motivation of that work comes from the fact that the frequent switching of the radio on/off will waste energy and, consequently, decrease the lifetime. The authors proposed the receiver-oriented sleep scheduling (ROSS) scheme to conserve energy by reducing the sleeping-waking frequency of the nodes. The proposed scheme works in a tree topology using a TDMA scheduling for transmissions. The ROSS scheme allocates the working time of each node from the root to the leaf nodes, where each node will be able to sleep immediately after forwarding all received data from its children. Due to the mechanism used to determine the working time of each node, the ROSS scheme achieves higher throughput and lower end-to-end delay in comparison to the related MAC protocols proposed for UWSNs.

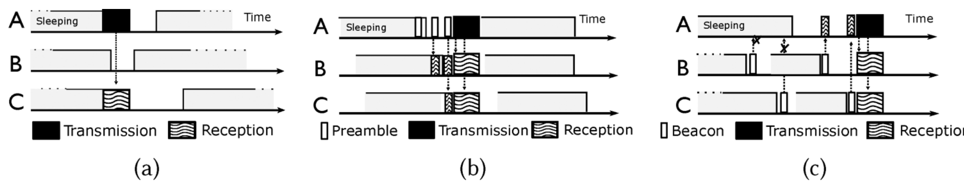


Fig. 5. Paradigms to design duty cycling protocols. (a) Naive duty cycling. (b) LPL. (c) LPP.

Coutinho et al. (2015b) proposed an analytical framework for the performance evaluation of duty cycling protocols based on the aforementioned three methodologies (naive, LPL, and LPP) in scenarios of UWSNs using opportunistic routing protocols, as shown in Figure 5. The authors evaluated the potentials for energy conservation of these approaches in comparison to the always-on radio configuration scenario. The obtained results showed that naive-based asynchronous duty cycling protocols achieved greater efficiency in terms of energy conservation. This is due to the absence of control message transmissions to ensure that both the receiver and sender nodes will be awake at the same time. However, due to the lack of this mechanism, this approach performed poorly in terms of message delivery.

Coutinho et al. (2016c) investigated how the appropriate selection of the sleep interval of nodes in duty-cycled UWSNs impacts the network lifetime. The authors proposed an analytical framework to evaluate the impact that the sleep interval control at the nodes have on the network lifetime. They argued that the amount of time a node spends sleeping must be periodically adjusted to achieve a balanced energy consumption between the nodes. This is due to the fact that a long sleep interval conserves energy at the receiver nodes, but it leads to high energy consumption of sender nodes due to the strobed preamble transmissions. Results obtained using a sleep interval control optimization formulation, considering traffic load and network density, showed that on-the-fly sleep interval adjustment is preferable, as it can prolong network lifetime by reducing the quick battery depletion of central nodes from a routing point of view.

5.2.1 Critical Analysis and Open Issues. From the literature review, it is evident that the research of duty cycling in UWSNs is still in its infancy. In fact, possible solutions for duty cycling in UWSNs appear to determine the design principles of topology control algorithms in this case. Because of that, the proposed solutions have considered particular topologies, as in Hong et al. (2013), or routing paradigms, as in Coutinho et al. (2016c).

In UWSNs, the design of duty cycling–based topology control protocols must carefully consider the overhead of this strategy, so a pairwise of communicating nodes will be awake during the message transmission. Herein, this challenge is critical for two main reasons. First, the signaling overhead may reduce message transmissions because of a possible increase in message collisions. This will require retransmissions, where new signaling rounds will occur. Second, the transmission cost is one order of magnitude higher than the receiving and idle costs. Therefore, a high signaling rate might result in greater energy consumption than in scenarios without duty cycle operation.

In addition, the design of a duty cycling protocol should consider the increment on the already high end-to-end delay in UWSNs. Since asynchronous duty cycling has been preferably considered in UWSNs, an intended receiver node may not be awake when the sender node has a data message to transmit. Therefore, the transmission will be delayed until the intended receiver wakes up. This per-hop delay increment might not be tolerable at times, such as in real-time applications. In this sense, opportunistic routing can be explored, as more than one neighboring node will likely continue forwarding the data message. Thus, a sender node will only wait until a first candidate node wakes up. In fact, this approach has been extensively explored in terrestrial WSNs (Cattani et al. 2016; Ghadimi et al. 2014).

6 MOBILITY ASSISTED–BASED TOPOLOGY CONTROL

In underwater sensor networks, topology control can be performed by controlling the mobility of some underwater nodes. In this approach, the basic idea is to move one or a few underwater nodes for new locations. This displacement can be done with the objective of improving network functioning or performance.

In the terrestrial WSN, mobility assisted–based topology control has been extensively designed to restore network connectivity (Younis et al. 2014). This is motivated by the fact that in these networks, network connectivity is frequently disrupted by node failures occasioned by either battery depletion or hardware problems. In these scenarios, new locations are computed for some mobile nodes. Afterward, these nodes move to the determined locations and act as bridges between the two previously disconnected network segments.

In the context of UWSNs, mobility assisted–based topology control algorithms have been used to improve data collection (Basagni et al. 2014; Forero et al. 2014), data routing (Coutinho et al. 2013a, 2015a), coverage (Cayirci et al. 2006), or even underwater node localization (Erol et al. 2007b). AUVs or nodes with depth-adjustment capabilities can be used for these purposes. The use of AUVs allows more flexible and efficient topology control, as they can move in any direction. Conversely, ordinary underwater nodes have a constrained mobility. They can usually move vertically—that is, they can adjust their depths. However, this approach is more affordable than AUVs and can therefore be deployed in different ways.

The mobility assisted–based topology control is probably the most powerful methodology for changing the network topology. We can state that the previously discussed topology control methodologies make "soft" changes in the network topology by enabling or disabling communication links. In fact, there are no physical changes regarding the location of the nodes, limiting the possible neighboring nodes of a given node. Conversely, using mobility assisted based topology control, nodes can be relocated, and, consequently, a more effective density control can be accomplished, enabling a new sets of neighboring nodes. Therefore, this approach can achieve better performance when topology control is used to improve coverage.

Topology control using a mobility assisted–based approach must carefully select the nodes to be moved and the location to which they will end up. In most of the network deployments, there are associated costs in moving mobile nodes, such as the energy cost. These costs should be considered when the topology control algorithm selects the nodes and new locations for them. This is to prevent mobile nodes from quickly depleting their batteries, which might incur disruption in the network connectivity. Therefore, independently of the use of AUVs or underwater nodes with depth-adjustment capabilities in UWSNs, the main research challenge in designing mobility assisted–based topology control is to propose efficient protocols for selecting the nodes to be moved and determining their new locations.

In the following, we discuss two mobility assisted–based topology control approaches, summarized in Table 8, according to the considered type of mobile nodes. The solutions presented in this section are qualitatively compared in Table 9.

6.1 Trajectory–Based Topology Control

Topology control algorithms for UWSNs in this category have used AUVs. In this approach, an AUV travels within the area, visiting a set of nodes, which will create and terminate communication links as it moves. This topology control methodology has been used to determine suitable

Table 8. Summary of the Mobility Assisted–Based Topology Control Methodology

Subcategory	Basic Solution	Challenges
Depth adjustment	Underwater sensor nodes are moved vertically for new locations.	Mobility; movement delay; energy cost for vertical movement; low-density deployments; changes in the sensing coverage area.
Trajectory based	AUVs follow well-defined trajectories to collect data from underwater sensor nodes.	High cost; energy limitation; localization and tracking.

UWSN topology reducing void nodes (Ghoreyshi et al. 2017), improve data collection (Forero et al. 2014), or enable much richer underwater applications relying on multimedia content (Fan et al. 2016). In this last case, AUVs equipped with optical and acoustic communication visit underwater sensor nodes and collect data from them by optical links whenever they are paired with the sensor node.

This heterogeneous architecture is intended to overcome the bandwidth-limited nature of the underwater acoustic channel, which can support data delivery of single readings of environmental variables (e.g., temperature, salinity, and pressure level). However, it is insufficient for handling multimedia content, obtained from high-resolution cameras, in UWSN applications.

In these applications, optical communication is preferable for data offloading. This is because the optical channel can achieve high data rates, in the order of several megabit per second, over short distances. Conversely, acoustic communication will still play a significant role in these AUV-aided heterogeneous UWSN architectures. For example, it will be used for the transmission of control data among long-range nodes, to provide information about sensed data, and to coordinate the AUV trajectory. Thus, the trajectory of the AUV can be determined from the existence of hot spots.

Some of the main research challenges, when designing topology control approaches using AUVs, arise from the design of AUV path planning algorithms. Since there is an associated cost for the AUV movement and a delay for the displacement of the AUV from its current position to the node to be visited, efficient AUV path planning solutions must be proposed to minimize the cost and achieve the desired user's expectation in terms of collected data. Moreover, these solutions must consider the technological and environmental constraints and challenges, such as energy, data storage, wind speed, and the roughness of the surface of the water.

A traditional AUV-based topology control approach uses the value of information (VoI) to determine the trajectory of an AUV in underwater sensor networks. In this approach, gathered data receives a VoI that would decrease as time elapses—that is, its importance to the application decreases as it becomes outdated. Based on the VoI function, the time that the previously sensed data was collected and movement speed of the AUV, its path is determined with the intention of maximizing the overall VoI of the data delivered to the application.

In this regard, Khan et al. (2014) proposed the use of an exponential-based monotonically decreasing function to calculate the VoI for the AUV path planning. Considering the devised VoI function, the following three AUV path-planning algorithms differ in the selection of the next node to be visited: (i) a neighboring node of the currently visited node, (ii) the next node of utmost importance (high VoI), and (iii) a randomly selected node. Khan et al. (2015) extended their work by using a devised VoI function for the proposal of six different heuristics for the path planning of multiple AUV mobile sinks. Finally, Khan et al. (2016) incorporated the AUV resurfacing schedule in the AUV path planning problem. The optimized resurfacing schedule of the AUV is essential for the offload of time-sensitive data (e.g., underwater surveillance applications) to the sink. To do so, the authors extended their exponential-based VoI function by considering the timestamp when the chunk is processed by the end-processing agent. Therefore, two proposed heuristics will

Table 9. Mobility Assisted–Based Topology Control Algorithms

Category & Proposal	Task	Approach	Goal	Constraint	Potential Applications
AUV based (Khan et al. 2014)	Timely data collection	Propose an exponential-based VoI function and the LPP, GPP, and RPP path AUV path planning heuristics for the selection of the next node to be visited by the AUV.	Improve data collection and reduce the data delivery delay of recently obtained data	Energy capacity of the AUV	Delay-constrained applications requiring high-fidelity data delivery, such as oil spill monitoring
AUV based (Khan et al. 2015)	Timely data collection	Propose the following six heuristics for VoI-based multiple mobile sinks (AUVs) path planning for data collection: (i) next-node visit based on maximum VoI, (ii) minimized tour time for path traversal, (iii) next-node visit based on maximum VoI with intermediate neighbor visit, (iv) load balancing in terms of nodes visited, (v) balanced distribution of nodes in terms of VoI, and (vi) partitioning map on the basis of node proximity.	Improve data collection	Energy capacity of multiple AUVs	Delay-constrained applications requiring high-fidelity data delivery, such as oil spill monitoring
AUV based (Khan et al. 2016)	Timely data collection	Propose to incorporate the AUV resurfacing time in the VoI function and AUV path planning algorithm	Improve data collection and reduce data delivery delay in time-sensitive applications	Energy capacity of multiple AUVs	Time-sensitive underwater monitoring applications, such as underwater surveillance and military target tracking applications
AUV based (Gjanci et al. 2017)	Data collection	Develop the AUV path finding GAAP heuristic for the selection of the next node to be visited. The next node selection is based on the expected VoI of the nodes at the arrival time of the AUV.	Improve data collection	Energy capacity of the AUV	Delay-constrained applications requiring high-fidelity data delivery
AUV based (Forero et al. 2014)	Data collection	Develop multiple AUV path planning considering the energy capacity of AUVs, battery recharge time, and their data storage capabilities.	Improve data collection and reduce data delivery delay	Energy capacity of multiple AUVs	Delay-constrained applications requiring high-fidelity data delivery
Depth adjustment (O'Roarke et al. 2012)	Data gathering	Develop the AquaNode underwater sensor node, which has a winch-based apparatus for vertical movement (depth adjustment).	Sensing and data collection of events of interest	–	General underwater monitoring applications
Depth adjustment (Jaffe and Schurgers 2006)	Data gathering	Develop the Drogue node, which has a buoyancy-based apparatus for vertical movement (depth adjustment).	Sensing and data collection of events of interest	–	General underwater monitoring applications

(Continued)

Table 9. Continued

Category & Proposal	Task	Approach	Goal	Constraint	Potential Applications
Depth adjustment (Basha et al. 2014)	Routing	Design eight algorithms to select the AquaNode devices that would surface for data delivery through radio frequency–based wireless channels.	Improve data delivery	Energy cost for depth adjustment	Long-term nonmobile applications requiring high-fidelity data delivery
Depth adjustment (Coutinho et al. 2013b)	Routing	Develop the DCR protocol for nonmobile UWSNs, which employs a depth adjustment procedure to tackle the communication void region problem.	Improve data routing	Vertical movement capabilities and energy cost for depth adjustment	Long-term nonmobile underwater monitoring applications, such as the monitoring of underwater equipment in offshore oil/gas exploration industries
Depth adjustment (Coutinho et al. 2015a)	Routing	Design the DTC and CTC depth adjustment–based topology control algorithms for disconnected and void nodes repositioning.	Improve network connectivity and data routing	Vertical movement capabilities and energy cost for depth adjustment	Long-term nonmobile underwater monitoring applications, such as the monitoring of underwater equipments of offshore oil/gas exploration industries

determine an optimized AUV path and resurface schedule considering the delay, not only from the data generation and its collection by the AUV but also from its generation until the delivery to the end-processing agent.

Gjanci et al. (2017) proposed an integer linear programming (ILP) formulation to determine AUV paths that maximize the VoI of collected data. The proposed ILP formulation considers realistic factors of UWSN and applications, such as communication rates, distances, and surfacing constraints of AUVs. From the ILP formulation, the greedy and adaptive AUV path finding (GAAP) heuristic is proposed, in which the selection of the next node to be visited by the AUV is based on the expected VoI of the node at the arrival of the AUV. Using the GAAP heuristic, the AUV decides to visit a node only if the collected data will increase the VoI of the data that will be delivered to the sink. Conversely, Forero et al. (2014) proposed a dynamic path planning algorithm for trajectory coordination of multiple AUVs. Their proposed algorithm considers the energy capacity of AUVs, battery recharge time, and their capacity for data storage. Moreover, the algorithm dynamically routes AUVs instead of using a predetermined trajectory, which allows them to adapt to changes in network conditions (e.g., volume of data to be collected, remaining energy in the AUVs, and battery recharge times).

The trajectory of an AUV will affect the network topology. As the AUV moves, new links are created but its previous interconnections will be lost. In this context, the use of VoI functions is helpful when determining the AUV path. In addition to the delay, other applications' requirements can be considered toward an improved quality of service (QoS) in the data collection process. However, current solutions have neglected the energy cost, which is an important aspect of UWSNs. The energy consumption regarding AUV mobility should be considered in the VoI functions. Moreover, the AUV path planning should consider the current battery status of underwater data collectors toward a balanced energy consumption of the underwater sensor nodes.

6.1.1 Critical Analysis and Open Issues. As discussed previously, the use of AUV-aided topology control has been proposed both for timely data collection and enabling multimedia content–based underwater sensor network applications. However, the efficient design of these topology control algorithms using mobile AUVs still faces several research challenges, as we discuss in the following.

One critical issue is the problem of on-demand (or reactive) AUV path planning. In general, the path of an AUV can be generated statically (proactively) or dynamically (reactively). In the former case, the trajectory of the AUV is planned prior to the beginning of its operation. In doing so, information regarding prior known obstacles is considered by path planning algorithms when computing efficient trajectories. In the latter, either the algorithm plans the AUV trajectories based on partial information known from the environment or it updates the AUV trajectories in reaction to changes in the environment or objectives.

In UWSNs, reactive AUV path planning topology control algorithms are desired. This is due to the high variability of the underwater acoustic channel and environment. In this scenario, underwater nodes could be inaccessible at a particular moment, either because of node failures or time-varying link qualities. Thus, in a scenario employing preplanned trajectories for the AUVs, they can visit unnecessary nodes because nodes failed or did not obtain the data from surrounding nodes or collector points. In this case, a reactive AUV path planning topology control algorithm can determine a new trajectory, as the decision maker perceives the occurrence of such events.

Another critical challenge faced when designing mobility assisted–based topology control using AUVs is the coordination of multiple AUVs. In some underwater network deployments, multiple AUVs can be deployed to achieve a better performance, such as a low delay for data retrieval. Therefore, there is the need for AUVs localization and trajectory coordination, especially in reactive AUV path planning algorithms. This avoids the situation of an AUV visiting a node immediately after the node offloads the data to a previous AUV.

However, the characteristics of the underwater acoustic channel and environment might diminish the performance of these approaches. When multiple AUVs are considered, an overhead to coordinate them might exist, as mentioned earlier. The frequent transmission, using long communication ranges of control messages for AUV coordination, can increase message collisions and waste energy of the underwater sensor nodes, either to receive or transmit these control messages.

6.2 Depth Adjustment–Based Topology Control

In UWSNs, some topology control algorithms use the vertical movement (depth adjustment capabilities) of underwater sensor nodes to perform the topology control. The basic idea behind this approach is to change the network topology by coordinately controlling the depth of some underwater sensor nodes.

Recent underwater sensor nodes have been equipped with depth adjustment capabilities. For instance, the AquaNode (O'Rourke et al. 2012) uses a winch-based apparatus that allows it to move vertically. In this mechanism, each underwater node is attached to a surface buoy or an anchor. Hence, the vertical movement of the node is achieved by adjusting the cable. The Drogue node (Jaffe and Schurgers 2006), however, entails a buoyancy-based apparatus for vertical movement. In this approach, an internal buoy is inflated by a pump, bladder, or another device. This changes the buoyancy of the node with respect to the water. Thus, the node emerges. Each approach has advantages and disadvantages, considering the movement speed and the energy cost to move it.

An important aspect of topology control algorithms in this category is that they can organize the network topology either in a *proactive* or *reactive* manner, as discussed in the following. In proactive algorithms, the depth adjustment of the selected nodes is performed immediately after the network deployment. Based on the position of the randomly deployed nodes, a subset of them is determined to be moved to new depths to accomplish the desired goal (e.g., improvement in coverage or network connectivity). Moreover, to achieve better results, proactive depth adjustment–based topology control can be done using the information of the entire network topology.

This procedure can be described as follows. First, an AUV (or a set of them) will travel along the deployment area and collect the location information of the deployed nodes. This can be done together with the AUV-aided underwater node localization systems (Erol et al. 2007a). Second, the topology control algorithm will determine the set of nodes that need to be moved, as well as their new depths. This selection is based on the initial topology and the desired goals. Third, AUVs can be employed to inform the selected nodes to move to new depths.

In reactive algorithms, depth adjustment decisions are made locally at some nodes. A given node, based on an event firing the topology control algorithm, determines whether or not it should move. This decision will be motivated by the network status or local topology. For this, the node will use the information from its neighborhood. After that, based on given criteria, the node will select a new depth. Reactive depth adjustment–based topology control algorithms are preferable in mobile UWSNs. For instance, they can be used to restore network connectivity, as nodes involuntarily move according to the ocean currents.

Herein, we discuss some preliminary solutions that used this approach for topology control. Accordingly, O'Rourke et al. (2012) proposed the use of depth adjustment of the nodes to improve data delivery. The authors suggested a multimodal underwater sensor node equipped with both underwater acoustic and radio frequency modems. Thus, each node can either deliver data through multihop acoustic communication or can surface and use radio frequency communication. Moreover, O'Rourke et al. (2012) proposed a set of algorithms to compute the energy and delay trade-offs of nodes, with the goal of selecting a subset of them to surface and transmit data through radio channels. Preliminary results showed that the greedy algorithm, which raises the nodes closer to the surface, can reduce communication costs and increase network lifetime.

Similarly, Basha et al. (2014) proposed a set of eight algorithms to select which nodes may surface. In this set of algorithms, there are both centralized algorithms and completely distributed ones. The idea is to select an effective communication strategy and design an efficient data routing protocol. To select the communication strategy (i.e., underwater communication or surface radio communication), the proposed algorithms consider the energy consumption of vertical movement and the energy costs relative to acoustic and radio frequency communication.

Coutinho et al. (2013a, 2013b, 2014a) proposed the use of depth adjustment for some nodes to improve underwater data routing. Coutinho et al. (2013a) proposed the CTC and DTC algorithms for topology control through depth adjustment of some nodes to reduce the fraction of isolated nodes (i.e., without a multipath to a sink) in sparse UWSN deployments.

Coutinho et al. (2013b) proposed the depth-controlled routing (DCR) geographic routing protocol, which uses depth adjustment–based topology control to handle void nodes. In addition, Coutinho et al. (2014a) proposed the GEDAR opportunistic routing protocol, which uses topology control based on depth adjustment of some nodes, for efficient data delivery in challenging mobile UWSNs. Despite significant differences in the proposed topology control algorithms and UWSN scenarios, the vertical movement design principle was able to cope with the shortcomings of the acoustic channel and geographic routing.

In the previous approaches, two critical issues may occur: first, high-energy consumption, and second, changes in the sensing coverage area. Energy cost is a shortcoming in some of the underwater node vertical movement technologies. In fact, in previous solutions, the network energy cost was excessive in highly sparse network deployments. A similar trend was found in the analyses performed in Coutinho et al. (2014b). This is because some nodes must be moved for long distances. Thus, this approach might shorten the lifetime of UWSN. Moreover, since some nodes are moved from their deployed depths, this approach may significantly change the initial coverage area. If there is no appropriate control of the nodes that will surface, the application might experience a lack of information of events happening in deep waters.

6.2.1 Critical Analysis and Open Issues. Even though the topology control approach is promising for UWSNs, some critical shortcomings need to be further investigated. As already mentioned, there is an energy cost associated with the vertical movement. Therefore, analytical models and deep investigations still need to be conducted to better characterize the scenarios in which depth adjustment–based topology control is more efficient.

Moreover, the depth adjustment of nodes should be performed in a controllable manner. The topology control algorithm must guarantee that the cascade effect, during the vertical movement, will not occur. The cascade effect may happen when the depth adjustment of a node is calculated relative to the depth of the neighboring nodes. It will occur when a node A, for instance, decides to move to a new depth, and a neighboring node B, based on the new location of the node A, determines that it should move as well. When both nodes reach the new depth, A will observe that B is in the proximity, and it might decide to move again. This procedure will then be repeated indefinitely.

In addition, we can observe from the literature review that less attention has been devoted to the problem of changing the sensing coverage. In this sense, the technology that enables vertical movement of the underwater nodes advances and reduces the energy cost for the movement; thus, topology control algorithms can be proposed for an in-rounds depth adjustment. Accordingly, underwater nodes might perform an initial overall adjustment to improve the sensing coverage area in terms of monitored depths. After that, whenever a set of nodes detects an event, surrounding or redundant nodes can adjust their depths to improve data delivery without compromising the sensing coverage. At the end of the event detection, they can return to their original locations.

7 FUTURE RESEARCH DIRECTIONS

Although a significant amount of research has been conducted on topology control in wireless ad hoc networks, sensor networks, and, more recently, in underwater sensor networks, there are several research directions that require additional exploration, particularly in UWSNs. Along with this survey, we identified and discussed several research directions related to the challenges of each proposed methodology to design topology control algorithms. Herein, we discuss some open research problems that warrant additional investigation, independently from the considered topology control methodologies.

7.1 Localized Topology Control

In wireless ad hoc and sensor networks, topology control is traditionally performed on the overall network topology, even when it is distributed and entails local information. An exception is when it is done for connectivity restoration after a node failure (Younis et al. 2014). Thus far, topology control in UWSN mimics this approach. However, the performance of a UWSN might be diminished by the overhead and energy cost to exchange information about nodes and topology.

In UWSNs, an example of an interesting strategy is a localized topology control. A localized topology control means that the topology organization occurs only in the critical parts of the networks. Due to the characteristics of the underwater acoustic channel, the transmission of control packets for topology discovery and information exchange might reduce the network performance. The overhead for the topology control will increase packet collisions and the needs for packet retransmissions. Conversely, a topology control could be performed exclusively in a few parts of the network. Thus, the high overhead and its undesired consequences, which could yet overcome the benefits of topology control, is reduced and confined to certain regions and nodes in need of an improved local topology organization.

In this direction, Coutinho et al. (2016d) proposed the PCen centrality metric to find high-demand nodes. The PCen metric identifies highly demanded nodes from the point of view of opportunistic routing (i.e., those nodes with a high likelihood of carried traffic load). The authors claimed that topology control closer to the high central nodes, identified by the PCen metric, can be done to improve data delivery and reduce energy consumption. In this sense, a smart and efficient sleep interval adjustment on critical nodes can be used to achieve energy balancing and to prolong the network lifetime. Moreover, the use of an AUV traveling around critical nodes to collect data can improve the performance of the application.

7.2 Hybrid and Adaptive Topology Control Algorithms

The underwater environment and acoustic channel are highly dynamic. Moreover, the underwater acoustic channel is characterized by its time-varying link quality. Therefore, hybrid and/or adaptive topology control algorithms might be more efficient for UWSNs, instead of the classical approach. In this direction, topology control algorithms must be able to react from changes in the link quality, noise intensity, and other factors of underwater environment and communication, to maintain the required QoS of the applications.

For instance, a proactive mobility assisted–based topology control can be performed to avoid communication void regions of geographic routing in UWSNs. Thus, the resulting UWSN topology will provide a high packet delivery rate, as data packets will no longer be discarded by void nodes. Moreover, the joint design of power control–based topology control can be reactively performed to handle the time variability of the acoustic links. Thus, each node will adjust its transmission power to guarantee that the proper next-hop node will receive the data packet.

The big challenge, therefore, will lie in efficiently collecting information to be used for hybrid and adaptive topology control. For a joint design of mobility assisted– and power control–based topology control, one might require information about the neighborhood, the quality of the acoustic link between the nodes, the residual energy of each neighbor to determine if it can be moved to a new depth, and the traffic load. The efficient collection of such heterogeneous information will be demanding due to the characteristics of the underwater acoustic channel.

7.3 Topology Control Underlying Other Techniques

Topology control algorithms can support other techniques used to improve the performance of a UWSN. More specifically, the topology of a UWSN can be controlled to lead to better performance of an algorithm or technique that is executing a critical task for the network application. In the following, we discuss how topology control would improve the performance of network coding and compressed sensing in UWSNs.

Network coding has been proposed to mitigate packet loss, reduce delay, and improve network throughput of loosely wireless network systems. Using network coding, selected *coding nodes* perform coding operations by means of a network coding function (e.g., linear randomized coding and XOR coding) to combine data received from distinct dataflows passing through them. At destination nodes, received packets are then decoded from the knowledge of the considered coding function and the messages used to create the given payload of the received packet. Moreover, lost data packets can be recovered at the receivers through the decoding of other combined packets, which overcome the traditional automatic repeat request (ARQ) error control.

Another technique that has been recently proposed to reduce the amount of carried-out traffic in underwater sensor networks is compressed sensing. Using this approach, each sensor node transmits its observation to a central node named the *fusion center*. Under certain conditions in the fusion center, a sparse signal can be recovered from a small number of random samples. This is possible because many types of information have a property called *sparseness* in transformation process (Li et al. 2013b). Since a small number of samples is enough to retrieve the information about the physical field, this technique reduces the number of collected and transmitted data, and is capable of tolerating some degree of packet loss.

In the preceding context, a proper topology control can increase network coding opportunities and the communication between ordinary underwater nodes and the fusion center node. Mobility-based topology control algorithms using AUVs or vertical displacement of some underwater nodes can control the topology toward better communication with the fusion center when compressed sensing is used, or create the classical butterfly topology, where network throughput is maximized when network coding is used. Moreover, a topology control algorithm can perform the right management of the sleep interval of the nodes to increase communication opportunities between source nodes and a central node acting as a coding node, or the fusion center nodes. In addition, power control–based topology control algorithms can select a suitable transmission power for coding nodes to improve the delivery probability of a coded packet.

7.4 Heterogeneous Technologies for Underwater Wireless Communication

To achieve a better performance and ensure the QoS, hybrid underwater communications have gained attention. Accordingly, underwater sensor nodes and vehicles are equipped with a few modems enabling underwater wireless communication using different technologies. For instance, Han et al. (2014) proposed the combination of acoustic and optical communication in AUVs, aimed to enable real-time video streaming from underwater wireless networks.

Further research of topology control in UWSNs should address the preceding scenario of heterogeneous technology for underwater wireless communication. The first research question that should be addressed is this: How should we consider the UWSN topology? In these scenarios, we might have several topologies given by the interconnection of the nodes by means of each underwater wireless communication technology, or an overall network topology given uniquely by the interconnection of the nodes, independent of the type of wireless link.

Therefore, topology control should be carried out considering the multiple characteristics that will arise from the joint use of heterogeneous underwater wireless communication technologies. For instance, long-range communication links, enabled from the acoustic channel, can be used for neighborhood discovery and information exchange. Thus, mobility assisted–topology control can be performed to achieve better alignment of the nodes to optimize data delivery through optical communication.

7.5 Heterogeneous Underwater Sensor Nodes

Recently, research efforts have been devoted to enabling the Internet of Underwater Things (IoUT) (Petrioli et al. 2014). The IoUT will be composed of smart connected underwater objects that will be used for a better monitoring and exploration of the vast unexplored water areas. The main characteristic of this envisioned scenario is the heterogeneity in terms of resources in smart underwater devices. In a single deployment, we might have low-cost and resource-constrained underwater sensor nodes, drifters, anchored underwater sensor nodes, smart submarines, and AUVs, for instance, for a better understanding of the deep ocean.

Herein, the challenge for topology control will be to determine efficient network topologies to improve networking services and applications, considering the different characteristics and capabilities that will arise from the use of heterogeneous underwater sensor nodes. For instance, AUVs can be used as key nodes for mobility assisted–based topology control, whereas anchored nodes can help the topology organization through their transmission power adjustment. Wireless interface management–based topology control should consider the heterogeneity, in terms of energy capacity, of the underwater nodes. In theory, it is preferable to keep AUVs asleep as much as possible to save energy, as they already have high energy cost to move. However, this topology control approach might disrupt the network connectivity when AUVs are considered for mobile data collection in anchored nodes.

7.6 SDN–Based Underwater Sensor Networks

Another recent research trend in UWSNs is the proposal of software-defined underwater sensor networks (Akyildiz et al. 2016; Demirors et al. 2015; Dol et al. 2017). SDN–based underwater sensor networks offer more flexibility and facilitate the simultaneous deployment of different underwater applications. Currently, SDN–based UWSNs have been proposed to support differentiated networking services for these simultaneous applications. In this context, topology control should be done in a way that will benefit all of these applications, or it should be adaptive in supporting the application demanding resources during a determined moment. In both situations, topology control will be challenging, due to the characteristics of the underwater environment, channel, high energy consumption for transmission, and highly dynamic network topologies of mobile UWSNs.

However, the critical challenge is when an SDN–based underwater sensor network supports conflicting applications. We might have some applications demanding high data delivery rate (e.g., oil spill monitoring) even though the network lifetime is shortened. Simultaneously, the SDN–based UWSN may prove networking features for periodic data collection from the oceans. This application might tolerate some packet loss if it can prolong the network lifetime. Moreover, the location of the nodes could be critical for the application (e.g., temperature recording at different depths). Therefore, the challenge is to determine how to perform topology control considering conflicting requirements of several applications in SDN–based UWSNs. In the preceding scenario, mobility assisted–based topology control through the depth adjustment of some nodes is impractical, given the requirements of the second application.

8 CONCLUSION

Topology control is fundamental for improving the performance of wireless ad hoc and sensor networks. In underwater sensor networks, it is also necessary to design efficient monitoring and exploration applications. In this network, topology control has been used to improve networking services and protocols to support distributed applications.

This article surveyed the research efforts related to topology control in underwater sensor networks. We classified the current approaches encountered in the literature according to the main methodology used to consciously make changes in the network topology. In doing so, we discussed the advantages, disadvantages, and challenges of each one, relating them to the challenges of the underwater environment and acoustic channel. Moreover, for each methodology, we pointed out some future research directions for tackling the current limitations. Finally, we discussed, in general terms, some open research problems that warrant additional investigation independently from the considered topology control methodologies.

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