Data Collection and Medium Access Control Solutions for Underwater Wireless Sensor Networks

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Abstract. *Underwater wireless sensor networks (UWSNs) can enable many applications in underwater environments. They face many challenges due to the characteristics of these environments and their use of acoustic or optical communications. Here we propose solutions for two existing problems in UWSNs. One of them is CAPTAIN, a cluster-based routing solution that explores the best of each communication technology to improve data collection. We also propose UW-SEEDEX, a MAC protocol that employs random time slot schedules to allow nodes to predict each other's transmission schedules to avoid collisions. Through simulations, we show how both proposed solutions perform better than other solutions from the literature.*

1. Introduction

Underwater wireless sensor networks (UWSNs) consist of sets of nodes with sensing, processing, storage, and wireless communication capabilities. These nodes are spread over a region to acquire data and perform other required tasks. Although wireless communication provides great flexibility for UWSNs, they also introduce many challenges. First, as energy is a very scarce resource, communications must be efficient. Another challenge comes from the direct impact of underwater environments' characteristics like salt concentration, pressure, and temperature in communications.

Also, since radio-frequency (RF) systems have some serious disadvantages in underwater environments, UWSNs are usually enabled by acoustic or optical communication.Acoustic systems, used by underwater acoustic sensor networks (UWASNs), provide long-range transmissions but with low throughput and high delays. Optical systems, on the other hand, provide high data rates over short range links and often require line-of-sight positioning. Both technologies can also be combined in hybrid communication systems to get the best of each. UWSNs whose nodes use such a hybrid system are here called underwater optical-acoustic sensor networks (UOASNs).

Due to these challenges, many communication solutions developed for terrestrial wireless sensor networks are not efficient when applied to UWSNs. So, it is necessary to either adapt existing solutions to the context of underwater environments or design new and efficient solutions that consider their constraints.

This work addresses two common network problems in different types of UWSNs. The first problem is data collection in UOASNs, which is defined as the process of routing data from sensor nodes to a particular node (or a set of nodes), denominated the sink node. The second problem addressed here is medium access control (MAC) in UWASNs, which consists of defining sets of rules for nodes to efficiently access a shared medium.

The main contributions of this work are:

- CAPTAIN, an algorithm for data collection in UOASNs; its techniques for building clusters, routing establishment, and data collection; and the evaluation of the algorithm through simulations, whose results show the benefits of using CAPTAIN instead of the shortest path algorithm.
- UW-SEEDEX, a MAC protocol for UWASNs that avoids collisions with low overhead by using random time slot schedules; the evaluation of the protocol, via simulations, showing that it can deliver more packets than other protocols from the literature, using, on average, fewer transmissions and consuming less energy.

2. Related Work

Currently, there are many routing protocols that can be used to collect data from underwater acoustic networks. Although these protocols can be used in UOASNs, they may suffer from inefficiency since they were not designed to take advantage of the two types of communication provided by these networks. To the best of our knowledge, only a few routing algorithms were proposed for UOASNs. MURAO is a cluster-based routing algorithm that performs data collection in UOASNs. Unlike CAPTAIN, it requires nodes to be spread so that the existence of gateway nodes (nodes in the intersection of two clusters) is guaranteed and considers that only cluster heads are equipped with both types of modems, while cluster members have only acoustic receivers and optical transceivers. Unlike the other routing algorithms for data collection, CAPTAIN is the only one that combines data aggregation and data collection for UOASNs.

During the literature review, we could not find any MAC protocol for UWSNs that uses random slot schedules. However, there are other protocols, such as ARNS and SEEDEX [Rozovsky and Kumar 2001], that target other types of networks. ARNS is a MAC protocol designed for satellite networks, while SEEDEX, which served as inspiration for our proposed solution, is a MAC protocol for terrestrial ad hoc networks. As both ARNS and SEEDEX are focused on networks that have different characteristics from the UWASNs, they do not directly deal with factors such as the high propagation delays faced by these networks. UW-SEEDEX, on the other hand, considers the delay propagation and, different from SEEDEX, adds acknowledgments to transmissions in time slots and employes an improved information dissemination scheme to deal with the characteristics of underwater acoustic channels.

3. CAPTAIN: A Data Collection Algorithm for UOASNs

CAPTAIN is an algorithm to perform data collection in UOASNs. It is designed for networks with multiple dense groups of nodes (clusters), where optical links can be used for data exchange within groups and acoustic links possibly connect various groups. The algorithm aims to explore the long range of acoustic transmissions and the high bandwidth of optical communication.

CAPTAIN is based on clustering and uses a data aggregation scheme to reduce the overall message traffic and save energy. The algorithm is composed of a configuration period and an operation period. Nodes organize themselves to create routes in the former so they can collect data in the later.

We can consider that CAPTAIN has three phases. In its first phase, it starts the configuration period by dividing the network into clusters, classifying nodes as cluster heads or members. To do so, some node (the sink node, for example) must begin the neighborhood discovery process by broadcasting a discovery message to the nodes around it. When a node A receives a discovery message sent by a node B, it registers B as an acoustic neighbor and uses information about the location of B to check if it is also an optical neighbor (is within the range of its optical modem). After receiving the discovery messages from its neighbors, a node use the information gathered, together with that on how much energy it has, to calculate its score. This score is sent to the node's neighbors and used to determine which nodes are becoming cluster heads and which ones are becoming cluster members. A node will be a cluster head if none of its optical neighbors has a score higher than its own, or a cluster member otherwise (nodes ID can be used for a tiebreaker).

After forming the clusters, nodes go to the next phase, where they establish routes to deliver data to the sink node(s). They first define the routes within the clusters and then create routes connecting the cluster heads. To create the routes within the clusters, their members use only the information already available to them, thus not requiring a new message exchange. Each member defines its neighbor with the highest score as being the next hop for its messages. This definition creates routes to take data from cluster members to cluster heads. To connect the cluster heads, nodes build a routing tree with the sink node as the root.

After joining the routing tree, a node can move to the third phase. This phase marks the beginning of the operation period, where nodes will start sending data to the sink node. Besides sending the own collected data, some nodes must also forward data collected by other nodes. In the tree routing, each node must forward all the data from its descendants (the nodes belonging to the subtree where it is the root). This phase also allows new nodes to enter the network and provide a head rotation scheme to prolong the network lifetime.

3.1. Simulation and Results

We implemented and evaluated CAPTAIN using a simulator[1]., comparing its performance with that of a Shortest Path Algorithm (SPA). Results showed that CAPTAIN was able to save more energy in many scenarios, consuming up to approximately 70% less than SPA in dense networks. This result is very important for underwater sensor networks since their nodes' life are very restricted. We could also observe that CAPTAIN could take more advantages of clusters in the networks than the SPA, resulting in more optical transmissions and less acoustic transmissions. Also, the average latency was generally lower when using CAPTAIN than when using SPA in networks with clusters. CAPTAIN also achieved rates of data collection per hour close to the ideal ones in these networks, using, on average, fewer acoustic transmissions than SPA. Therefore, CAPTAIN is suitable for underwater optical-acoustic sensor networks and has better performance when nodes are deployed in clusters.

4. UW-SEEDEX: A Pseudorandom-Based MAC Protocol for UWASNs

UW-SEEDEX is a TDMA-based MAC protocol designed for UWASNs. Inspired on the existing MAC protocol for terrestrial networks named

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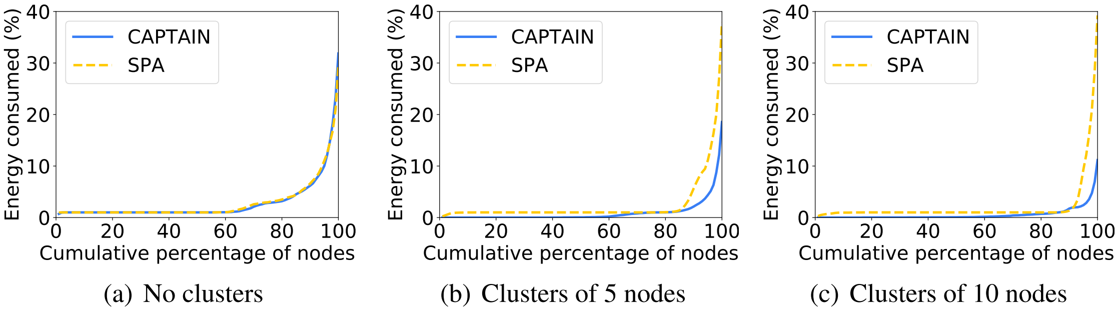
[1] Available at `https://github.com/epmcj/captain-sim`.



(a) No clusters (b) Clusters of 5 nodes (c) Clusters of 10 nodes

Figure 1. Cumulative percentage of nodes that spent a portion of their energy during the period of network activity.

SEEDEX [Rozovsky and Kumar 2001], UW-SEEDEX avoids collisions with low overhead by employing random time slot schedules produced from seeds. As SEEDEX, the proposed MAC protocol employes random schedules driven by pseudorandom number generators so that nodes can easily publish their schedule just by sharing their seeds. Therefore, nodes can opportunistically decide when to transmit.

The schedules are sequences of slots that define two possible states for nodes: ”Listening” (*L*) or ”Possibly Transmitting” (*PT*). Nodes must remain silent (do not transmit) when in *L* states, while they may send packets to others in *PT* states.

The key idea of this scheme is to use random time slot schedules that are created based on pseudorandom number generators. Each node initially chooses a seed and then uses it together with some method to generate its slot schedule. This method can be a Bernoulli process, where each slot state is selected based on a probability parameter p of it to be, for example, a *PT* one. If all nodes use the same generation method, then they only need to exchange their seeds to determine the entire schedules of others.

After knowing the seeds of all the nodes in its two-hop neighborhood, a node is able to decide the good moments to transmit packets. These moments are the ones where the source (S) and the destination (D) nodes are, respectively, in states *PT* and *L*. S can use its seed and the D’s seed to predict both slot schedules and thus easily find such slots. S can also check the schedules of D’s neighbors to determine how many of them will also be in the *PT* state and so transmit the packet with probability equal to $p_t = min(\alpha/(n+1), 1)$, where n is the number of other neighbors of the destination also in the *PT* state, α is a parameter used to control how aggressive a node can be while trying to transmit, and the min function restricts the probability values to valid ones.

To cope with the characteristics of the underwater acoustic channel, UW-SEEDEX adopts a slightly different seed dissemination scheme than SEEDEX and considers the propagation delay and acknowledgments when determining the time slot length and in the process of information dissemination. The UW-SEEDEX operation cycle, shown in Figure 2, is composed of two components that are interspersed over time: an update and a communication interval. Update intervals are periods where nodes exchange information about their seeds and states so they can better plan their future transmissions.

Communication intervals are sequences of time slots that nodes can use to transmit or receive packets. These slots define *PT* or *L* states. Their length must be at least as

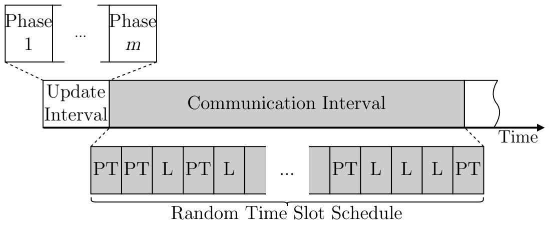


Figure 2. UW-SEEDEX operation cycle.

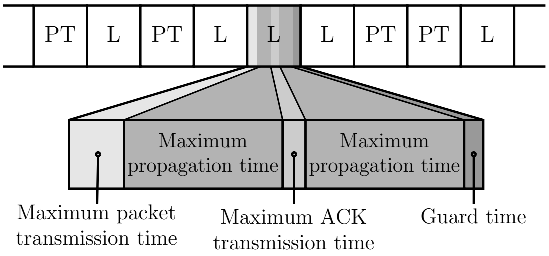


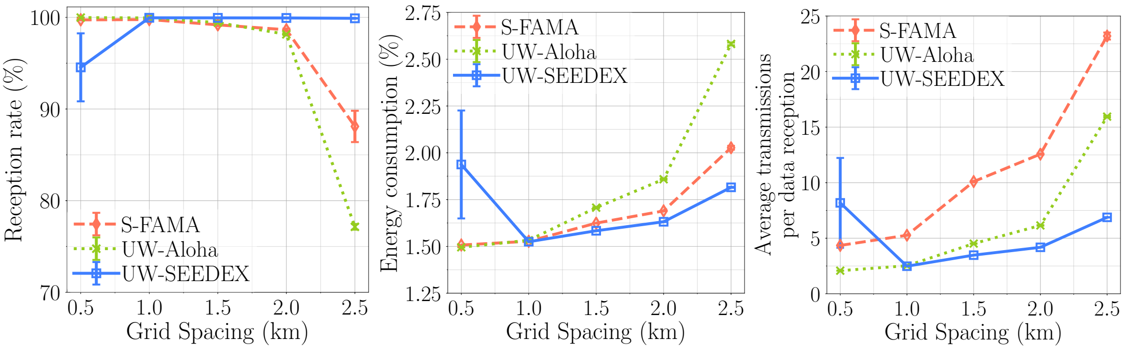
Figure 3. Time slot for one successful transmission.

long as the time required for sending one data packet and, if confirmation is required, also receiving an acknowledge (ACK) for it. Therefore, it must take into account the maximum time to transmit a packet, the maximum propagation delay, the maximum time to transmit an ACK, and a guard time to account for possible variations in the propagation delay and any clock drift. Figure 3 illustrates the composition of a time slot where one packet and one ACK can be transmitted.

4.1. Simulation and Results

We performed simulations using the ns-3.30 simulator to evaluate the performance of UW-SEEDEX in multiple test scenarios. We implemented UW-SEEDEX and two other MAC protocols from the literature: Slotted FAMA (S-FAMA) [Molins and Stojanovic 2006] and UW-Aloha [Peng et al. 2009]. More details about the simulation settings can be found in Section 5.3 of the dissertation.

Through extensive simulations, we show that the protocol can deliver more packets than protocols such as within the same time window, using, on average, fewer transmissions than both of them and with low energy consumption. Figure 4 shows the performance of the three MAC protocols in networks with different node densities (using grid deployments with different grid spacings). We also extensively evaluated the protocol parameters via simulations. UW-SEEDEX presented reception rates close to 100%.



(a) (b) (c)

Figure 4. Performance of the MAC protocols as a function of the network density.

5. Conclusions

We first proposed a data collection solution for UOASNs named CAPTAIN. It clusters networks, builds a routing three from the sink node, and then relays the collected data and maintains the routes. We evaluated CAPTAIN by comparing it with the shortest path algorithm (SPA) through simulations. Results show that CAPTAIN can save more energy (principally in dense networks), presents lower average latency, and achieve data collection rates close to the ideal ones using, on average, fewer acoustic transmissions than SPA. Therefore, CAPTAIN is suitable for UOASNs.

Next, we proposed the MAC protocol for UWASNs called UW-SEEDEX. It employs pseudorandom time slot schedules so that nodes can predict other schedules and consequently avoid collisions. We also used simulations to evaluate UW-SEEDEX. Results showed that UW-SEEDEX could deliver more messages while using fewer transmissions and consuming less energy than the other protocols.

6. Publications

1. Câmara Júnior, E. P. M., Vieira, L. F. M., and Vieira, M. A. M. (2020). CAPTAIN: A data collection algorithm for underwater optical-acoustic sensor networks. Computer Networks, 171:107145. (Qualis A2)

2. Câmara Júnior, E. P. M., Vieira, L. F. M., and Vieira, M. A. M. (2021). UW-SEEDEX: a pseudorandom-based MAC protocol for underwater acoustic networks. IEEE Transactions on Mobile Computing, pages 1–1. (Qualis A1)

3. da Silva Santos, E. R., Câmara Júnior, E. P. M., Vieira, M. A. M., and Vieira, L. F. M. (2019). Aplicações de monitoramento de tráfego utilizando redes programáveis ebpf. XXXVII SBRC. SBC. (Qualis A4). ***In Portuguese***.

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