OPPORTUNISTIC VOID AVOIDANCE ROUTING PROTOCOL FOR UNDERWATER SENSOR NETWORKS

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Abstract*— Opportunistic void avoidance routing (OVAR) protocol has been proposed for UWSNs. It is an any cast, geographic and opportunistic routing protocol. OVAR switches to the recovery mode procedure which is based on topology control through the depth adjustment of the void nodes, instead of the traditional approaches using control messages to discover and maintain routing paths along void regions. Increasing attention has recently been devoted to underwater sensor networks (UWSNs) because of their capabilities in the ocean monitoring and resource discovery. UWSNs are faced with different challenges, the most notable of which is perhaps how to efficiently deliver packets taking into account all of the constraints of the available acoustic communication channel. The opportunistic routing provides a reliable solution with the aid of intermediate nodes' collaboration to relay a packet toward the destination. In this paper, we propose a new routing protocol, called opportunistic void avoidance routing (OVAR), to address the void problem and also the energy-reliability trade-off in the forwarding set selection. OVAR takes advantage of distributed beaconing, constructs the adjacency graph at each hop and selects a forwarding set that holds the best trade-off between reliability and energy efficiency. The unique features of OVAR in selecting the candidate nodes in the vicinity of each other leads to the resolution of the hidden node problem. OVAR is also able to select the forwarding set in any direction from the sender, which increases its flexibility to bypass any kind of void area with the minimum deviation from the optimal path. The results of our extensive simulation study show that OVAR outperforms other protocols in terms of the packet delivery ratio, energy consumption, end-to-end delay, hop count and traversed distance.

Index Terms— Heterogeneous networks, LTE, next generation network, wireless mesh network, reinforcement learning, and routing protocol.

I. INTRODUCTION

Ocean bottom sensor nodes are deemed to enable applications for oceanographic data collection, pollution monitoring, offshore exploration and tactical surveillance applications. Multiple Unmanned or Autonomous Underwater Vehicles (UUVs, AUVs), equipped with underwater sensors, will also find application in exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. To make these applications viable, there is a need to enable underwater communications among underwater devices. Underwater sensor nodes and vehicles must possess self-configuration capabilities, i.e., they must be able to coordinate their operation by exchanging configuration, location and movement information, and to relay monitored data to an onshore station.

Wireless Underwater Acoustic Networking is the enabling technology for these applications. UnderWater Acoustic Sensor Networks (UW-ASN) consist of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area. To achieve this objective, sensors and vehicles self-organize in an autonomous network which can adapt to the characteristics of the ocean environment.

The above described features enable a broad range of applications for underwater acoustic sensor networks:

- **Ocean Sampling Networks**. Networks of sensors and AUVs, such as the Odyssey-class AUVs, can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment.
- **Pollution Monitoring** and other environmental monitoring (chemical, biological, etc.).
- **Distributed Tactical Surveillance**. AUVs and fixed underwater sensors can collaboratively monitor areas for *surveillance*, *reconnaissance*, *targeting* and *intrusion detection* systems.

Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate at long distances through conductive sea water only at extra low frequencies (30 – 300 *Hz*), which require large antennae and high transmission power. Optical waves do not suffer from such high attenuation but are affected by scattering. Thus, links in underwater networks are based on *acoustic wireless communications* [1].

The traditional approach for ocean-bottom or ocean column monitoring is to deploy underwater sensors that record data during the monitoring mission, and then recover the instruments [2]. This approach has the following disadvantages:

- Real time monitoring is not possible. This is critical especially in surveillance or in environmental monitoring applications such as seismic monitoring. The recorded data cannot be accessed until the instruments are re-covered, which may happen several months after the beginning of the monitoring mission.
- No interaction is possible between onshore control systems and the monitoring instruments. This impedes any adaptive tuning of the instruments, nor is it possible to reconfigure the system after particular events occur.
- If *failures* or *misconfigurations* occur, it may not be possible to detect them before the instruments are re-covered. This can easily lead to the complete failure of a monitoring mission.
- The amount of data that can be recorded during the monitoring mission by every sensor is limited by the capacity of the onboard storage devices (memories, hard disks, etc).

Therefore, there is a need to deploy underwater networks that will enable real time monitoring of selected ocean areas, remote configuration and interaction with onshore human operators. This can be obtained by connecting underwater instruments by means of wireless links based on acoustic communication.

Many researchers are currently engaged in developing networking solutions for terrestrial wireless ad hoc and sensor networks. Although there exist many recently developed network protocols for wireless sensor networks, the unique characteristics of the underwater acoustic communication channel, such as limited bandwidth capacity and variable delays, require for very efficient and reliable new data communication proto-cols. The main differences between terrestrial and underwater sensor networks can be itemized as follows:

- **Cost**. Underwater sensors are more expensive devices than terrestrial sensors.
- **Deployment**. The deployment is deemed to be more sparse in underwater networks.
- **Spatial Correlation**. While the readings from terrestrial sensors are often correlated, this is more unlikely to happen in underwater networks due to the higher distance among sensors.
- **Power**. Higher power is needed in underwater commu-nications due to higher distances and to more complex signal processing at the receivers.

Major challenges in the design of Underwater Acoustic Networks are:

- Battery power is limited and usually batteries can not be recharged, also because solar energy cannot be exploited;
- The available bandwidth is severely limited [3];
- Channel characteristics, including long and variable prop-agation delays, multi-path and fading problems;
- High bit error rates;
- Underwater sensors are prone to failures because of fouling, corrosion, etc.

In this survey, we discuss several fundamental key aspects of underwater acoustic communications. We discuss the communication architecture of underwater sensor networks as well as the factors that influence underwater network design. The ultimate objective of this paper is to encourage research efforts to lay down fundamental basis for the development of new advanced communication techniques for efficient underwater communication and networking for enhanced ocean monitor-ing and exploration applications.

The remainder of this paper is organized as follows. In Section II, we introduce the communication architecture of underwater acoustic networks. In Section III, we investigate the underwater acoustic communication channel and summarize the associated physical layer challenges for underwater networking. In Section IV we discuss the challenges associated to the design of a new protocol stack for underwater commu-nications, while in Section V we draw the main conclusions.

II. UNDERWATER ACOUSTIC SENSOR NETWORKS (UW-ASN) COMMUNICATION ARCHITECTURE

In this section, we describe the communication architecture of Underwater acoustic sensor networks. The reference architectures described in this section are used as a basis for discussion of the challenges associated with underwater acoustic sensor networks. The underwater sensor network topology is an open research issue in itself that needs further analytical and simulative investigation from the research community. In the remainder of this section, we discuss the following architectures:

- **Static two-dimensional UW-ASNs for ocean bottom monitoring**. These are constituted by sensor nodes that are anchored to the bottom of the ocean. Typical appli-cations may be environmental monitoring, or monitoring of underwater plates in tectonics [4].
- **Static three-dimensional UW-ASNs for ocean column monitoring**. These include networks of sensors whose depth can be controlled by means of techniques discussed in Section II-B, and may be used for surveillance appli-cations or monitoring of ocean phenomena (ocean bio-geo-chemical processes, water streams, pollution, etc).

A. Two-dimensional Underwater Sensor Networks

A reference architecture for two-dimensional underwater networks is shown in Fig. 1. A group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors. By means of wireless acoustic links, underwater sensor nodes are interconnected to one or more *underwater sinks* (uw-sinks), which are network devices in charge of relaying data from the ocean bottom network to a surface station. To achieve this ob-jective, uw-sinks are equipped with two acoustic transceivers, namely a *vertical* and a *horizontal* transceiver. The horizontal transceiver is used by the uw-sink to communicate with the sensor nodes in order to: i) send commands and configuration data to the sensors (uw-sink to sensors); ii) collect monitored data (sensors to uw-sink). The vertical link is used by the uw-sinks to relay data to a *surface station*. Vertical transceivers must be long range transceivers for deep water applications as the ocean can be as deep as 10 km. The surface station is equipped with an acoustic transceiver that is able to handle multiple parallel communications with the deployed uw-sinks. It is also endowed with a long range RF and/or satellite transmitter to communicate with the *onshore sink* (os-sink) or to a *surface sink* (s-sink).

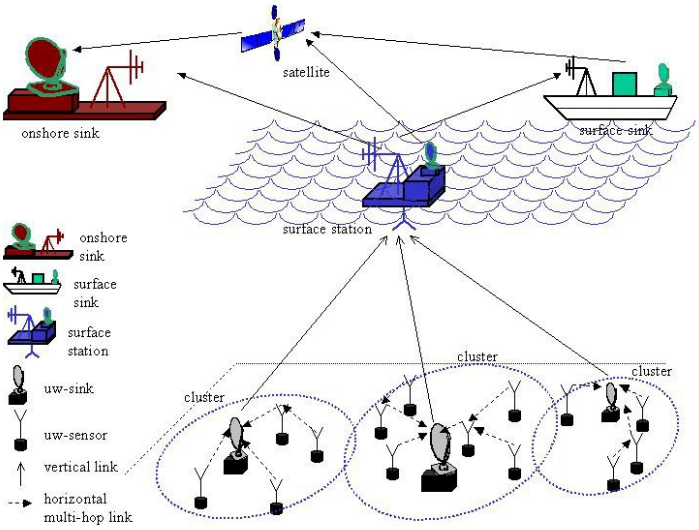

Fig. 1. Architecture for 2D Underwater Sensor Networks.

Sensors can be connected to uw-sinks via direct links or through multi-hop paths. In the former case, each sensor directly sends the gathered data to the selected uw-sink. This is the simplest way to network sensors, but it may not be the most energy efficient, since the sink may be far from the node and the power necessary to transmit may decay with powers greater than two of the distance. Furthermore, direct links are very likely to reduce the network throughput because of increased acoustic interference due to high transmission power. In case of multi-hop paths, as in terrestrial sensor networks [5], the data produced by a source sensor is relayed by intermediate sensors until it reaches the uw-sink. This results in energy savings and increased network capacity but increases the complexity of the routing functionality as well. In fact, every network device usually takes part in a collaborative process whose objective is to diffuse topology information such that efficient and loop free routing decisions can be made at each intermediate node. This process involves signaling and computation. Since, as discussed above, energy and capacity are precious resources in underwater environments, in UW-ASNs the objective is to deliver event features by exploiting multi-hop paths and minimizing the signaling overhead nec-essary to construct underwater paths at the same time.

B. Three-dimensional Underwater Sensor Networks

Three dimensional underwater networks are used to detect and observe phenomena that can not be adequately observed by means of ocean bottom sensor nodes, i.e., to perform cooperative sampling of the 3D ocean environment. In three-dimensional underwater networks, sensor nodes float at different depths in order to observe a given phenomenon. One possible solution would be to attach each uw-sensor node to a surface buoy, by means of wires whose length can be regulated so as to adjust the depth of each sensor node. However, although this solution allows easy and quick deployment of the sensor network, multiple floating buoys may obstruct ships navigating on the surface, or they can be easily detected and deactivated by enemies in military settings.

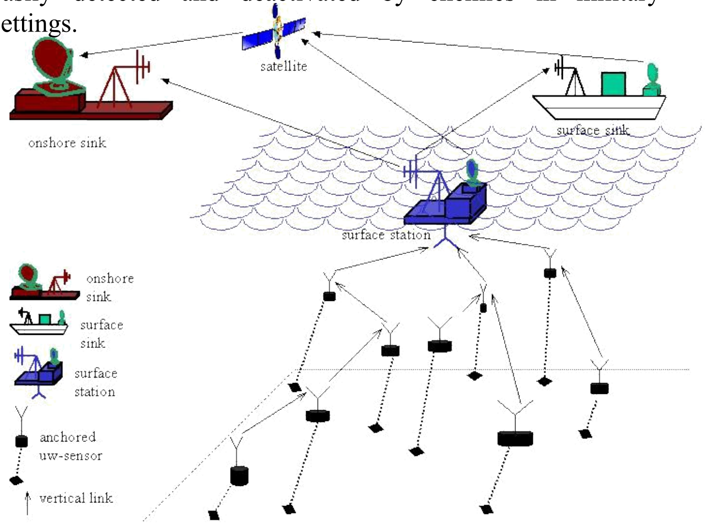

Fig. 2. Architecture for 3D Underwater Sensor Networks.

TABLE I

AVAILABLE BANDWIDTH FOR DIFFERENT RANGES IN UW-A CHANNELS

	Range [km]	Bandwidth [kHz]
Very Long	1000	< 1
Long	10 ¡ 100	2 ¡ 5
Medium	1 ¡ 10	¼ 10
Short	0:1 ¡ 1	20 ¡ 50

Very Short	< 0:1	> 100

For these reasons, a different approach can be to anchor sensor devices to the bottom of the ocean. In this architecture, depicted in Fig. 2, each sensor is anchored to the ocean bottom and equipped with a floating buoy that can be inflated by a pump. The buoy pushes the sensor towards the ocean surface. The depth of the sensor can then be regulated by adjusting the length of the wire that connects the sensor to the anchor, by means of an electronically controlled engine that resides on the sensor.

Many challenges arise with such an architecture, that need to be solved in order to enable 3D monitoring, including:

- **Sensing coverage**. Sensors should collaboratively regulate their depth in order to achieve full column coverage, according to their *sensing ranges*. Hence, it must be possible to obtain sampling of the desired phenomenon at all depths.
- **Communication coverage**. Since in 3D underwater networks there is no notion of uw-sink, sensors should be able to relay information to the surface station via multi-hop paths. Thus, network devices should coordinate their depths such a way that the network topology is always connected, i.e., at least one path from every sensor to the surface station always exists.

III. BASICS OF ACOUSTIC COMMUNICATIONS

Underwater acoustic communications are mainly influenced by *path loss*, *noise*, *multi-path*, *Doppler spread*, and *high and variable propagation delay*. All these factors determine the *temporal and spatial variability* of the acoustic channel, and make the available bandwidth of the *UnderWater Acoustic (UW-A) channel* limited and dramatically dependent on both range and frequency. Long-range systems that operate over several tens of kilometers may have a bandwidth of only a few kHz, while a short-range system operating over several tens of meters may have more than a hundred kHz bandwidth. In both cases these factors lead to low bit rates [6]. Moreover, the communication range is dramatically reduced as compared to the terrestrial radio channel.

Underwater acoustic communication links can be classified according to their range as *very long*, *long*, *medium*, *short*, and *very short* links [1]. Table I shows typical bandwidths of the underwater channel for different ranges. Acoustic links are also roughly classified as *vertical* and *horizontal*, according to the direction of the sound ray. As shown after, their propagation characteristics differ consistently, especially with respect to time dispersion, multi-path spreads, and delay variance. In the following, as usually done in oceanic literature, *shallow water* refers to water with depth lower than 100*m*, while *deep water* is used for deeper oceans.

In the following we analyze the factors that influence acoustic communications in order to state the challenges posed by the underwater channels for underwater sensor networking. These include:

Path loss:

- *Attenuation.* Is mainly provoked by absorption due to conversion of acoustic energy into heat, which increases with distance and frequency. It is also caused by scattering and reverberation (on rough ocean surface and bottom), refraction, and dispersion (due to the displacement of the reflection point caused by wind on the surface). Water depth plays a key role in determining the attenuation.
- *Geometric Spreading*. This refers to the spreading of sound energy as a result of the expansion of the wavefronts. It increases with the propagation distance and is independent of frequency. There are two common kinds of geometric spreading: *spherical* (omni-directional point source), and *cylindrical* (horizontal radiation only).

Noise:

- *Man made noise.* This is mainly caused by machinery noise (pumps, reduction gears, power plants, etc.), and shipping activity (hull fouling, animal life on hull, cavitation).
- *Ambient Noise.* Is related to hydrodynamics (movement of water including tides, currents, storms, wind, rain, etc.), seismic and biological phenomena.

Multi-path:

- Multi-path propagation may be responsible for severe degradation of the acoustic communication signal, since it generates Inter-Symbol Interference (ISI).
- The multi-path geometry depends on the link configuration. Vertical channels are characterized by little time dispersion, whereas horizontal channels may have extremely long multi-path spreads, whose value depend on the water depth.

High delay and delay variance:

- The propagation speed in the UW-A channel is five orders of magnitude lower than in the radio channel. This large propagation delay (0.67 *s=km*) can reduce the throughput of the system considerably.
- The very high delay variance is even more harmful for efficient protocol design, as it prevents from accurately estimating the round trip time (RTT), key measure for many common communication protocols.

Doppler spread:

- The Doppler frequency spread can be significant in UW-A channels [1], causing a degradation in the performance of digital communications: transmissions at a high data rate cause many adjacent symbols to interfere at the receiver, requiring sophisticated signal processing to deal with the generated ISI.

Most of the described factors are caused by the chemical-physical properties of the water medium such as temperature, salinity and density, and by their spatio-temporal variations. These variations, together with the wave guide nature of the channel, cause the acoustic channel to be *temporally and spatially variable*. In particular, the horizontal channel is by far more rapidly varying than the vertical channel, in both deep and shallow water.

IV. A PROTOCOL STACK FOR UNDERWATER ACOUSTIC COMMUNICATIONS

In this section, we briefly discuss the design of a new protocol stack for underwater acoustic communications. In Sections IV-A, IV-B, IV-C and IV-D we discuss physical, data link, network and transport layer issues in underwater sensor networks, respectively.

A. Physical Layer

Until the beginning of the last decade underwater modem development was based on non-coherent frequency shift keying (FSK) modulations, since these techniques do not require phase tracking, which is a very difficult task in underwater.

Although non-coherent modulation schemes are characterized by a high *power efficiency* , their low *bandwidth efficiency* makes them unsuitable for high data-rate multiuser networks. Hence, coherent modulation techniques have been developed for long-range, high-throughput systems. In the last years, fully coherent modulation techniques, such as phase shift keying (PSK) and quadrature amplitude modulation (QAM), have become practical due to the availability of powerful digital processing [2].

In horizontal underwater channels, especially in shallow water, the time-variability of the channel is the primary limitation to the performance of conventional receivers. Multi-path phenomena create two problems. The first one is the delay spread, which causes ISI at the receiver side. The other one is the phase shift of the signal envelope. Thus, high speed phase coherent communications are difficult because of the combined effect of the time varying multi-path and of the Doppler spread [7].

B. Data Link Layer

Multiple access techniques are developed to allow devices to access a common medium, sharing the scarce available band-width in an efficient and fair way. Channel Access Control in UW-ASN poses additional challenges due to the peculiarities of the underwater channel, in particular limited bandwidth and high and variable delay.

Multiple access techniques can be roughly divided into two main categories [8]: i) *contention free*, such as FDMA, TDMA, and CDMA and ii) *non-contention free*, which are either based on *random* access (ALOHA, slotted-ALOHA), on *carrier sense* access (CSMA), or on *collision avoidance with handshaking* access (MACA, MACAW). In the following we discuss the suitability of each of these techniques for underwater networks.

Frequency division multiple access (FDMA) divides the available band into sub-bands, and assigns each sub-band to a device. Due to the narrow bandwidth in UW-A channels and to the vulnerability of limited band systems to fading, FDMA is not suitable for UW-ASN [2].

Time division multiple access (TDMA) divides time into slots, providing time guards to limit packet collisions from adjacent time slots. These time guards are designed to be proportional to the propagation delay of the channel. Due to the characteristics of the underwater environment it is very challenging to realize a precise synchronization, with a common timing reference, which is required for a proper utilization of time slots in TDMA. Moreover, due to the high delay and delay variance of the UW-A channel, TDMA efficiency is limited because of the high time guards required to implement it.

Code division multiple access (CDMA) allows multiple devices to transmit simultaneously over the entire frequency band. Signals from different devices are distinguished by means of pseudo-noise codes that are used for spreading the user signal over the entire available band. This makes the signal resistant to frequency selective fading caused by multi-paths. In conclusion, although the high delay spread which characterizes the horizontal link in underwater channels makes it difficult to maintain synchronization among the stations, especially when orthogonal code techniques are used [9], CDMA is a promising multiple access technique for underwater acoustic networks.

ALOHA is a class of MAC protocols that do not try to prevent packet collision, but detect collision and retransmit lost packets. In the UW-A environment, as in the case of TDMA, ALOHA protocols are affected by low efficiency, mainly due to the slow propagation of the acoustic channel. Moreover, the need for retransmissions increases the power consumption of sensors, and ultimately reduces the network lifetime.

Carrier sense multiple access (CSMA) protocols are aimed at reducing the packet retransmissions, by monitoring the channel state: if the channel is sensed busy, packet transmission is inhibited so as to prevent collisions with the ongoing transmission. If the channel is sensed free, transmission is enabled. However this approach, although it prevents collisions at the sender, does not avoid collisions at the receiver due to the *hidden and exposed terminal problems* [8].

Contention based techniques that use handshaking mechanisms, such as RTS/CTS in shared medium access (e.g., MACA, IEEE 802.11) are impractical in underwater, due to the following reasons: i) Large delays in the propagation of RTS/CTS control packets lead to low throughput; ii) The high propagation delay of underwater channels impairs the carrier sense mechanism; iii) The high variability of delay in handshaking packets makes it impractical to predict the start and finish time of the transmissions of other stations. Thus, collisions are highly likely to occur.

Many novel access schemes have been designed for terrestrial sensor networks, whose objectives are to maximize the network efficiency and prevent collisions in the access channel. These similarities would suggest to tune and apply those schemes in the underwater environment; on the other hand, the main focus in medium access control in WSN is on energy-latency tradeoffs. S-MAC [10], for example, aims at decreasing the energy consumption by using sleep schedules with virtual clustering. Anyway, although this non-contention free access scheme is provided with an effective collision avoidance mechanism, it may not be suitable for an environment where dense sensor deployment cannot be assumed, as discussed in Section II.

C. Network Layer

The *network layer* is in charge of determining how messages are routed within the network. In UW-ASNs, this translates into determining which path should data packets follow from the source that samples the physical phenomenon to the onshore sink.

In the last few years there has been an intensive study in routing protocols for ad hoc wireless networks [11]. However, due to the different nature of the underwater environment and applications, there are several drawbacks with respect to the suitability of the existing solutions for Underwater Acoustic Networks. The existing routing protocols are usually divided into three categories, namely *proactive*, *reactive* and *geographical* routing protocols [11]:

- **Proactive protocols**(e.g., AODV, DSR). These proto-cols attempt to minimize the message latency induced by route discovery, by maintaining up-to-date routing information at all times from each node to every other node. This is obtained by broadcasting control packets that contain routing table information (e.g., distance vectors). These protocols provoke a large signaling overhead to establish routes for the first time and each time the network topology is modified because of mobility or node failures, since updated topology information has to be propagated to all the nodes in the network. This way, each node is able to establish a path to any other node in the network, which may not be needed in UW-ASNs. For this reason, proactive protocols are not suitable for underwater networks.
- **Reactive protocols**(e.g. GPSR, PTKF). A node initiates a route discovery process only when a route to a destination is required. Once a route has been established, it is maintained by a route maintenance procedure until it is no longer desired. These protocols are more suitable for dynamic environments but incur a higher latency and still require source-initiated flooding of control packets to establish paths. Thus, both proactive and reactive protocols incur excessive signaling overhead due to their extensive reliance on flooding. Reactive protocols are deemed to be unsuitable for UW-ASNs as they also cause a higher latency which may even be amplified by the slow propagation of acoustic signals in the underwater channel. Moreover the topology of UW-ASNs is unlikely to vary dynamically on a short time scale.
- **OOVAR algorithm(**e.g. VBF,APR). The aim of the OVAR algorithm is to move void nodes to new depths to resume the Geographic routing whenever it is possible. The depth adjustment is based on the neighbour nodes closet to the sonoboys location in order to organize the network topology and improve the routing task. The current forwarder node forward the packet to neighbour node closet to the sink based upon the energy based routing.

D. Transport Layer

In this section we briefly discuss the existing reliable data transport solutions for Wireless Sensor Networks, along with their shortcomings in the underwater environment, and the fundamental challenges for the development of an efficient *reliable transport layer* protocol for UW-ASNs.

In sensor networks reliable event detection at the sink should be based on collective information provided by source nodes and not on any individual report from each single source. Hence, conventional end-to-end reliability definitions and solutions can be inapplicable in the underwater sensor field, and could lead to waste of scarce sensor resources. On the other hand, the absence of a reliable transport mechanism altogether can seriously impair event detection due to underwater challenges. Thus, the UW-ASN paradigm necessitates a new *event transport reliability* notion rather than the traditional end-to-end approaches.

A transport layer protocol is needed in UW-ASNs not only to achieve *reliable collective transport* of event features, but also to perform *flow control* and *congestion control*. The primary objective is to save scarce sensor resources and increase network efficiency. A reliable transport protocol should guarantee that the applications are able to correctly identify event features estimated by the sensor network. Congestion control is needed to prevent the network from being congested by excessive data with respect to the network capacity, while flow control is needed to avoid that network devices with limited memory are overwhelmed with data transmissions.

Several solutions have been proposed to address the trans-port layer problems in Wireless Sensor Networks (WSN). For example, in [13], *Event-to-Sink Reliable Transport* (ESRT) protocol is proposed to achieve reliable event detection with minimum energy expenditure. However, the ESRT mechanism relies on spatial correlation among event flows which may not be easily leveraged in underwater acoustic sensor networks. Hence, further investigation is needed to develop efficient transport layer solutions.

V. CONCLUSIONS

In this paper, we overviewed the main challenges for efficient communications in underwater acoustic sensor networks. We outlined the peculiarities of the underwater channel with particular reference to networking solutions for monitoring applications of the ocean environment. The ultimate objective of this paper is to encourage research efforts to lay down fundamental basis for the development of new advanced communication techniques for efficient underwater communication and networking for enhanced ocean monitoring and exploration applications.

REFERENCES

[1] M. Stojanovic, “Acoustic (underwater) communications,” in *Encyclope-dia of Telecommunications*, J. G. Proakis, Ed. John Wiley and Sons, 2003.

[2] J. Proakis, J. Rice, E. Sozer, and M. Stojanovic, “Shallow water acoustic networks,” in *Encyclopedia of Telecommunications*, J. G. Proakis, Ed. John Wiley and Sons, 2003.

[3] J. G. Proakis, E. M. Sozer, J. A. Rice, and M. Stojanovic, “Shallow water acoustic networks,” *IEEE Communications Magazine*, pp. 114– 119, Nov. 2001.

[4] L. Freitag and M. Stojanovic, “Acoustic communications for regional undersea observatories,” in *Proceedings of Oceanology International*, London, U.K., mar 2002.

[5] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: A survey,” *Computer Networks (Elsevier) Journal*, vol. 38, no. 4, pp. 393–422, Mar. 2002.

[6] J. Catipovic, “Performance limitations in underwater acoustic telemetry,”
IEEE Journal of Oceanic Engineering, vol. 15, pp. 205–216, July 1990.

[7] M. Stojanovic, J. Catipovic, and J. Proakis, “Phase coherent digital communications for underwater acoustic channels,” *IEEE Journal of Oceanic Engineering*, vol. 19, no. 1, pp. 100–111, Jan. 1994.

[8] R. Jurdak, C. V. Lopes, and P. Baldi, “A survey, classification and comparative analysis of medium access control protocols for ad hoc networks,” *IEEE Communications Surveys & Tutorials*, vol. 6, no. 1, First Quarter 2004.

[9] D. N. Kalofonos, M. Stojanovic, and J. G. Proakis, “Performance of adaptive MC-CDMA detectors in rapidly fading rayleigh channels,”
IEEE Transactions on Wireless Communications, vol. 2, no. 2, pp. 229– 239, Mar. 2003.

[10] W. Ye, J. Heidemann, and D. Estrin, “An energy-efficient MAC protocol for wireless sensor networks,” in *Proceedings of IEEE INFOCOM 2002*, vol. 3, New York, NY, USA, June, pp. 1567–1576.

[11] M. Abolhasan, T. Wysocki, and E. Dutkiewicz, “A review of routing protocols for mobile ad hoc networks,” *Ad Hoc Networks*, vol. 2, pp. 1–22, Jan. 2004.

[12] T. Melodia, D. Pompili, and I. F. Akyildiz, “Optimal local topology knowledge for energy efficient geographical routing in sensor networks,” in *Proceedings of IEEE INFOCOM 2004*, Hong Kong S.A.R., PRC, March 2004.

[13] Y. Sankarasubramaniam, O. B. Akan, and I. F. Akyildiz, “ESRT: event-to-sink reliable transport for wireless sensor networks,” in *Proceedings of ACM MOBIHOC 2003*, Annapolis, MD, USA, June, pp. 177–188.