Protocols for Underwater Wireless Sensor Networks - Challenges and Solutions

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Abstract—**The underwater environment poses challenges for communication that can make terrestrial solutions ineffective. However, the mature terrestrial solutions are based on decades of real-world research and experience, proving their sustainability and reliability. Although not suitable for direct replication, it may be wise to take advantage of these proven solutions. With this in mind, it is valuable to study successful terrestrial approaches and evaluate their ability to support the harsh underwater environment, and to assess how procedures and algorithms can be adapted for efficient underwater communication. In this paper, we revisit frequently used Medium Access Control (MAC) protocols and discuss the challenges they face in the underwater environment. In addition, underwater challenges related to multi-hop data collection are discussed. To improve reception reliability in the highly dynamic underwater environment, we focus on broadcast solutions that are constrained to avoid network flooding. Location-based techniques look very promising in this regard. Related to the MAC layer, our recommendation is that underwater communication solutions should focus on preventing collisions at receiver, while reducing the time between packet reception.**

Keywords-UWSN; underwater wireless sensor networks; Medium Access Control MAC; underwater routing.

I. INTRODUCTION

The United Nation (UN) sustainability goal #14, life below water [1], calls for underwater surveillance solutions to monitor the marine environment and strengthen ecosystem knowledge. To this end, sensor networks can be essential building-blocks in systems used by the ocean industries and public surveys for monitoring the seabed and water-column conditions. The network can contribute to sustainable exploitation of underwater resources by monitoring environmental parameters, and ensure responsible growth with well-controlled environmental impact.

Like terrestrial sensor networks, Medium Access Control (MAC) and network layer protocols are important to build sustainable networks. The goal of the MAC is to wisely share the network media between the nodes to provide efficient data collection. The network layer enables data from remote nodes to reach its destination. The protocols must adapt to the technology challenges related to the underwater media, such as low propagation speed, low and dynamic channel capacity, interference, ambient noise and asymmetric links, and so forth. In addition, the sensors are mainly battery charged and battery replacement is unfeasible. Furthermore, the ocean current may move the sensors. Thus, the protocols should provide solutions that cope with the dynamic environments and, simultaneously, reduce the energy consumption of the nodes.

Current underwater wireless solutions are mainly based on underwater acoustic transmission [2]. The signal propagation for acoustic underwater communication is five orders of magnitude slower than light speed; in addition, it is affected by temperature, salinity and depth [3][4]. The low propagation speed presents a fundamental challenge in coordinating the access to the shared communication medium. The room available for medium access control is compressed, and limited channel capacity should not be used for resource reservation processes requiring large protocol overhead.

Network layer protocols establish routing paths to enable multihop transmission, which can be used to increase the area covered by the network and/ or to reduce the output power, i.e., reduce transmission range, and save energy. The routing paths are formed based on specified criteria that aim to support the overall goal for the communication and/or to support overall network goals. For instance, the data can be transmitted over several paths simultaneously to support reliable communication or the data can be sent alternately over different available paths to balance the energy consumption in the network to prevent early depletion of nodes. However, due to the dynamic characteristic of the channel, and potential movement of sensor nodes, it is difficult to construct proactive routing paths, while reactive paths introduce high transmission delay. On the contrary, broadcasting can limit the delay and reduce the need for proactive configuration. In addition, the reliability is improved because the data are transmitted over several paths. However, the broadcast should be constrained to reduce network traffic and limit the energy consumption of the nodes. Thus, the peculiar characteristic of the environment means that protocols used in terrestrial communication require adjustments to provide efficient underwater communication. To this end, the contribution of this paper is to discuss characteristics that are challenging when converting basic terrestrial MAC layer protocols for use in underwater environment. In addition, network layer protocols that enable constrained multicast are investigated. Basic multicast should be avoided to prevent excessive network traffic as well and excessive energy consumption.

The rest of the paper is structured as follows. In Section 2 we present the related work. MAC layer protocols their issues related to the underwater environment are discussed in Section 3. Network layer protocols, and their issues, are discussed in Section 4. In Section 5 we present the conclusion.

II. RELATED WORK

The increasing interest in life and resources below water has mobilized a wide range of research on underwater sensor networks. The communication protocols are important to enable efficient operation. Thus, a range of solutions are suggested in the literature, and various surveys present and discuss selected solutions focusing on various aspects. A thorough discussion of MAC protocols for underwater acoustic networks is found in [5]. It is emphasized that further studies should focus on methods that handle the long propagation delay in ways that improve the utilization of the available bandwidth. For instance, one way is by allowing concurrent transmission as long as packet-collision at the receiver is prevented. Boukerche and Sun [6] discuss the underwater channel modeling, MAC and routing protocols, and localization schemes. It is pointed out that underwater environment represents a much more complex environment than the hypothesis that the existing approaches are commonly based upon. The complex environment characteristics are the reason that we, for network layer solutions, focus on constrained broadcast rather than single path solutions that are more vulnerable for changing channel characteristics.

Khisa and Moh [7] focus on energy-efficient routing protocols, and categorize the protocols using a new taxonomy. Energy consumption is also very much in focus when discussing localization-based and localization-free routing protocols, along with routing issues in [8]. In the conclusion, Khalid et al. point out that all protocols have pros and cons such that a protocol that is best for all cases cannot be found. The same is pointed out in [9] where routing protocols for acoustic sensor networks are assessed according to feasible application scenarios. An earlier survey that gives a nice overview of routing protocols and network issues is presented in [10]. Terrestrial routing protocols are also compared with Underwater Wireless Sensor Networks (UWSNs) in the survey. The survey presented in [11] focuses on cross-layer designed routing protocols. The authors define cross layer design as a design where algorithms from different layers can exchange information with each other, and point out that layered designs are better for creating adaptive solutions. A substantial part of the protocols suggested for UWSNs do, at least to some degree, follow the definition of cross-layer solutions defined in the paper. For instance, using this definition, all network layer protocols that use location or energy level as selection criteria will be categorized as cross-layer protocols.

Our focus is to present the issues that affect the MAC and network layer protocols. We review basic MAC layer algorithms and describe their weakness related to underwater communication. At the network layer, the focus is on methods that reduce broadcast. Due to the dynamic environment, the links are very unreliable. Broadcast communication is therefore advantageous compared to communication over pre-decided dedicated links. However, simple broadcast is a waste of energy.

III. MAC PROTOCOLS

MAC protocols have a large impact on the overall network performance because they coordinate the nodes' access to the medium. The access must be shared fairly between the nodes, the scarce bandwidth resource must be efficient utilized, packet collisions should be avoided, and the access delay must be limited. In addition, sustainable solutions require energy-efficient operations that lengthen the network lifetime and reduce the management cost. To this end, the impact for the various states of the communication processes must be investigated to develop the most optimal solution. In addition, dynamic environments and low channel capacity require adaptive and bandwidth-efficient protocols.

The access methods generally used can be categorized as fixed-assignment protocols, demand-assigned protocols and random-access protocols [12]. In fixed-assignment protocols, the channel is divided between the nodes such that nodes can access the medium without any risk of collisions. Typical protocols used are Time Division Mutiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). These protocols provide predictable access delay, and efficient utilization of available bandwidth. In addition, no energy is wasted on collisions. However, static resource reservation increases the packet loss probability in the highly dynamic underwater environment. In addition, the assigned resources require signaling to renegotiate resources when the network topology changes or if nodes require more resources due to increased traffic load.

Demand-assigned protocols provide short term channel assignments. Polling schemes belong to this class of protocols. The nodes may emit request for channel allocation and successful allocation is confirmed back to the nodes with description of the allocated resources. The resource may be in terms of number and positions of TDMA slots. Time slotted communication is illustrated in Figure 1. The administration of resources can be distributed to some key-nodes in the network, for instance to cluster heads in clustered networks. However, network-wide resource reservation is complex as traffic from nodes in adjacent areas can interfere. In addition, underwater currents or seafloor changes may move the nodes. Furthermore, efficient TDMA requires precise synchronization which is challenging in underwater environments due to the long and variable transmission delay, however short periods of static and predictable propagation delay may provide synchronization that is accurate enough [13].

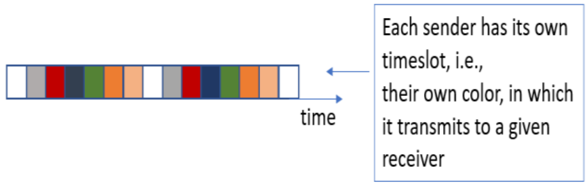

Figure 1. Time slotted communication. TDMA

The nodes in random-access protocols are uncoordinated and operate in a fully distributed manner. ALOHA is one of the earliest and most important protocols in this category. In the simplest version of ALOHA, the nodes transmit the packets as soon as they are generated. Successfully receiving the packet, the receiver transmits an Acknowledgement packet (ACK) back to the sender. If the sender does not receive ACK, it assumes that a collision has occurred. It waits a random amount of time (backoff) before retransmitting the packet. ALOHA works well when the traffic load is low. Under heavier load the number of collisions increases, increasing the delay and energy consumption, and reducing the throughput efficiency. In slotted ALOHA, the time is divided into timeslots, and packet transmission can only start at the beginning of a timeslot. The slot time is long enough to accommodate the longest allowed packets. Thus, only simultaneously transmitted packets can collide. However, because of the long transmission delay, this is not true in underwater communication. In addition, to avoid collisions, the slot length must also take the transmission time as well as packet length into consideration. That is, the transmission time between the sender and the node that is furthest away, but still within the sender's transmission range (interference range), must be considered.

Another popular random-access protocol is Carrier Sense Multiple Access with Collision Avoidance (CSMA/ CA), which is a random-access scheme with carrier sense and collision avoidance through random backoff. Different backoff algorithms can be used, but they roughly follow the following procedure: To avoid disrupting ongoing transmissions the nodes listen (carrier sense) to the channel, and choose a random number of backoff slots within a contention window. After the channel has been idle for a period equal to Distributed Interface Space (DIFS), the backoff value is decremented for each idle timeslot observed on the channel. As soon as the counter expires, the node accesses the medium. See illustration in Figure 2, where node A transmits a packet after the channel has been idle for DIFS plus the time it takes for the backoff value to be counted down. Node B has to wait until the channel has been idle for DIFS before it starts counting down the backoff value. A collision triggers retransmission with a new random selection of backoff time, and for each collision the contention window doubles. This is called exponential backoff. An explicit ACK is sent by the receiver upon successful reception of the packet. Using slotted CSMA, the backoff equals a random number of timeslots. Asymmetric links affect the communication efficiency especially when reliable communication is required. The reason is that when ACK messages are lost, the packets will be re-transmitted. Re-transmitted packets increase network traffic, which increases collision probability and also the energy consumption.

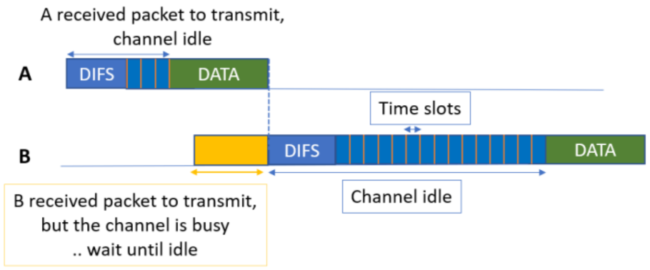

Figure 2. Carrier Sense Multiple Access CSMA

Furthermore, carrier sense protocols are susceptible to hidden node problem and unfair access. The slow propagation speed can lead to unfair access since there is special bias in estimating clear channel. Nodes close to the signal source get a clear channel earlier providing them with more access opportunities [14]. Another spatial unfairness is when nodes closer to the receiver may always win Request To Send (RTS) contentions since their requests are always received earliest [15]. The hidden node problem is due to the distance between the transmitting and receiving node. A transmitting node, N_{T1}, cannot detect activity at the receiver, Ns, that is caused by a sending node, N_{T2}, whose transmission reaches the receiver, but not the node N_{T1}. To reduce the hidden-node problem, Request To Send/ Clear To Send (RTS/CTS) can be used. After the sending node has obtained channel access it sends a RTS packet to the receiver. The packet includes a time-field that indicate the duration of the overall transaction. Successfully receiving the RTS means that there are no hidden nodes that are currently creating interference at the receiver side. The sender replies with an CTS, which also includes the duration time-field. Receiving the CTS the transmitter starts transmitting of the data packet. Thus, signaling the data transmission with both RTS and CTS, reduced the hidden node problem. In addition, neighbors of both the sender and the receiver are informed about the transmission and its duration. To account for the long transmission delay in underwater environment, the nodes must delay data transmission according to the longest possible delay, and the relatively long time-span increases the probability of transmission from a neighboring node. Thus, basic access control processes, such as carrier sense, reservation of the media, and ACK are more time-consuming and more management is required if these processes are to be optimized for neighbors at different distances.

Channel utilization and the first-in-first-out fairness police may also suffer from the long delay. The latter is the case if transmissions arrive out-of-order because the propagation delay from various senders is unequal. Channel utilization is reduced because collision-free reception is not guaranteed although the transmissions from different nodes are collision-free. Likewise, concurrent transmission may not lead to collision [16]. To improve the media utilization, receiver-centric solutions can be used to handle the unequal delay that exists between the various transmitting nodes. Receivers can arrange the transmission time for the transmitters so that collisions are avoided, while avoiding that the time between each received packet is unnecessarily long, such as suggested in [17]. The major challenge of the solution is prediction and management of delays, which require frequent information exchange between nodes, especially under dynamic channel conditions.

No solution can take all challenges into account. Thus, no solutions fit all scenarios as confirmed in the at-sea-experiment presented in [18], where the performance of three well-known MAC layer protocols, namely CSMA, T-Lohi [19][20], and Distance Aware Collision Avoidance Protocol (DACAP), is evaluated in an extensive sea-test during NATO at-sea campaigns. CSMA is the simplest of these protocols, where, to prevent collisions, the nodes listen to detect if the media is idle before transmission. If not idle, the nodes back-off according to an exponential back-off mechanism after which it again listens for a silent channel. ACK can be used for reliable communication. Applying T-Lohi, the node transmits a reservation-tone, after which it listens to the channel for the duration of a Contention Round (CR). If no other tones are heard during CR, the data packet is transmitted. Otherwise, it enters back-off state for a random number of CR before repeating the procedure. The most advanced of the three protocols is DACAP in which RTS/ CTS is used to reserve the channel. To warn about possible interference, the destination node sends a short warning packet to its sender if it overhears control packets from other nodes after sending its CTS and before receiving the associated data packet. If the sender overhears a control packet, or receives a warning form its destination while waiting for CTS, it aborts data communication. Using two different modems, the results reported in [18] for the three different MAC protocols show similar trends, although the overall protocol performance is significantly affected by the delays and overheads associated with the acoustic modem used. Furthermore, the results presented show that different traffic load, channel conditions and evaluation metric call for different solutions. Basically, solutions should be able to adapt, in a distributed way, to dynamically changing conditions. Using DACAP, the network performance is deteriorated when the traffic load is increased. ACK packet improves packet delivery ratio as long as the link is symmetric, however this is not always the case. CSMA reduces the transmission attempts since the channel is reserved by the data packet itself, however, the whole packet has to be retransmitted when collisions occur. The end-to-end delay of CSMA and DACAP use exponential backoff making the delay increase rapidly with increased number of retransmissions. Not using exponential backoff, T-Lohi has lower end- to- to lay, the price payed is higher packet loss.

In contrast to single-channel protocols discussed so far, multiple-channel protocols rely on several channels for communication to increase network throughput, reduce channel access delay, and potentially save energy. Neighboring nodes can communicate simultaneously, provided that they communicate using unequal data channels. Furthermore, control signals sent on a different channel will not affect the data that is sent. In [21], the control channel is slotted such that each node in a neighborhood is assigned a unique slot. Thus, also control packet are prevented from collisions. The solution suggested in [22] present a quorum-based data channel allocation to prevents collisions. However, generation and management of multichannel protocols is complex, and require advanced modems. In addition, if the nodes are equipped with only one transceiver, it means that they can only work one channel at a time, either on the control channel or on the data channel. When this is the case, the handshaking protocols such as RTS/CTS must be tuned to prevent triple-hidden terminal problem [23]. The triple-hidden problem occurs if two of the nodes in a neighborhood are communicating on a data channel. Simultaneously, another two nodes use the control channel for handshaking and agree to use channel A for data communication. The first two nodes will then be unaware of the data channel that the last two nodes selected. Thus, if the first two nodes want to initiate a new communication, they may select data-channel A, creating a collision.

Central one-hop network solutions simplify media access management and general network complexity at the cost of network coverage and network dynamic. Collisions can easily be avoided using a polling approach where the nodes are prohibited from transmission unless polled by the central node. The polling sequence is not required to be sequential; it can contain repetitions to support nodes with various amount of sensor-data [24]. To approach the throughput gained using TDMA, [25] suggest a centralized approach. The gateway measures the delay to each individual node to organize the nodes' transmission time and sequence. The gateway manages the network operation such that the data from all the nodes are received in strict order, resembling a subdivision frame. Although interesting approaches, they require the nodes to stay awake to listen for polling requests.

To summarize, there is no single solution that works best in all scenarios, and there is probably a need for solutions that can be adapted to dynamic changes. Furthermore, most of the underwater MAC protocols suggested follow terrestrial approach, trying to avoid transmission collision, although this will not guarantee against collision at reception [5]. To efficiently utilize the scarce bandwidth available underwater, the focus should be on the receiver side, solutions must reduce the time between packet reception while simultaneously preventing collisions at the receiver.

IV. NETWORK LAYER PROTOCOLS

Multi-hop communication can be used to increase the area covered by the network, or it can be used to reduce the distance between nodes. The advantage of reducing the distance is that the nodes' output power can be reduced to save energy. Also, the reduced distance can be used to increase the bit rate by increasing the transmission frequency and bandwidth. Furthermore, short distance between nodes increases the granularity of the surveyed area which may be valuable to pick up local variations and trends related to the parameters surveyed. On the other hand, longer distances between nodes in multi-hop networks can reduce equipment and management costs.

Multihop communication entails challenges such as increased network traffic and imbalance in the energy consumption in the network. Traffic increases because data packets must be forwarded, and management information must be exchanged to generate and maintain the routing paths. Energy imbalance occurs since the nodes in the vicinity of the sink must forward packets for all remote located nodes. Furthermore, the harsh underwater environment makes the generation of routing path more challenging. For instance, it is likely that the quality of a substantial amount of the links are time varying, thus proactively generated paths may not be reliable. Reactively created paths, on the other hand, introduce long delay. In addition, the links may be unidirectional or asymmetric, which makes it difficult to utilize paths that may be well-working and stable for communication in the correct direction. Broadcasting alleviates the challenges related to generating routing paths since all candidate paths are tried, and no specific routing paths needs to be generated. However, the broadcast must be constrained to prevent excessive network traffic, and to reduce the energy consumption of the nodes.

Opportunistic routing [26] can be an efficient method to constrain broadcasting. The basic idea is that all receivers contend to forward packets, i.e., the senders broadcast the packets which are forwarded by the most optimal receiver. Location-based protocols can be used for opportunistic routing in underwater environments. Using a greedy scheme, packets are always forwarded by the node located closest to the sink. This is illustrated in Figure 3, where the green node transmits a packet. The circle around the green node illustrates green node's transmission range. The red node is the destination, i.e., the sink. The orange node is the node inside the green node's transmission range that is closest to the sink. Thus, the orange node forwards the packet. Only local information is used to decide whether the received data should be forwarded, no routing data needs to be exchanged. For instance, each data packet contains information about the destination's location. Nodes that receive the packet start a timer that is proportional to their own distance to the destination. If the node overhears the packet being forwarded by a neighboring node before its own timer reaches zero, it refrains from forwarding the packet. Otherwise, it forwards the packet. The long delay in underwater communication requires that the timer that sets the holding-time (the time between a packet is received until it is potentially forwarded) is wisely set. Two aspects must be considered. First, the timer must be long enough to ensure that a packet forwarded by a more preferred node is received by the less preferred node before the timer of the less preferred node expires. Remember, due to the underwater environment, it takes time for the forwarded packet to reach the less preferred nodes. Second, it is likely that the node in the more preferred location receives the packet later because it is probably located closer to the sink, and further form the transmitter. To sum up: wait until the most-preferred node receives the packet, then wait for the packet relayed by this most-preferred node to reach the less-preferred nodes. Taking both of these aspects into consideration increases the delay in the network. In addition, when the number of potential successor nodes is high, a wide range of distinct holding-time-values is required to prevent multiple node timers from expiring simultaneously. To provide a broad range of distinct holding-time-values, the average delay in the network increases.

Location-based opportunistic protocols require that nodes know their location. GPS is unfeasible as an underwater location service. One method of solving the underwater location problem is to let some dedicated nodes, with known locations, send out beacons at regular intervals. Based on received signal, other nodes can use methods like triangulation to determine their own location. Received power and/ or time delay of acoustic signals offer better precision than when using terrestrial radio signals. However, some nodes may be located such that they cannot receive the beacons emitted to estimate locations. To prevent data from these nodes from being lost, a method such as suggested in [27] can be used: The nodes that do not receive location information use a reactive protocol to send data to the best-located neighbor node.

Routing pipe can be used to reduce the number of potential forwarding nodes, and reduce the probability of excessive network traffic for opportunistic protocols. In addition, it alleviates the increased delay needed to accommodate the broad range of distinct holding-time-values discussed above. Assuming a vector from the sender to the target node, the routing pipe is a cylinder with adjustable radius centered around that vector. Nodes inside the cylinder are candidate forwarding nodes. The transmitted packet carries the position of the sender node, the target node, and the forwarding nodes to enable the receivers to determine whether they are located inside the routing pipe, and whether they are located closer to the destination than the transmitting node. This is illustrated in Figure 4. The green node transmits a packet toward the sink (the red node). All nodes within the green circle encircling the green node are covered by transmission. The packet is forwarded by the

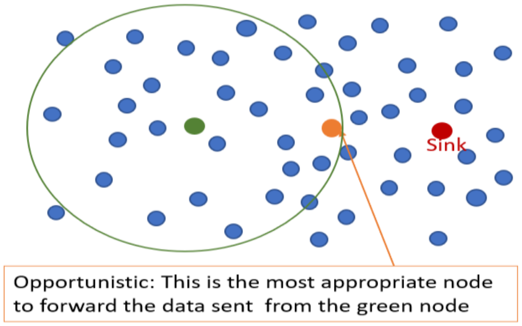

Figure 3. Opportunistic routing.

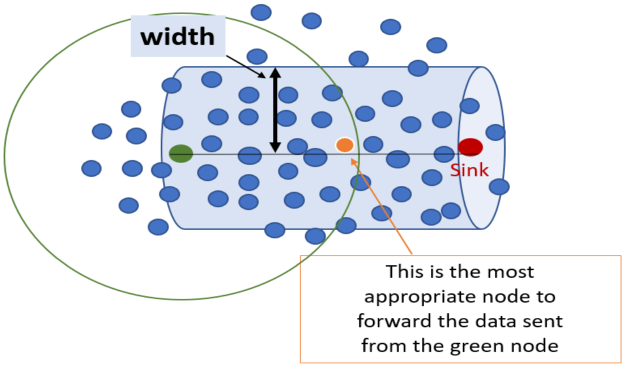

Figure 4. Time slotted communication. TDMA

orange node since it is the node inside the pipe (blue shaded cylinder) that is closest to the sink. Adjusting the width of the cylinder or the transmission range, adjusts the number of candidate forwarders. In [28], to reduce the chances of forwarding data packets, nodes with less energy than the transmitting node intentionally calculates a reduced pipe diameter. Thus, they reduce that chance of being inside the cylinder formed by the sender-receiver vector and diameter. This is done to improve the energy balance in the network.

A challenge related to location-based routing is the void region that may exist in the network. To prevent data loss, some measures are needed to find detours around the potential voids. A simple algorithm for finding detours around voids is to switch to broadcasting when approaching voids regions. Other measures to avoid void generally require that information is exchanged between the nodes. In the depth-based approach suggested in [29], the node examines its neighbors to check whether they can provide positive progress toward the destination. If not, the node requests information from two-hop nodes to adjust its depth such that positive forwarding can be resumed. To reduce the void problem, and improve the Packet Delivery Ratio (PDR), a holding-time that takes several factors into considerations is suggested in [30]. Firstly, a reliability index is calculated based on the energy of the current node and the energy of the forwarding region. In order to limit formation of energy holes and thereby increase the reliability, the forwarding region with the highest energy is selected. Secondly, an advancement factor is used: The depth of the note is calculated so that a small decrease in the depth gives an exponential increase in priority. This reduces the probability of duplicate packet transmissions because the priority difference is significant, even for a low change in depth. Third, a shortest path index is used. It combines the number of hops toward the destination and the average depth of the nodes in the next hop.

Other well-known algorithms used in terrestrial Wireless Sensor Networks (WSNs) to reduce broadcasting, such as probabilistic and counter-based schemes may be well-worth testing in underwater environments. Counter-based schemes are based on the fact that broadcasting a message that has already been broadcasted by several neighboring nodes will not give a substantially increase the area covered. Thus, the nodes are prevented from rebroadcast messages if the expected additional coverage is limited. Basically, the nodes count the number of times a message is received while waiting for medium access. If the counter becomes higher than a threshold, the transmission is canceled, otherwise the message is transmitted [31][32].

In probabilistic schemes, the nodes will rebroadcast messages with a probability P. If P = 1 the data packets are broadcasted. There is a certain probability that no neighbors choose to forward a packet. To ensure the progress of a packet towards the destination, the sender can re-emit the packet if no forwarded packets are heard. However, to ensure the packet's progress, the sender may need to re-emit the packet several times, which increases network traffic. In addition, the packet may have been forwarded by nodes connected over a unidirectional link, which means that the re-emitted packets are a waste of both energy and bandwidth.

To summarize, due to the dynamically changing channel condition and the long propagation delay in the underwater environment, broadcasting may be a better solution than reusing terrestrial routing protocols that generate specific routing paths. Broadcast-based forwarding is likely to improve the probability of packets reaching their intended destination. However, the broadcasting procedure should be constrained to reduce both energy consumption and network traffic.

V. CONCLUSION

MAC and network layer solutions for underwater communication require that characteristics such as long propagation delay, dynamic channel characteristic and limited bandwidth are considered. Long delays are especially challenging for MAC protocols. The time available for access control is reduced, and the limited channel resources should not be depleted by large amount of management traffic. For efficient utilization of the limited channel capacity, the focus should be on the solutions that both reduce the time between received packets, and, at the same time, prevent packet collisions at the receiver.

Dynamic channel properties make it challenging to generate fixed routes. To reduce the probability of packets being lost during forwarding, we recommend to use constrained broadcasting techniques. Location-based techniques seem to be especially promising, and should be further investigated.

In our future work, we will perform extended simulations of some of the protocols we have discussed in this paper. The protocols that show promising simulation results will be further evaluated in experimental tests.

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