

Collision Tolerant and Collision Free Packet Scheduling for Underwater Acoustic Network Localization

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ABSTRACT: Medium access control (MAC) determines how sensor nodes share the channel for packet exchanging. To obtain the maximum network efficiency for accomplishing a specific task, the network has to adapt its parameters accordingly. In other words, different MAC protocols are required for different tasks. Localization is a crucial task of an underwater acoustic sensor network (UASN) which requires multiple packet exchanges. This article concerns the problem of designing a MAC protocol for a UASN which efficiently schedules the localization packets of the anchors. Knowing the relative positions of the anchors and their maximum transmission range, the scheduling protocol takes advantage of the long propagation delay of underwater communications to minimize the duration of the localization task. First, we formulate the concept of collision-free packet transmission for localization, and we show how the optimum solution can be obtained. Furthermore, we model the problem as a mixed integer linear program both in single-channel and multi-channel scenarios.

KEYWORDS: "Collision Tolerant and Collision Free PacketScheduling"

I. INTRODUCTION

Underwater acoustic communication

Underwater acoustic communication is a technique of sending and receiving messages below water. There are several ways of employing such communication but the most common is by using hydrophones. Underwater communication is difficult due to factors such as multi-path propagation, time variations of the channel, small available bandwidth and strong signal attenuation, especially over long ranges. Compared to terrestrial communication, underwater communication has low data rates because it uses acoustic waves instead of electromagnetic waves. At the beginning of the 20th century, some ships communicated by underwater bells, the system being competitive with the primitive Maritime radio navigation service of the time. The later Fessenden oscillator allowed communication with submarines.

The past three decades have seen a growing interest in underwater acoustic communications because of its applications in marine research, oceanography, marine commercial operations, the offshore oil industry and defence. Continued research over the years has resulted in improved performance and robustness as compared to the initial communication systems. A series of review papers provides an excellent history of the development of the field until the end of the last decade (Baggeroer, 1984; Catipovic, 1990; Stojanovic, 1996; Kilfoyle and Baggeroer, 2000). In this paper, we aim to provide an overview of the key developments in the field since the beginning of this decade. We also hope to provide an insight into some of the open problems and challenges facing researchers in this field in the near future. High-speed communication in the underwater acoustic channel has been challenging because of limited bandwidth, extended multipath, refractive properties of the medium, severe fading, rapid time variation and large Doppler shifts. In the initial years, rapid progress was made in deep water communication, but the shallow water

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channel was considered difficult. In the past decade, significant advances have been made in shallow water communication.

In contrast, acoustic waves enable communications over long-range links, because they suffer from relatively low absorption. Thus, this is the preferred technology to develop reliable UWSNs and is the main focus of this paper. The characteristics of the acoustic underwater channel and the difficulties in underwater communication are discussed. The differences between acoustic and radio-based communication open a new research field in UWSNs.

Underwater Acoustic Sensor Networks

Underwater Acoustic Sensor Networks consists of a number of sensor nodes, stationary or mobile, connected wirelessly via acoustic communication modules deployed to monitor various events of interest collaboratively. The objective is achieved by having a set of autonomous devices in a network which can self-organize and adapt to deep-sea conditions. Underwater communication is mainly done using low frequency and low data rate acoustic modems with a set of nodes transmitting their data to a buoyant gateway that relays the data to nearest coastal monitoring and control station. While UASN is a promising new field and may help in exploring what's hidden in the amazingly unfathomed world that lies underwater, there are a few challenges as well. For setting up underwater applications, not all the techniques and algorithms for UASNs can derive from the already seasoned land based WSNs as some of the phenomena are primarily different. Radio frequency (RF) communications was never a choice for underwater communication due to the swift decrease in the transmission range and hence lower data rates of the RF modules as we go deep down the ocean. Acoustic communication has been the technology of choice for decades when it comes to transmitting signals underwater, but with their hefty price tags and heavy power usage, underwater acoustic modems are not at all feasible for UASNs with applications as it'sy-bitsy as measuring the amount of pollution from a fishing farm at the sea bed.

Some of the traditional work about the underwater

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.

No real-time monitoring. The recorded data cannot be accessed until the instruments are recovered, which may happen several months after the beginning of the monitoring mission. This is critical especially in surveillance or in environmental monitoring applications such as seismic monitoring.

No on-line system reconfiguration. Interaction between onshore control systems and the monitoring instruments is not possible. This does not impede any adaptive tuning of the instruments, nor is it possible to reconfigure the system after particular events occur.

No failure detection. If failures or misconfigurations occur, it may not be possible to detect them before the instruments are recovered. This can easily lead to the complete failure of a monitoring mission.

Limited storage capacity, the amount of data that can be recorded during the Monitoring mission by every sensor is limited by the capacity of the on board storage devices (memories, hard disks).

Recent technologies for under water communications

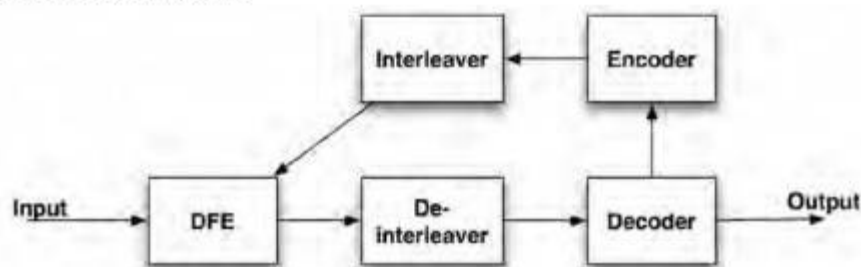
The shallow water acoustic communication channel exhibits a long delay spread because of numerous multipath arrivals resulting from surface and bottom interactions. Movement of transducers, ocean surface, and internal waves lead to rapid time variation and, consequently, a high Doppler spread in the channel. Coherent modulation schemes such as phase shift keying (PSK) along with adaptive decision feedback equalizers (DFE) and spatial diversity combining have been shown to be an effective way of communication in such channels (Stojanovic et al., 1993). However, the long delay spread (often hundreds of symbols) and rapid time variation of the channel often makes this approach computationally too complex for real-time implementations.

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Basic structure of a turbo DFE



Although the underwater channel has a long impulse response, the multipath arrivals are often discrete. This opens up the possibility of using a sparse equalizer with tap placement based on the actual channel response. This can potentially dramatically reduce the number of required taps and hence lead to a lower complexity, faster channel tracking and an enhanced performance. In Stojanovic et al. (1999), the authors proposed an algorithm to track the channel explicitly and determine the tap placement for the DFE based on this channel estimate. The equalizer and the channel estimator are separately updated throughout the packet. The channel estimator can update either the whole estimate or a set of selected channel coefficients at one time, depending on computational and channel considerations. The algorithm uses spatial diversity by multi-channel combining before equalization. Another algorithm for robust automated DFE tap placement in sparse channels is presented in Lopez and Singer (2001). The algorithm alternates between tap placement for the feedforward and feedback filters in the DFE. A stopping criterion is defined in terms of the estimated mean square error (MSE) rather than a fixed number of taps.

As increased model order leads to increased estimation noise, a model order penalty is imposed in the optimization. When used with multiple receivers for exploiting spatial diversity, the algorithm uses the same number of taps in each receiver. An empirically tuned version of the algorithm was successfully demonstrated in an experiment using a 4-hydrophone receiver array. The algorithm placed an average of 10 feed forward taps and 25 feedback taps; this is a significantly smaller number than the number of taps required in a conventional DFE for shallow water communication. In Weichang and Preisig (2007), the authors develop a sparse channel estimation technique based on the delay-Doppler-spread function representation of the channel. As this representation is an approximation of a rapidly time-varying channel, it captures the channel structure and its dynamics simultaneously. In the paper, the authors compare the performance of recursive least square (RLS) estimation, sparse channel impulse response estimation and the proposed method. Sparse partial response equalizers (sPRE) exploit the sparse nature of the underwater channel to shorten the impulse response of the channel. When combined with a low-complexity belief propagation (BP) detector, the residual inter-symbol interference (ISI) from the sPRE can be used for multipath diversity. Data collected during an experiment in Kauai was used to demonstrate a communication scheme based on a sPRE with a BP detector (Roy et al., 2006).

Conventional equalization techniques require a training period during which the equalizer converges. However, blind equalization techniques use only the statistical properties of the signal and do not require an explicit training sequence. They typically converge slower than training based methods and therefore their use has been limited to long or continuous data streams. In Labat et al. (2003), the authors show that a blind DFE, when combined with an appropriate iterative procedure, provides good performance on short data bursts. DFE structures suffer from error propagation due to the feedback of erroneous decisions in the loop. Hence powerful forward error correction (FEC) codes are needed to ensure low bit error rate (BER) communication. Turbo codes are a class of powerful codes that utilize iterative information exchange between two decoders to correct errors. Inspired by this idea, researchers have developed turbo equalization techniques where iterative interactions between the equalizer and a decoder result in joint estimation, equalization and decoding (Sozer et al., 2001). The data to be transmitted is encoded, interleaved and transmitted. The receiver treats the combination of the encoder, interleaver and channel as a serial concatenated code. A maximum a posteriori probability (MAP) equalizer is used along with a decoder as the two components of the turbo

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decoder. The turbo decoder's output is used in the feedback loop of the DFE to reduce errors. Although MAP equalization is computationally intensive, per-survivor processing (PSP) helps reduce the number of trellis states used in channel equalization. Experimental testing at 1 km range in very shallow waters with a vertical 8-hydrophone receiver array showed that the algorithm performed significantly better than DFE. The algorithm however had some difficulty with sparse channels; future work combining sparse equalization techniques with turbo equalization may help address this difficulty.

The error estimate can be split into the minimum achievable error and the excess error. The excess error component is strongly affected by rough sea conditions. Through a scattering function analysis, it was also shown that the rate of change of propagation path length for the surface bounced arrival is a primary contributor to the error. This suggests that the ability to effectively track the surface bounced arrival may provide an improved equalizer performance.

Phase Conjugation

Due to the symmetry of the linear wave equation, if the sound transmitted from one location is received at other locations, reversed and retransmitted; it focuses back at the original source location. This is the principle behind time reversal mirrors (TRM) or its frequency domain equivalent—active phase conjugation. The temporal compression effect of TRM reduces the delay spread of the channel while the spatial focusing effect improves signal-to-noise ratio (SNR) and reduces fading. An experiment conducted in 1999 demonstrated such a TRM communication system in shallow waters (Edelmann et al., 2002). The larger the number of transmitters, the better the TRM focus. Thus, TRM based communication systems effectively utilize spatial diversity at the transmitter rather than the receiver. In fact, the spatial focusing precludes the use of multiple receivers for spatial diversity, but opens up the possibility of spatial multiplexing and low probability of intercept (LPI) communications. Although TRM helps reduce delay spread of the channel, it does not eliminate ISI completely. The system was successfully demonstrated at ranges up to 5 km using a single transmitter and a 14-hydrophone receiver-array. More recently, Gomes et al. (2006) presents results from an experiment off the west coast of Portugal where the authors compare the performance of several methods including equalization, PPC and combinations of both methods. In Song et al. (2006), the authors study the benefits of spatial diversity in PPC communications. They also show that adaptive equalization can be effectively combined with PPC to estimate and eliminate residual ISI. In the experimental results presented, gains of up to 5 dB were obtained through equalization in the case of a fixed transmitter/receiver. When the transmitter was moving, the channel varied more rapidly and the gain from equalization increased to 13 dB. In another experiment, it was found that continuous channel updates and Doppler tracking are required before time reversal in order to achieve acceptable performance in the presence of ocean variability (Song et al., 2008). This ocean variability was shown to be primarily a result of interaction of the acoustic field with the dynamic ocean surface. The computational simplicity of phase conjugation-based communication systems makes them extremely attractive. However, the use of such systems is constrained by the quasi-static channel requirement that is fundamental to the idea. The quasi-static constraint may be somewhat relaxed in cases where an adaptive equalizer is used in conjunction with a phase conjugation scheme. Rapidly changing channels resulting from moving communication nodes may limit the use of phase conjugation in mobile applications.

Channel Modelling

A good understanding of the communications channel is important in the design and simulation of a communication system. A good review of channel modelling work prior to the year 2000 has been presented in Bjerrum-Niese and Lutzen (2000). At high frequencies appropriate for shallow water communications, ray theory provides the framework for determining the coarse multipath structure of the channel. However, such a model does not encapsulate the time-varying nature of the channel. By augmenting this model with a time-varying surface model, a shallow water channel can be simulated (Bjerrum-Niese et al., 1996). As acknowledged by the authors, the primary limitation of such a channel model is the availability of an accurate and calibrated surface time-variation model. Moreover the time-variation in the channel is not limited to surface reflected arrivals. If the received signal is a sum of a large number of multipath arrivals, each of which are modeled as a complex Gaussian stochastic processes, the resulting model is the well-known Rayleigh fading channel. Some researchers model the shallow water channel as a Rayleigh fading channel but others challenge that assumption, especially when discrete arrivals can clearly be seen in

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the channel response. There has been no consensus among researchers on the model applicable in shallow waters. Recently, a ray theory-based multipath model, where the individual multipath arrivals are modeled as Rayleigh stochastic processes, has been shown to describe the medium range very shallow water channel accurately (Chitre, 2007). The physics resulting in the time-variation of each arrival is not fully understood, but it may result from micro-multipath or internal waves. Theoretical and experimental studies of acoustic propagation through anisotropic shallow water environments in the presence of internal waves (Badiy et al., 2007) may form the basis of further physics-based channel modeling research in the future. Channel modelling in the surf zone is especially difficult because of the large impact of the rapidly time-varying surface on the acoustics. The scattering of acoustic signals off shoaling surface gravity waves results in a time-varying channel impulse response and occasional caustics characterized by intense, rapidly fluctuating arrivals (Preisig and Deane, 2004). Through a combination of experimental measurements and propagation modeling, the authors showed that the high intensity arrivals were often due to focusing by surface gravity waves and caustic formation. Hence most channel impulse response algorithms have difficulty coping with surf zones. Further work in this area is needed to help improve performance of communication systems in surf zones.

Multi-carrier Modulation

Multi-carrier modulation is an attractive alternative to a broadband single-carrier communication system. By dividing the available bandwidth into a number of narrower bands, orthogonal frequency division multiplexing (OFDM) systems can perform equalization in frequency domain, thus eliminating the need for complex time-domain equalizers. OFDM modulation and de-modulation can easily be implemented using fast Fourier transforms (FFT). In shallow waters in the Mediterranean sea, an experiment was conducted to compare the performance of OFDM with direct sequence spread spectrum (DSSS), both using differential PSK modulation (Frassati et al., 2005). The authors reported good OFDM performance ($BER < 2 \times 10^{-3}$) at ranges up to 6 km. At the same ranges, the DSSS performance was found to be significantly poorer. OFDM equalization is simplified greatly if a guard interval longer than the delay spread is allowed between consecutive OFDM symbols. This guard period is usually implemented as a cyclic prefix to maintain orthogonality of the sub-carriers. However, when the delay spread is long, the prefix length can become undesirably long and affect the efficiency of transmission significantly. In Morozov and Preisig (2006), the authors explore the use of maximum likelihood sequence detection (MLSD) on individual sub-carriers when the symbol period is smaller than the delay spread. An algorithm to perform joint channel estimation and MLSD using a low complexity PSP was proposed and experimentally demonstrated in the paper. Channel shortening techniques such as sPRE may also be used in future OFDM systems to reduce the prefix length and improve bandwidth efficiency. To conserve energy, the cyclic prefix can be replaced by a zero prefix (ZP). Optimal de-modulation of ZP-OFDM requires a computationally intensive matrix inversion operation. In Li et al. (2006), the authors use pilot-based channel estimation with a low complexity overlap-add de-modulation to implement an OFDM system. By using maximum-ratio combining over the data from multiple receivers, the authors utilize the spatial diversity available to further increase the robustness of the system. **Underwater Networking**

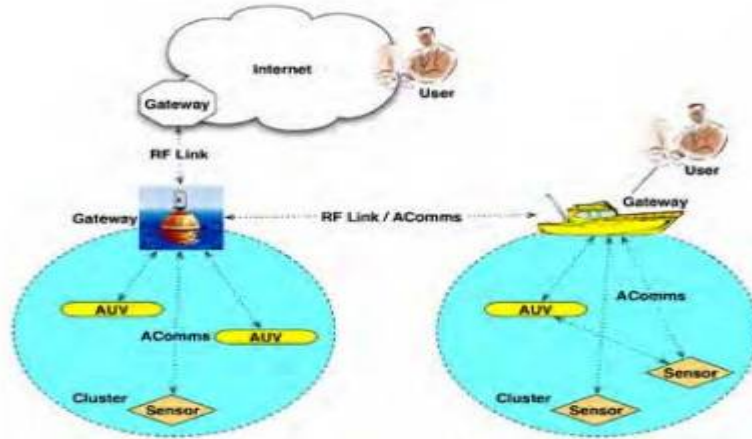
A recent survey on research in underwater protocol development presents a good overview of the subject (Akyildiz et al., 2006). The state of the art in current underwater networking technology is oriented towards a setup as shown in Figure 2. The network consists of a set of underwater local area networks (UW-LAN, also known as clusters or cells), connected to each other via gateway nodes. A gateway node provides administration, security and routing between multiple UW-LANs and other wireless or wired networks. In a cluster, the exact choice of physical layer protocol may depend on factors such as specific channel conditions, security reasons, processing capability, data rate requirements and energy efficiency. In view of the limited bandwidth underwater, a high level of cross layer optimizations or transcending of traditional layer boundaries may be needed to provide high data rates. We now review some of the recent work and future challenges.

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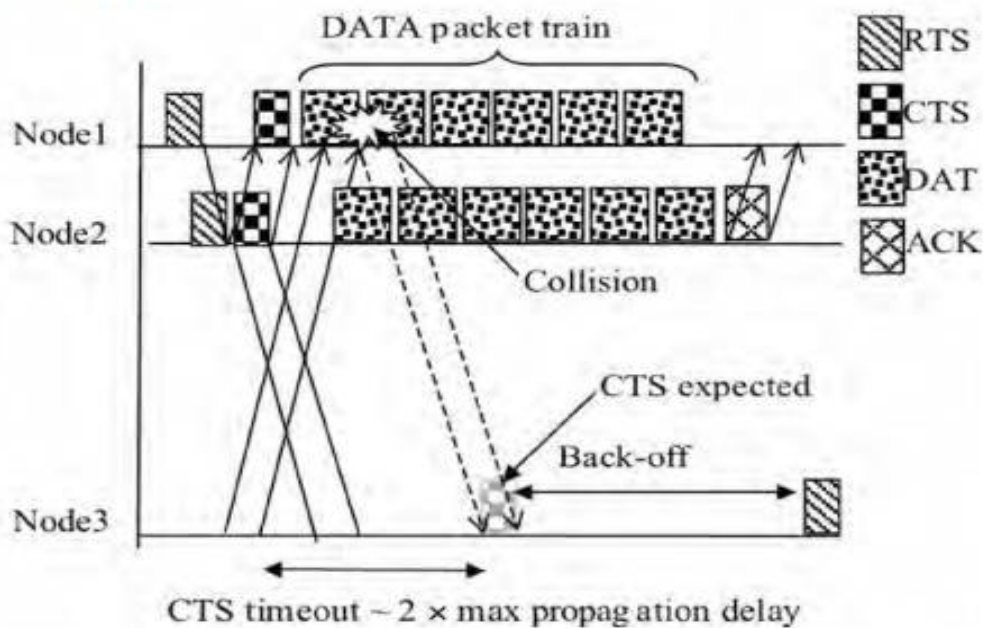
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A topology for underwater networks



In Sozer et al. (2000), the authors review MAC protocols such as ALOHA and MACA and present results on throughput and delay performance. MACA-based protocols are found to be highly suited in many scenarios underwater where scalability is important and time-synchronization is not available (Kebkal et al., 2005; Heidemann et al., 2006; Molins and Stojanovic, 2006; Xie and Cui, 2006). However in some sensor networks, RTS/CTS mechanisms could perform poorly due to latency issues and inefficiency for small payload packets (Turgay and Erdal, 2006). Protocol extensions and enhancements of MACA have been investigated to suit them better to underwater channel. For example, a WAIT command extension has been investigated in Sozer et al. (2000) and Doukkali et al. (2006). A WAIT command is send back by the receiver if it is currently busy and intends to send a CTS later on.

Packet trains in MACA protocol



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II. LITERATURE REVIEW

Underwater Acoustic Communication Channels: Propagation Models and Statistical Characterization [Milica Stojanovic, Northeastern University James Preisig, Woods Hole Oceanographic Institution]

Acoustic propagation is characterized by three major factors: attenuation that increases with signal frequency, time-varying multipath propagation, and low speed of sound (1500 m/s). The background noise, although often characterized as Gaussian, is not white, but has a decaying power spectral density. The channel capacity depends on the distance, and may be extremely limited. Because acoustic propagation is best supported at low frequencies, although the total available bandwidth may be low, an acoustic communication system is inherently wideband in the sense that the bandwidth is not negligible with respect to its center frequency. The channel can have a sparse impulse response, where each physical path acts as a time-varying low-pass filter, and motion introduces additional Doppler spreading and shifting. Surface waves, internal turbulence, fluctuations in the sound speed, and other small-scale phenomena contribute to random signal variations. At this time, there are no standardized models for the acoustic channel fading, and experimental measurements are often made to assess the statistical properties of the channel in particular deployment sites. Underwater acoustic channels are generally recognized as one of the most difficult communication media in use today. Acoustic propagation is best supported at low frequencies, and the bandwidth available for communication is extremely limited. For example, an acoustic system may operate in a frequency range between 10 and 15 kHz. Although the total communication bandwidth is very low (5 kHz), the system is in fact wideband, in the sense that bandwidth is not negligible with respect to the center frequency. Sound propagates underwater at a very low speed of approximately 1500 m/s, and propagation occurs over multiple paths. Delay spreading over tens or even hundreds of milliseconds results in frequency-selective signal distortion, while motion creates an extreme Doppler effect. The worst properties of radio channels — poor physical link quality of a mobile terrestrial radio channel and high latency of a satellite channel — are combined in an underwater acoustic channel.

Localization Algorithms of Underwater Wireless Sensor Networks: A Survey

[Guangjie Han, Jinfang Jiang, Lei Shu, Yongjun Xu and Feng Wang]

In Underwater Wireless Sensor Networks (UWSNs), localization is one of most important technologies since it plays a critical role in many applications. Motivated by widespread adoption of localization, in this paper, we present a comprehensive survey of localization algorithms. First, we classify localization algorithms into three categories based on sensor nodes' mobility: stationary localization algorithms, mobile localization algorithms and hybrid localization algorithms. Moreover, we compare the localization algorithms in detail and analyze future research directions of localization algorithms in UWSNs. The majority of the earth's surface is covered by water. Various underwater applications have been researched, e.g., environmental monitoring, undersea explorations, disaster prevention, mine reconnaissance, etc. Traditional monitoring systems are expensive and complicated. These equipments utilize individual and disconnected equipments to collect data from their surrounding environments. The emergence of UWSNs provides new opportunities to explore the ocean. In UWSNs, conventional large, expensive, individual ocean monitoring equipments are replaced by relatively small and less expensive underwater sensor nodes that are able to communicate with each other via acoustic signals. Many technologies for UWSNs have been researched, e.g., medium access control (MAC) and secure routing protocols, localization technologies and time synchronization schemes. Localization is one of the most important technologies since it plays a critical role in many applications. Generally, there are three kinds of sensor nodes in UWSNs: anchor nodes, unknown nodes and reference nodes. Unknown nodes are responsible for sensing environment data. Anchor nodes are responsible for localizing unknown nodes. They can acquire their position in advance using GPS systems or artificial arrangement. Reference nodes consist of localized unknown nodes and initial anchor nodes. Localization process of an unknown node can be described as how the node determines its position by limited communication with several anchor nodes or reference nodes using some specific localization technologies. Although various localization algorithms have been proposed for terrestrial WSNs, they are not suitable for UWSNs. The major difference between UWSNs and terrestrial WSNs is the different communication signals.

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Area Localization Scheme (ALS)

For large scale UWSNs, identifying the exact location of every unknown node may not be feasible. Therefore, an efficient Area Localization Scheme (ALS) is proposed for UWSNs. ALS was firstly proposed for terrestrial WSNs. This scheme estimates the position of every unknown node within a certain area rather than its exact location. The main responsibility of anchor nodes is to send out signals with different levels of power to localize unknown nodes. Unknown nodes simply listen to the signals and record the anchor nodes' IDs and their corresponding power levels. Together with collected data, the recorded information is sent to sink node. Sink node is assumed to know the positions of all anchor nodes and their respective transmitted power levels. Therefore, with proper signal propagation algorithms, sink node is able to draw out the map of areas divided by all the anchor nodes' transmitting signals. Then, sink node can localize unknown nodes. The advantages of ALS are its being range-free and having no synchronization requirement. Moreover, all complex calculations are handled by the powerful sink node instead of unknown nodes. This reduces energy consumption of unknown nodes and extends the lifetime of network. Localization coverage can be appropriately broadened by adjusting the transmitting power of anchor nodes.

III. CONCLUSION

We have formulated the problem of scheduling the localization packets of the anchors in single-channel and multi-channel partially-connected underwater sensor networks. We have introduced the concept of dynamic multi-channel packet scheduling. In this approach the network splits the existing channel into several sub channels adaptively in order to reduce the scheduling time. Furthermore, we have proposed two low-complexity algorithms in order to minimize the duration of the localization task. We have shown that the proposed algorithms perform near optimal, and much better than other alternative solutions such as TDMA-based or position-unaware approaches.

IV. FUTURE WORK

Furthermore, through comprehensive simulations, it has been revealed that the mean of the localization task duration depends on the number of sub channels, localization packet length, the anchors' maximum transmission range, the number of collision-risk neighbors and their modified average distances. We have found that, multi-channel scheduling approaches perform better than their single-channel ones especially when the ratio of the packet length to the average pair-wise distance is low. Moreover, we observed that a system that adjusts the number of sub channels dynamically has the highest performance among other position aware algorithms. The proposed scheduling algorithms cannot directly be used for cooperative localization, unless a localized sensor node participates in the localization process as an anchor before scheduling. In the future, we want to address the problem of localization when most of the underwater nodes are not under the coverage of the anchors. The optimal scheduling protocol for such networks can be considered as an extension of the work carried out in this paper.

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