Spatial Reuse TDMA for Broadcast Ad-Hoc Underwater Acoustic Communication Networks

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Abstract

Underwater acoustic communication (UWAC) is often the only viable solution to establish an ad-hoc underwater communication network. The specific features of UWAC, arising from the physics of underwater acoustics, make the design of resource-efficient media access control (MAC) protocols important as well as challenging. In this paper, we tackle this task considering ad-hoc UWAC networks that support high-traffic broadcast communication. To this end, we propose the application of the spatial reuse concept and the exploitation of direct sequence spread spectrum used at the UWAC physical layer to obtain a new hybrid spatial-reuse time-division multiple access (HSR-TDMA) protocol. By tracking the time-varying network topology, our protocol adaptively optimizes the set of active communication nodes and overcomes problems of UWAC networks such as the near-far problem, flickering, and formation of islands. Pertinent performance parameters, namely network availability, message reliability, and transmission rate are analyzed for the proposed protocol. Evaluation of these analytical performance expressions demonstrates the significant advantages of HSR-TDMA over commonly used conventional TDMA for broadcast UWAC networks. We also report performance results for both the HSR-TDMA and the conventional TDMA protocol from a sea trial at the Haifa harbor, which corroborate the results obtained from the analysis.

Index Terms

Underwater acoustic communication (UWAC), broadcast networks, media access control (MAC), spatial reuse, time-division multiple access (TDMA).

I. INTRODUCTION

Underwater communication has become a popular research area due to the many applications that require undersea communication such as oceanography data collection, ocean exploration, undersea navigation, and control of autonomous underwater vehicles (AUV) to name just a few. Since radio frequency communication does not propagate well underwater, long communication ranges are only possible through the use of acoustic waves.

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However, the implementation of underwater acoustic communication (UWAC) systems is rendered challenging by factors such as limited available bandwidth, long propagation delay, long delay spread, large Doppler spread, and time-varying channel conditions [1], [2]. Hence, even though UWAC systems have been implemented for many years, the design of UWAC systems enabling underwater applications with high quality of service (QoS) requirements remains a demanding task [3]. In this context, networking aspects of UWAC systems have recently started to attract significant interest in the research community [4]. This particularly concerns the development of advanced media access control (MAC) protocols as a key element towards efficient communication networks [5].

The UWAC channel poses some unique challenges for MAC protocol design compared to, e.g., MAC design for RF wireless networking. The typically low signal-to-noise-power ratio (SNR) of UWAC links and the long propagation delay require careful tradeoffs between latency and reliability [6]. In particular, the low sound speed in water entails significant propagation delays, which are of the same order as packet transmission durations [6]. Thus, automatic repeat request (ARQ) protocols, needed to compensate for the low reliability, greatly increase system latency [7]. The different sound speed layers [1], and physical obstacles, such as harbor docks and natural reefs in near shore environments, create acoustic non-line-of-sight scenarios. In these situations and when transmission range is large, multi-hop relaying is needed. Furthermore, the long propagation delay and high outage rates together with the time-varying network topology, due to permanent movement of network nodes, render centralized control in UWAC networks difficult [6]. Finally, due to absorption loss and ambient noise increasing and decreasing with frequency, respectively [1], [8], only a narrow signal bandwidth is available for UWAC, which motivates MAC design solutions that use the time or code domain, rather than the frequency domain.

Aloha and slotted Aloha protocols are popular protocols for low packet rate UWAC networks [4]. Although latency is low for these protocols [9], the considerable penalty for packet collision due to the long propagation delay has led to the development of more complex protocols for controlling the packet collision rate [3], [4], [10]. The most commonly used collision-avoidance protocols are the handshake type protocols based on request to send (RTS) and clear to send (CTS) messages [3]. However, due to the long propagation time, collisions between data packages and RTS messages from different nodes can occur frequently. One approach to solve this problem is to invoke ARQ mechanisms [11]. The same concept is suggested in [12], where a node reserves the channel after winning a series of contention rounds.

It is well known that contention based medium access suffers from low throughput for high-traffic networks. MAC protocols for contention-free UWAC networks are based on time-division multiple access (TDMA) [6], in which each node is allocated a unique time slot for transmission. Although TDMA yields higher throughput for high-traffic networks compared to (collision avoidance) Aloha-type protocols, throughput is still limited due to the significant idle time per time slot which is needed to account for the propagation delay. This guard time can be reduced by using propagation delay estimates to stagger transmissions [13].

The usually low SNR and thus reliability of UWAC links has led to the application of direct sequence spread spectrum (DSSS) techniques at the UWAC physical layer [14], [15]. DSSS signaling is robust to frequency selective fading and facilitates mitigation of impulsive and narrowband noise. The low cross-correlation of DSSS symbols
created by different pseudo-random spreading sequences renders it also suitable to combat signal collisions, i.e., to establish code division multiple access (CDMA). For example, [16] presented a hybrid Aloha/CDMA MAC protocol in which nodes randomly access the channel and adapt signal power and CDMA sequence length for the payload part of the packet. For broadcast communication, [17] introduced a spatial reuse TDMA protocol making use of CDMA to resolve packet collisions. Similarly, CDMA is exploited in [18] to accomplish spatial reuse TDMA. Each node is assigned to a cluster such that the communication within clusters is based on TDMA, assuming short intra-cluster transmission range, and adjacent clusters use orthogonal modulation symbols in a CDMA fashion.

In this paper, we consider underwater applications that require frequent and periodic transmission of broadcast packets, such as the sharing of navigation information, command and control systems, or sending “alive” messages for diver safety, etc. In such UWAC networks, the network nodes can be mobile AUVs, human divers, anchored floating sensors, or offshore buoys, etc. Such applications are very common and require high network throughput [19]. Hence, different from most existing UWAC MAC protocols, which focus on reliability and latency issues for low-traffic networks and the need to establish fast secure links [4], we are interested in a MAC protocol that optimizes the network throughput for broadcast applications. Towards our objective, we continue the line of research presented in [17], [18] and propose a spatial reuse TDMA protocol with CDMA for collision avoidance, which we refer to as hybrid spatial reuse TDMA (HSR-TDMA) protocol. More specifically, we formulate a constrained resource-allocation problem and develop a pragmatic solution, which trades off network performance with computational complexity and sensitivity to topology changes, and which lends itself for the derivation of analytical performance expressions. Different from [17], we do not require full connectivity in the network, and unlike [18], the CDMA component is independent of a node’s location in the network and thus spatial reuse is not limited to clusters. Furthermore, our approach does not rely on the setup of clusters with dedicated cluster heads and bridges, which makes it less sensitive to topology changes. Since we consider broadcast transmission, adaptation of transmit power and length of spreading sequence [16] or timing advance [13] are not applicable. Numerical results from network simulation and sea trial experiments demonstrate the performance gains from using the proposed HSR-TDMA compared to conventional TDMA.

The remainder of this paper is organized as follows. In Section II, we motivate spatial reuse TDMA for UWAC networks and develop and describe the proposed protocol. Section III provides an analytical framework for performance evaluation of HSR-TDMA. In Section IV, we present and discuss numerical results obtained for synthetic UWAC environments and in a sea trial to illustrate the performance advantages afforded by the proposed HSR-TDMA. Conclusions are offered in Section V.

II. DERIVATION OF THE HSR-TDMA PROTOCOL

In this section, we first discuss the benefits of spatial reuse TDMA for high-traffic UWAC networks and then derive and describe in detail the new HSR-TDMA Protocol. Throughout this paper we consider broadcast transmission in a multihop network with a pre-determined number of nodes, \( N_{\text{nodes}} \), collected in \( N_{\text{nodes}} = \{1, \ldots, N_{\text{nodes}}\} \).
A. TDMA and Spatial Reuse TDMA

In any TDMA protocol the network nodes are time synchronized and the time axis is divided into slots during which subsets of nodes transmit. The sequence of subsets is periodic, and we refer to the collection of slots within one period as a TDMA frame. The TDMA slot duration includes an idle time determined by the (maximal) transmission range of the system to account for the propagation delay. We note that synchronization requirements of TDMA are easily met in UWAC networks due to the large time slot duration compared to clock shifts.

In the conventional TDMA protocol, a frame consists of $N_{\text{nodes}}$ slots $t = 1, \ldots, N_{\text{nodes}}$. Node $i$ is allowed to transmit during the $t$-th slot if and only if $i = t$. While this TDMA protocol ensures collision-free multiple access, availability of transmission resources to nodes is low and thus throughput and latency performances are poor, especially in large networks [3]. This problem is compounded in UWAC networks due to the mentioned long propagation delay, and thus resource availability becomes an issue even for relatively small networks.

The limited (time slot) resources in TDMA can be more efficiently used by applying the concept of spatial reuse well known from multihop wireless networks, e.g. [20]–[24]. In spatial reuse TDMA, throughput is increased by scheduling several nodes to transmit in the same time slot [20]. There is a large variety of scheduling algorithms for spatial reuse TDMA, considering point-to-point or broadcast traffic, maximization of availability or minimization of frame length, and different collision and fairness constraints, cf. [20]–[24] and references therein.

Spatial reuse TDMA is an appealing concept for UWAC. First, UWAC networks are often not fully connected, i.e., some nodes are not within the transmission range of other nodes. These situations can result from physical obstacles such as docks or ships in harbor environments or near-shore reefs, and range dependent path loss and high attenuation due to depth differences between nodes [1]. In such cases, some nodes can transmit simultaneously without causing collisions of their signals. Second, DSSS based signaling used in UWAC modems enables CDMA. Thus, a node which receives multiple signals sent concurrently from different nodes is able to separate and detect them (we qualify this assumption further below), and spatial reuse TDMA can be combined with CDMA, cf. [17], [18].

B. Objectives and Assumptions

Since network throughput depends on network topology and on the packet generation rate at each node it is hard to optimize for broadcast communications. Therefore, following e.g., [25], [22], we consider maximization of network availability, under certain additional constraints as explained in the following, when formulating the scheduling optimization algorithm. Combining availability with reliability of packet transmissions through the network, we obtain the successful packet transmission rate (STR). The STR is closely linked to throughput and thus adopted as main performance criterion in this paper. Hence, the main objective of this work is to develop a broadcast schedule for spatial reuse TDMA that achieves high STR by exploiting network topology information while providing certain performance guarantees and robustness in case of imperfect knowledge due to topology changes.

We represent the UWAC network by an $N_{\text{nodes}} \times N_{\text{nodes}}$ connectivity matrix $C$, where the $(i, j)$-th element, $c_{i,j}$, is one if nodes $i$ and $j$ are connected via a single-hop communication link and zero otherwise. (For the moment,
we assume $C$ to be symmetric, i.e., $c_{i,j} = c_{j,i}$. We refer to node $j \neq i$ as a neighbor of node $i$ if $c_{i,j} = 1$.

We consider two possible conflicts in the network: 1) primary conflicts in which nodes $i$ and $j$ are scheduled to transmit in the same time slot while $c_{i,j} = 1$ and 2) secondary conflicts in which packets originating from nodes $i$ and $j$ collide at a third node $p$ while $c_{i,j} = 0$ (cf. [21], [22]). Respecting the half-duplex constraint of most UW AC transducers [26], we do not allow primary conflicts. That is, neighbor nodes are never assigned to the same time slots. However, secondary conflicts are allowed making use of DSSS signaling at the physical layer, which is widely used in UW AC systems to successfully cope with channel distortions [14]. We note that UW AC has the advantage that the spreading factor required for channel handling is usually sufficient to also enable multiple access (i.e., CDMA), cf. e.g. [15], [27]. This is because, different from CDMA in radio networks, the significant attenuation in the underwater acoustic channel and specifically the absorption loss render the effect of simultaneous transmissions from remote nodes on signal-to-interference-and-noise-power ratio (SINR) negligible. Furthermore, differences in the propagation delay experienced by data packets sent from different nodes in the same time slot have the effect of reducing interference in case of collisions. We therefore assume that a node can successfully detect simultaneous transmissions from its neighbors and thus resolve secondary conflicts, unless the SINR drops below a certain threshold, which is the well known near-far problem of single-channel receivers [16].

Next, we wish to avoid starvation problems in the multihop network. Therefore, each node needs to be allotted at least one time slot in every TDMA frame. Following [6] we assume that the number of nodes in the network is small with a relatively short transmission range of several kilometer. This allows practical implementation of TDMA scheduling as transmission delay is still tolerable. We further assume that the network topology is slowly time varying such that (often) a sufficiently accurate estimate of the network connectivity matrix, is available. To this end, each node establishes a connection list (CL), which is a list of its neighbors. The CLs are determined online in the network by identifying the transmitter of arriving packets at each node and using a sensitivity mechanism as we further discuss below. The CL is then shared with other nodes by piggy backing it to outgoing packets.

Since packets are broadcasted for the applications considered, each node can extract the most recent CLs of other nodes and construct the connectivity matrix $C$ while tracking topology changes in the network. Finally, to ensure robustness to outdated topology information, we impose a static and globally known skeleton TDMA schedule, which is identical to conventional TDMA with $N_{\text{nodes}}$ slots. Such an approach has also been chosen in [22] to build up a conflict free schedule (taking secondary conflicts into account) in a distributed fashion. In doing so, the proposed HSR-TDMA protocol described in the next section falls back to the conventional TDMA protocol in the case that topology information cannot be obtained reliably due to fast topology changes.

\footnote{We would like to mention that the proposed HSR-TDMA protocol could also be applied to non-DSSS system, for which secondary conflicts are prohibited. To this end, one would apply the protocol to a virtual connectivity matrix which is obtained from squaring the connectivity matrix such that nodes located two-hops away are turned into neighbor nodes.}

\footnote{Note that the transmission of such an CL need not be considered as an extra overhead for HSR-TDMA, since it is already required for multihop routing [3].}
C. The HSR-TDMA Protocol

Following the rationale given above, the core idea of the HSR-TDMA protocol is (i) to use the conventional TDMA protocol as an underlying common protocol with node \( i \) as designated node for time slot \( t = i \), referred to as the slot node, and in addition (ii) to adaptively identify available nodes that can transmit during the same slot without causing packet collisions. These nodes are referred to as joining nodes for this time slot, while the rest of the network nodes are referred to as receiving nodes. The classification of the network nodes is performed in an ad-hoc fashion, based on the shared connectivity matrix \( C \).

Let us define \( I_t \) as the set of slot and joining nodes in time slot \( t \). We can then formalize the corresponding scheduling problem for maximizing the availability as follows:

\[
\text{max} \sum_{t=1}^{N_{\text{nodes}}} |I_t| \quad (1a)
\]

subject to

\[
I_t \subseteq N_{\text{nodes}}, \quad \forall t = 1, \ldots, N_{\text{nodes}} \quad (1b)
\]

\[
i \in I_t, \quad i = 1, \ldots, N_{\text{nodes}} \quad (1c)
\]

\[
c_{j,k} = 0 \quad \forall j, k \in I_t, j \neq k, t = 1, \ldots, N_{\text{nodes}} \quad (1d)
\]

Constraint (1d) is the half-duplex constraint, i.e., spatial reuse is applied only if the connectivity matrix of the UWAC network is not full, while constraint (1c) enforces the skeleton TDMA schedule and as such a simple notion of fairness and robustness to topology changes.

1) Graph Coloring — Optimal Solution: Representing the network as an undirected graph with vertices being network nodes and edges being network links, and mapping time slots into colors, problem (1) can be considered as a graph coloring problem [28]. Given a set of \( N_{\text{nodes}} \) colors, we attempt to maximize the total number of colors assigned to all nodes. The solution of (1) is then found as \( I_t \) being maximal independent sets of the graph, such that \( I_t \) contains node \( i \) and has maximal cardinality. From the NP-completeness of finding the largest maximal independent set of a graph [28] it follows that also (1) is NP-complete.

2) Suboptimal Solution: We suggest another scheduling approach which is a sub-optimal solution to (1) but has two distinct advantages: (i) it has polynomial worst case complexity (rather than exponential complexity as the optimal solution), and (ii) it is amenable to analytical performance evaluation.

We start from the skeleton TDMA schedule (constraint (1c)) with node \( i \) being the slot node in time slot \( t = i \). Avoiding primary conflicts, each time slot includes a guard interval the size of the maximal expected propagation delay in the channel. Hence, as in any TDMA protocol, the efficiency of our protocol is inversely proportional to the transmission range. Then, additional nodes are added to each time slot. For this purpose, each edge is assigned a unit weight and the shortest-path matrix, \( H \), with elements \( h_{i,j} \) being the minimal number of hops required for transmitting a packet from node \( i \) to node \( j \), is established running a polynomial-time shortest-path technique such as the Dijkstra algorithm [29] on \( C \). Since nodes at hop distance one from the slot node cannot transmit due to constraint (1d), nodes at hop distance two from the slot node can safely use the time slot, as long as nodes at hop
distance three do not transmit and so on. Thus, nodes with even hop distance to the slot node are candidate joining nodes, while nodes with odd hop distance to the slot node are set to be receiving nodes. In cases where nodes with even hop distance to the slot node are neighbors, only one of these nodes can become a joining node. To resolve this conflict, each candidate joining node \( j \) is assigned a weight \( w_{j,t} \) for slot \( t \), and the candidate with the largest weight among the competing nodes becomes the joining node. In order to achieve fairness among candidate joining nodes, \( w_{j,t} \) are assigned afresh in each TDMA frame. This is accomplished by random generation of weights in each TDMA frame at all nodes, which use a common random-generator seed and reference time for updating weights. Defining

\[
K_{j,t} = \{ k \in \mathcal{N}_{\text{nodes}} | c_{j,k} = 1, h_{t,j} = h_{t,k} \}
\]

(2)

for \( j, t \in \mathcal{N}_{\text{nodes}}, j \neq t \), the proposed schedule for HSR-TDMA can be formalized as follows:

\[
\text{Initialize } I_t = \{ t \} \quad \text{(skeleton TDMA schedule)} \quad (3a)
\]

If \( (h_{t,j} \mod 2 = 0) \land (w_{j,t} > w_{k,t} \forall k \in K_{j,t}) \) then \( j \in I_t \) \quad \text{ (} j \neq t \text{ is a joining node)} \quad (3b)

D. Example for the HSR-TDMA Protocol

As an example, we apply the HSR-TDMA protocol to a 10-node network with the topology shown in Figure 1. The selected joining nodes according to the HSR-TDMA schedule are listed for the 10 time slots of a TDMA frame. We observe that in all time slots several nodes are selected as joining nodes, which improves overall network availability compared to the conventional TDMA protocol. In fact, always five nodes transmit simultaneously, unless bottleneck nodes 2 and 5 are involved, resulting in an average of 4.2 transmissions in each time slot. From Figure 1 we also observe that the neighbor nodes 6 and 7 are in equal hop-distance to all other network nodes. Thus, only one of them can join the slot node transmissions at each time. We note that the achievable network availability for the HSR-TDMA protocol improves with increasing sparsity of the connectivity matrix \( C \), i.e., spatial reuse of network resources increases for less connected networks.

E. Nuisance Effects in UWAC Networks

1) Symmetry: In the formulation of the HSR-TDMA protocol we have tacitly assumed symmetric links, i.e., both \( C \) and \( H \) are symmetric matrices (and thus the network graph is undirected). However, in the underwater channel links between nodes located at different depths might not be reciprocal due to different absorption losses [1]. In addition, short term different noise levels at nodes can exist due to close-by sources of interference. These effects give rise to asymmetric components in \( C \) and \( H \). Since in the HSR-TDMA protocol non-connected nodes may transmit simultaneously, we apply a conservative strategy and replace all asymmetric components \( c_{i,j} \neq c_{j,i} \) of \( C \) by \( c_{i,j} = c_{j,i} = 1 \) to force symmetry. Since \( H \) is obtained based on \( C \), it also becomes symmetric. Note that the symmetrized connectivity matrix, denoted \( C_{\text{sym}} \) in Algorithm 2 below, is generated locally, whereas the actual CLs giving rise to a (possibly) asymmetric \( C \) are shared throughout the network.
2) **Flickering:** In situations of low SNR, node movements, or channel variations, a link can become unstable, which is known as the *flickering* problem. In this case, the connectivity matrix is (locally) fast time varying and may become ambiguous throughout the network as topology updates are not made sufficiently often. As a result, the HSR-TDMA protocol would become unstable. We account for the flickering problem by introducing counters $b_1$ and $b_2$ used for adding and removing communications links to the CL, respectively. Considering that, due to the TDMA skeleton schedule, node $j$ is guaranteed to transmit in the $j$th slot, this slot is observed for the purpose of establishing CLs. Then, node $j$ is added to the CL of node $i$ only if $b_1$ successive packets transmitted from node $j$ have arrived successfully. Denoting by $P_{e,pac}(i,j)$ the packet error rate (PER) for the link between $i$ and $j$, the probability for node $i$ to receive $k$ successive packets transmitted from node $j$ is $p_{suc}(i,j) = (1 - P_{e,pac}(i,j))^k$. Hence we can lower bound the miss-detection probability, $p_{mis}$, by choosing $k$ such that $p_{suc}(i,j) < p_{mis}$. Since $P_{e,pac}(i,j)$ is difficult to estimate before a link between nodes $i$ and $j$ has been established, a maximal expected PER, $p_{e,max}$, based on transmission range of the system (see Section III-B) can be used. Thus, as a pragmatic solution we suggest the selection of $b_1$ such that

$$
(1 - p_{e,max})^{b_1} > 1 - p_{mis},
$$

where $p_{mis}$ is set according to the tolerated miss-detection rate in worst-case links. On the other hand, node $j$ is removed from the CL of node $i$ if node $i$ did not receive a packet transmitted from $j$ in the last $b_2$ TDMA frames. Since the probability of receiving at least one packet in $k$ frames is given by $1 - (P_{e,pac}(i,j))^k$, we adjust $b_2$ according to

$$
(p_{e,max})^{b_2} < p_{drop},
$$

where $p_{drop}$ represents an acceptable dropping probability for the expected worst-case link.

Figure 2 shows $b_1$ and $b_2$ according to (4) and (5), respectively. Results are shown as a function of the transmission range and two different levels of $p_{mis}$ and $p_{drop}$, where $p_{e,max}$ was determined according to the derivations in Section III-B using the system and channel parameters given in Section IV-A1. We note that in our system only high values of $p_{mis}$ and $p_{drop}$ are considered since (i) these apply for worst-case links and (ii) the values of $P_{e,pac}(i,j)$ are high for transmission ranges above 1 Km, which are of our interest.

3) **Fast Topology Variations:** Applying the above sensitivity mechanism introduces a delay in the update of CLs. The values of $b_1$ and $b_2$ can be regarded as the convergence parameters of the scheduling protocol, since the process of recovery from topology changes does take on the order of $b_1$ and $b_2$ TDMA frames for adding and removing links, respectively. However, when topology changes faster than the convergence time of the protocol or when topology updates bearing packets are lost, CLs may be outdated, and scheduling conflicts may occur. Furthermore, multihop routes would break resulting in packet losses. To account for these fast topology variations, we extend the sensitivity mechanism beyond neighbor nodes such that if a node $i$ did not receive a packet (via a single or multiple hops) from node $j$ in $b_3$ TDMA frames, it refrains from transmitting in slot $j$. In doing so, the protocol degenerates to conventional TDMA in situations where topology updates are outdated. The value $b_3$ trades off robustness to
fast topology variations (increases with smaller $b_3$) and availability gain over conventional TDMA also in case of packet losses. A pragmatic choice is $b_3 = h \cdot b_2$, where $h$ is the maximal number of hops in the network.

4) Multiple Access Interference (MAI): Because of DSSS signaling and thus CDMA ability available in UWAC modems, the HSR-TDMA protocol permits secondary conflicts. However, strong MAI created by nodes in close proximity to a receiver may prevent proper message decoding, which is known as the near-far problem [16]. The high signal attenuation in the underwater acoustic channel renders the near-far problem more challenging than in radio networks, as it may occur even for small differences in distance to a common receiver. We note that adaptation of transmission power and spreading length, as applied in [16] for unicast transmission, is not applicable to deal with the near-far problem in the broadcast case considered here.

We refer to the receiver node in a near-far situation as the center node, the nearby nodes (which cause the problem) as the interfering nodes, and the more distant nodes whose transmissions are blocked as the jammed nodes. As an example, consider Topology 5 in Figure 8, where node 1 is located further away from node 2 than node 4. Here, nodes 1, 2, and 4 are the jammed node, the center node, and the interfering node, respectively.

As a result of the near-far effect, a jammed node appears to be connected to the center node, but not vice-versa. That is, the connectivity matrix $C$ becomes asymmetric as discussed above. Unlike temporal instabilities of $C$ due to flickering or short-term interference, asymmetry due to MAI is stable. Hence, the identities of the center, interfering, and jammed nodes can be detected from observing long-term asymmetric components of $C$. After this detection step, the near-far situation is resolved by virtually connecting the interfering and jammed nodes in the connectivity matrices of these nodes, so that only one of these nodes is allowed to transmit in every time slot. This is accomplished using the weighting mechanism of the HSR-TDMA protocol (see Section II-C). In the example above, we virtually connect nodes 1 and 4, which forces them to transmit in different time slots and eliminates the near-far conflict. After remedying the near-far situation, $C$ becomes symmetric again. The interfering and jammed nodes maintain their time sharing mode until the near-far problem disappears due to topology changes.

5) Islands: It can also occur that transmissions from a certain node are no longer received by any other node, which we refer to as an island node. Since island nodes are identified based on $C$, the detection time is a function of the parameter $b_2$ from (5). Since assigning time slots to an island node is inefficient, the TDMA time slot of an island node is reused. Upon detecting an island node, another node will be declared as the slot node for the corresponding time slot, again applying the weighting mechanism of the HSR-TDMA protocol, and the rest of the networks nodes will adapt their joining node status accordingly. In order to give the island node a chance to re-connect to the network, in every second TDMA frame no other node will acquire the island node’s time slot. We note that an island node does not need to take any action to rejoin the network other than transmitting in its designated time slot. Since the island node’s designated time slot remains idle in every second TDMA frame, once the node is in the range of the other network nodes, its transmission can be detected and the process of including the node into the network schedule is treated like a topology change.
F. Pseudo-code for the HSR-TDMA Protocol

The pseudo-codes for the connectivity matrix update and the scheduling for the HSR-TDMA protocol are shown in Algorithms 1 and 2 below (for clarity, the cases of dealing with fast topology variations and island nodes are omitted).

a) Algorithm for Connectivity Matrix Update: The procedure to update $C$ and the CL of node $i$ is described in Algorithm 1. From the packet arriving from a node $j \neq i$ the CL of node $j$ is extracted and used to update the $j$th row of $C$ at node $i$ (lines 8 and 9). Furthermore, for slot nodes $j$ counters $r_j$ and $q_j$ are incremented (lines 14, 16) or decremented (line 20), depending on whether a packet has been successfully transmitted from that node. Note that, to expedite the discovery of new links and thus avoid collisions, $r_j$ is incremented for every received packet. At the end of the TDMA frame, the CL of node $i$ is updated according to the value of the counters $r_j$ and $q_j$ (lines 26-33). Finally, the hop-distance matrix $H$ is computed (line 34) and the CL of $i$ is included in outgoing broadcast packets (line 35).

b) Algorithm for Scheduling in HSR-TDMA: The procedure of scheduling in the HSR-TDMA protocol is described in Algorithm 2. First, it is checked whether node $i$ is the slot node (line 3) or a joining node in time slot $t$ (lines 8, 9), using the symmetrized connectivity matrix $C_{\text{sym}}$ (line 2). Then, based on the non-symmetrized $C$, possible near-far conflicts are determined and resolved using the weighting mechanism (lines 10-20). If the node is a slot node or a joining node, it is scheduled to transmit in time slot $t$ (lines 5 and 22).

III. ANALYSIS OF THE HSR-TDMA PROTOCOL

Having presented the HSR-TDMA protocol, in this section we derive analytical expressions for its pertinent performance parameters, namely availability, reliability, and finally STR performance.

A. Availability for the HSR-TDMA Protocol

The availability for a node is determined by the number of time slots in a TDMA frame in which the node transmits. A node $i \in \mathcal{N}_{\text{nodes}}$ is assigned as slot node in slot $t = i$ and a candidate joining node for slots $t \neq i$ if and only if

$$
\eta_{t,i} = (h_{t,i} + 1) \mod 2
$$

is equal to 1. The number of nodes with which it competes for becoming a joining node can be expressed as

$$
z_{t,i} = \sum_{j=1}^{\mathcal{N}_{\text{nodes}}} \eta_{t,j} \mathbb{1}(h_{t,j} = 1) \mathbb{1}(t \neq i),
$$

where $\mathbb{1}(x)$ is the truth function, which is 1 if the proposition $x$ is true, and 0 otherwise.

Assuming that weights (see Section II-C2) are assigned such that absolute fairness is achieved, node $i$ wins the competition with probability $1/(z_{t,i} + 1)$. Hence, the average number of time slots per frame given to node $i$ follows as

$$
N_i = \frac{\mathcal{N}_{\text{nodes}}}{\sum_{t=1}^{\mathcal{N}_{\text{nodes}}} \frac{\eta_{t,i}}{z_{t,i} + 1}}.
$$
Algorithm 1 Connectivity matrix update at node $i$, for one TDMA frame with $N_{\text{nodes}}$ slots

1: // $r_j$, $q_j$, $j = 1, \ldots, N_{\text{nodes}}$, $j \neq i$, are counters for received packets from node $j$
2: // Loop over slots in one TDMA frame
3: for ($t = 1$ to $N_{\text{nodes}}$, $t \neq i$) do
4:   // Loop over nodes
5:   for ($j = 1$ to $N_{\text{nodes}}$, $j \neq i$) do
6:     // Update connectivity matrix according to received CLs
7:     if ($j$ is the source of an arriving packet) then
8:       Extract CL $L_j$ from packet
9:       $C_j := L_j$ // $C_j$ is $j$-th row of $C$
10:    end if
11:   // Update CL, considering slot node
12:   if ($j$ is the transmitter of an arriving packet) then
13:     // Increment counters ($b_1$ and $b_2$ are according to (4) and (5))
14:     $r_j := \min (r_j + 1, b_1)$
15:     if ($j = t$) then
16:       $q_j := \min (q_j + 1, b_2)$
17:     end if
18:   else
19:     if ($j = t$) then
20:       $r_j := \max (r_j - 1, 0)$, $q_j := \max (q_j - 1, 0)$
21:     end if
22:   end if
23:   end for
24: end for
25: // At the end of each TDMA frame, add and remove nodes from connectivity list
26: for ($j = 1$ to $N_{\text{nodes}}$, $j \neq i$) do
27:   if ($r_j = b_1$) then
28:     $c_{i,j} := 1$
29:   end if
30:   if ($q_j = 0$) then
31:     $c_{i,j} := 0$
32:   end if
33: end for
34: Generate $H$ using Dijkstra algorithm over $C$
35: Include CL $C_i$ in outgoing packets

B. Reliability for the HSR-TDMA Protocol

1) Orthogonal CDMA: We first consider the idealized scenario of CDMA with orthogonal spreading sequences, i.e., zero MAI, and a direct link from a node $i$ to a node $j$, i.e., $h_{i,j} = 1$. Neglecting intersymbol interference, the symbol error probability (SEP) is determined by the per-symbol SNR, $\gamma(i,j)$, for transmission from $i$ to $j$. For example, for $M$-ary pulse amplitude modulation (PAM) we obtain [30]

$$P_{e,\text{sym}}(i,j) = \frac{M - 1}{M} \text{erfc} \left( \sqrt{\gamma(i,j)} \right).$$

(9)
Algorithm 2 HSR-TDMA function at node $i$ during time slot $t$

1: // Enforce symmetric connectivity matrix
2: $C_{\text{sym}} := C \ast C^T + (C + C^T) \mod 2$  // $\ast$ denotes the Hadamard product operation
3: if ($t == i$) then
4: // Node $i$ is slot node
5: Transmit
6: else
7: // Check whether node $i$ is joining node
8: Compute $K_{i,t}$ from (2) for $j \in \mathcal{N}_{\text{nodes}}, j \neq t$, based on $C_{\text{sym}}$
9: Compute $I_t$ according to (3)
10: if ($i \in I_t$) then
11: // Check whether there is a near-far problem, based on $C$ from Algorithm 1
12: $M := \{m|m \in I_t, h_{t,m} = h_{t,i} \pm 2\}$
13: for ($m \in M$) do
14: $Q := \{j|c_{j,m} = 0, c_{j,i} = c_{m,j} = 1\} \cup \{j|c_{j,i} = 0, c_{j,m} = c_{i,j} = 1\}$
15: if ($Q \neq \emptyset$) then
16: if ($w_{i,t} < w_{m,t}$) then
17: EXIT
18: end if
19: end if
20: end for
21: // Node is joining node
22: Transmit
23: end if
24: end if

Assuming the application of forward error correction that can correct up to $q$ errors, the error probability for packets (PEP) for a direct link from $i$ to $j$ is given by

$$P_{e,\text{pac}}(i, j) = \sum_{e=q+1}^{N_{\text{sym}}} \left( \frac{N_{\text{sym}}}{e} \right) (P_{e,\text{sym}}(i, j))^e (1 - P_{e,\text{sym}}(i, j))^{N_{\text{sym}}-e}, \quad (10)$$

where $N_{\text{sym}}$ is the number of encoded symbols in a packet.

We now can use (10) to obtain the fraction of packets that arrive successfully in a broadcast transmission using multihop. To this end we assume that the routing protocol has determined a route to transmit a packet from a source node $S$ to destination node $D$ through relay nodes $i_k, k = 1, \ldots, L_{S,D} - 1$, where $L_{S,D}$ is the number of hops. While a discussion of the routing mechanism is beyond the scope of this paper, we note that the analysis does not depend on the specifics of the routing protocol. For example, considering the routing of packets from node $S = 1$ to node $D = 3$ in Topology 2 in Figure 8 using shortest hop-distance routing [31] based on matrix $H$, we have $L_{S,D} = h_{S,D} = 2$ and $i_1$ can be either node 2 or node 4. The PER can be expressed as

$$P_{e,\text{pac}}(S, D) = 1 - \prod_{k=0}^{L_{S,D}-1} (1 - P_{e,\text{pac}}(i_k, i_{k+1})) \quad (11)$$
where $i_0 = S$ and $i_{L_0,D} = D$. Since all packets are broadcast, the success rate for a source node $S$ is given by

$$\rho_{\text{suc},S} = \frac{1}{N_{\text{nodes}}} - \sum_{D=1, D \neq S}^{N_{\text{nodes}}} 1 - P_{e,\text{pac}}(S, D) . \quad (12)$$

2) Non-orthogonal CDMA: Even if orthogonal spreading sequences are used at different nodes for transmission, DSSS signals at UWAC receivers will not be orthogonal due to the effect of link-dependent channel impulse responses, and thus MAI occurs [4], [16]. We again consider a direct transmission from node $i$ to node $j$ and are interested in the per-symbol SINR $\gamma_{i,j}(t)$, which now is also a function of the time slot $t$. Another node $k \neq i, j$ transmits simultaneously, if and only if

$$\zeta_{i,k}(t) = \eta_{t,k} \mathbb{1}(h_{i,k} > 1) \prod_{(1 \leq \ell \leq N_{\text{nodes}}, \eta_{t,\ell}(h_{k,\ell} > 1) = 1)} 1 \mathbb{1}(\omega_{k,t} > \omega_{\ell,t}) , \quad (13)$$

is equal to 1. Hence, we can express the SINR as

$$\gamma_{i,j}(t) = \frac{P_{i,j}}{\sum_{k=1, k \neq i, j}^{N_{\text{nodes}}} \beta_{k,i} \zeta_{i,k}(t) P_{k,j} + P_{\text{noise}}/L_{\text{spread}}} \quad (14)$$

where $P_{i,j}$ denotes the signal power received at node $j$ from transmission at node $i$, which is a function of inter-node distance, frequency band, water salinity and temperature, and other parameters [1], [2], $P_{\text{noise}}$ is the noise power, and $\beta_{k,i}$ is the cross-correlation of the spreading sequences of nodes $k$ and $i$, which is usually inversely proportional with the spreading length $L_{\text{spread}}$ [30]. Note that (14) accounts for interference from all nodes transmitting in the same time slot. However, due to the large attenuation in underwater acoustic channels [1], we expect negligible interference from nodes located more than two-hops away from the transmitter.

To obtain an SINR expression independent of the weights $w_{i,t}$, which allows us to infer SINR directly from a given topology, we consider the average SINR for the link from node $i$ to node $j$. That is, we replace $\zeta_{i,k}(t)$ from (13) by

$$\bar{\zeta}_{i,k}(t) = \eta_{t,k} \mathbb{1}(h_{i,k} > 1) \times \frac{1}{z_{t,k} + 1} , \quad (15)$$

with $z_{t,k}$ from (7). Hence, we approximate the SINR in (14) with

$$\bar{\gamma}_{i,j}(t) = \frac{P_{i,j}}{\sum_{k=1, k \neq i, j}^{N_{\text{nodes}}} \beta_{k,i} \bar{\zeta}_{i,k}(t) P_{k,j} + P_{\text{noise}}/L_{\text{spread}}} \quad (16)$$

Substituting $\gamma_{i,j}(t)$ into (9) and using (10) leads to the PEP estimate $P_{e,\text{pac}}(i, j, t)$ for slot $t$, whose average

$$P_{e,\text{pac}}(i, j) = \frac{\sum_{t=1}^{N_{\text{nodes}}} \eta_{t,i} P_{e,\text{pac}}(i, j, t)}{\sum_{t=1}^{N_{\text{nodes}}} \eta_{t,i}} \quad (17)$$

is used in (12) to finally obtain an approximation for the success rate $\rho_{\text{suc},S}$ in non-orthogonal CDMA for all
\( S \in N_{\text{nodes}} \).

C. STR for the HSR-TDMA Protocol

The STR measures the rate of successfully delivered broadcast packets. Using the expressions for availability and reliability derived above, the normalized average STR measured as packets per node and time slot is given by

\[
\rho = \frac{1}{N_{\text{nodes}}} N_{\text{nodes}} \sum_{i=1}^{N_{\text{nodes}}} N_{i} \times \rho_{\text{succ},i}.
\]

D. Remarks on Fairness

In HSR-TDMA we reuse the spatial domain of the network to increase the number of time slots given to each node. Due to the underlying skeleton TDMA schedule, each node has a duty cycle of at least \(1/N_{\text{nodes}}\). Thus, HSR-TDMA avoids node starvation. However, the HSR-TDMA protocol does not achieve uniform fairness. For example, in the star topology 3 in Figure 8, node 2 has a significantly lower availability than the other nodes. Hence, nodes 1, 3, and 4 may not be able to use all available time slots for broadcasting messages since packets would not be re-transmitted by node 2. We note that this problem exists also in conventional TDMA. A possible remedy would be to assign more (or longer) time slots to node 2, which would be used to relay more packets and reduce average availability in favor of fairness. Clearly, such actions would require knowledge of traffic generation at each node and the applied routing scheme.

Alternatively, the scheduling problem \((1)\) could be modified to include a stronger notion of fairness. For example, the utility function

\[
f(x) = (1 - \xi)^{-1} x^{1-\xi},
\]

where the parameter \(\xi\) is typically large, is commonly used to achieve max-min fairness [32]. For the case considered here, the utility function in \((1a)\) could be replaced by \(\min_{i=1}^{N} f(x_i)\), where \(x_i\) is the number of time slots assigned to node \(i\).

IV. PERFORMANCE EVALUATION OF THE HSR-TDMA PROTOCOL

In this section, we present numerical results to demonstrate the performance of the proposed HSR-TDMA protocol, in particular in comparison to the conventional TDMA protocol. For a comprehensive and practically relevant evaluation, we have tested the protocols both in computer simulations and sea trial experiments.

A. Simulations

We first describe the simulation setup, in particular the system parameters, channel model, and the considered network topologies, and then present and discuss the simulation results.
1) System and Channel Model: We consider a UWAC transmission system that applies a signal bandwidth of 10 kHz and a transmitter intensity level of $SL = 155$ dB/µPa@1m (see [1, Ch. 2]). The ambient noise spectral density is assumed as $NL = 50$ dB/µPa/Hz, and we use the widely accepted transmission loss model [1, Ch. 5]

$$TL(d_{i,j}) = 10 \lambda \log_{10} \left( \frac{d_{i,j}}{1 \text{ m}} \right) + \alpha d_{i,j} \text{ dB},$$

(20)

where $d_{i,j}$ is the distance from node $i$ to node $j$, $\lambda$ is the propagation loss parameter, dependent on the underwater medium structure, and $\alpha$ is the absorption loss parameter, dependent on the carrier frequency, water salinity and water temperature among other factors. For simplicity, both $NL$ and $\alpha$ are assumed constant in the signal frequency band (an assumption that generally holds only for narrow band communication). Assuming typical parameters of $\lambda = 2$ and $\alpha = 3$ dB/km (which implies a carrier frequency of about 30 kHz [1]), we have a per-DSSS-chip SNR of, for example, $\gamma_{\text{chip}}(i, j) = 2$ dB for $d_{i,j} = 1000$ m.

The simulation system applies binary phase-shift keying (BPSK, $M = 2$) and DSSS signaling with Gold sequences of length $L_{\text{spread}} = 15$ at all nodes, so that a worst-case cross-correlation of $\beta_{i,j} = 0.38$ between sequences from nodes $i$ and $j$ results [30]. DSSS increases the per-symbol SNR to $\gamma(i, j) = \gamma_{\text{chip}}(i, j) L_{\text{spread}} = 13.8$ dB at $d_{i,j} = 1000$ m. An $(N_{\text{sym}} = 7, q = 1)$ Reed-Solomon code over $\mathbb{F}(2^3)$ is applied for error correction [see Eq. (10)].

2) Topologies: To consider different classes of network topologies, identified by the number of network nodes, we place nodes randomly in a square area of size $5 \text{ km} \times 5 \text{ km}$. Four horizontal obstacles and one vertical obstacle are included at random positions and with lengths being uniformly distributed in $[100, 200]$ m. Only two restrictions are applied when placing the network nodes: (i) A node must not be placed on an obstacle. (ii) There will be no island node. The latter constraint is applied to allow meaningful comparisons of the HSR-TDMA and TDMA protocols.

The connectivity matrix was created such that $c_{i,j} = 0$ if an obstacle obstructs the line-of-sight path between nodes $i$ and $j$ or if $d_{i,j}$ was such that, according to $TL(d_{i,j})$ in (20) and thus $\gamma(i, j)$, $P_{e,\text{pac}}(i, j) > 10^{-4}$ in (10). Multihop routing of the broadcast packets is performed based on a minimal hop-distance routing mechanism.

3) Simulation Results:

a) Fixed Topology: We first show performance results for the specific 10-node topology illustrated in Figure 1, which also shows the schedule for the HSR-TDMA protocol. Since this schedule varies over time due to the weighting mechanism in case of multiple candidate joining nodes (nodes 6, 7 and 9, 10 for this topology), results are averaged over multiple time frames.

Figure 3 presents the per-node STR $\rho, \frac{N_i}{N_{\text{nodes}}} \rho_{\text{pac},i}$, for the HSR-TDMA protocol with $N_i$ from (8), $\rho_{\text{pac},S}$ from (12), and $P_{e,\text{pac}}(i, j)$ from (10) and (17) for orthogonal CDMA and for non-orthogonal CDMA, respectively, as function of the source node. Also included is the per-node STR for conventional TDMA, which is approximately $1/N_{\text{nodes}} = 1/10$ for $\rho_{\text{pac},i} \approx 1$ for all nodes. The very good match of analytically obtained and measured per-node STR for HSR-TDMA confirms the expressions derived in Section III. Next, we observe the considerable advantage of HSR-TDMA over conventional TDMA scheduling in terms of STR for all nodes. The largest improvements are
obtained for nodes \{1, 3, 4, 8\}, which share the same time slots and have the largest maximal independent sets in the network graph. Nodes 9 and 10 are candidate joining nodes only in time-slots 2 and 5, in which they compete with each other. Therefore, they achieve the lowest STR, which is however still twice the STR for conventional TDMA. We note that the average STR over all nodes, i.e., \( \rho \) from (18) is increased by a factor of about 4.2.

b) Random Topology: We now consider networks with randomly generated topologies as described in Section IV-A2. More specifically, each 100 random networks with \( N_{\text{nodes}} = 3, \ldots, 10 \) nodes are generated to obtain indicative performance results. Figure 4 shows the average outage probability (averaged over source node index and topology) for the HSR-TDMA protocol. We observe that the assumption of orthogonal CDMA leads to somewhat optimistic results, especially for networks with relatively larger number of nodes. This is due to more secondary conflicts with increasing network size. For example, for \( N_{\text{nodes}} = 10 \) the average outage rate for HSR-TDMA with non-orthogonal CDMA is increased by a factor of 4 compared to HSR-TDMA with orthogonal CDMA (and thus conventional TDMA). Again, the analytical approximation from Section III-B2 provides fairly accurate performance estimates. The results for average STR, defined in (18), as a function of the number of nodes in the network, \( N_{\text{nodes}} \), are shown in Figure 5. It can be seen that the HSR-TDMA schedule leads to significant STR improvements compared to conventional TDMA. The results for HSR-TDMA with the orthogonal and realistic CDMA are almost indistinguishable, which is due to the relatively benign error rate deterioration in the latter case as seen in Figure 4. Also included in Figure 5 is the maximal achievable STR according to problem (1), i.e., when the optimal graph coloring solution mentioned in Section II-C1 is applied. We observe that the additional gain over HSR-TDMA is relatively little compared to the gain of HSR-TDMA over TDMA. In other words, the pragmatic HSR-TDMA solution performs very close to the optimal approach while having the advantages of lower complexity for relatively large networks and analytical tractability.

Finally, we observe that STR decreases with increasing \( N_{\text{nodes}} \) for all schedules shown in Figure 4. This phenomenon is well known for wireless ad-hoc networks, for which the per-node throughput has been shown to decrease as the number of nodes grows [33].

c) Topology Variations: To illustrate the behavior of the HSR-TDMA protocol in case of topology changes, we consider random topologies with \( N_{\text{nodes}} = 10 \) and add or remove a single link from the network graph. The adaptation of the protocol to the topology change is measured by means of the collision rate defined as

\[
\nu(t) = \frac{1}{L} \sum_{i=1}^{N_{\text{nodes}}} \Omega_i(t),
\]

where \( \Omega_i(t) \) is the number of collisions of packets originated from node \( i \) (new and relayed packets) at time slot \( t = 1, 2, \ldots \) after the topology change occurred, and \( L \) is the number of communication links in the network after the topology variation occurred. Figure 6 shows the average of \( \nu(t) \) as a function of \( t \), where the average is over all possible topologies and all possible one-link topology changes in a network of \( N_{\text{nodes}} = 10 \) nodes. The convergence parameters, \( b_1 \) and \( b_2 \), were chosen according to Figure 2 for a transmission distance of 1200m (i.e., \( b_1 = b_2 = 2 \)). Figure 6 shows an interesting phenomenon which is that first the collision rate increases after the topology change...
before it decreases to zero. This is due to the amount of discrepancy between topology information available at nodes, which first increases when updated topology information propagates through the network. We observe that in our simulations convergence to the new protocol occurred after a maximum of only 3.1 TDMA frames.

B. Sea Trial

To complement the simulation-based performance analysis, which necessarily assumed a simplified model of the underwater acoustic channel, we next present performance results from a sea trial that was conducted in May 2009 in the Haifa harbor shown in Figure 7.

1) Sea Trial Setup: The trial included four vessels, each of which represented an individual node in the network. The four vessels were placed in various locations inside the harbor and the transducers were located in a fixed depth of 3 m. The vessel locations were obtained based on GPS. The nodes sent frequent broadcast navigational messages, to which the current connection lists of the nodes were piggy backed. Each time slot consisted of a 5 seconds data packet followed by an idle time of 1 second accounting for the maximal propagation delay in the channel, and an additional (large) idle time of 9 second required for on-line decoding in our experimental setting. Hence, the TDMA frame was 1 minute. During the trial a greedy mechanism (cf. [34]) was used for routing packets.

We remark that we choose $b_1 = b_2 = 2$ according to Figure 2 for $p_{mis} = 0.8, p_{drop} = 0.3$, and 1200 m, which was the maximal transmission range in the harbor, and that nodes transmit their CLs with each broadcast packet to mitigate scheduling conflicts due to packet losses.

In order to test the network performance in various topologies, the vessels moved throughout the trial between the harbor docks (see Figure 7) into the six different topology structures illustrated in Figure 8. To create a dynamic scenario, we paused the operation of the network each time the vessels moved to a different location. The nodes saved their previous topology information such that when the network operation continued, the nodes assumed the previous topology still exists. Full connectivity between the network nodes (Topology 1 in Figure 8 and locations 1A, 2A, 3A, and 4A in Figure 7) was initially tested. In this state, the network was expected to function in a conventional TDMA fashion since all hop distances are one. Thus, each node was expected to transmit exactly once in every TDMA frame. Then, vessels 1 and 3 moved to locations 1B and 3B in Figure 7 so that the acoustic line of sight connection between nodes 1 and 3 disappeared (Topology 2 in Figure 8). During this part of the trial, flickering occurred when transmissions from node 1 were temporarily received in node 3 and vice versa, due to reflections from harbor docks and ship hulls. Next, vessel 4 moved to point 4B in Figure 7 creating a star-like topology around node 2 (Topology 3 in Figure 8). In this topology, node 2 was expected to transmit once in every TDMA frame while the rest of the nodes would transmit three times per frame, when using HSR-TDMA. Then, vessel 3 moved to point 3C in Figure 7 resulting in a tandem topology illustrated as Topology 4 in Figure 8. All nodes were expected to transmit twice in every TDMA frame. Moving vessel 1 to location 1C in Figure 7 created a near-far situation (Topology 5 in Figure 8), since the distance between nodes 1 and 2 was 1000 m while the distance between nodes 2 and 4 was only 300 m. It was expected that nodes 1 and 4 would sense the near-far problem and stop sharing the same time slot, and thus use one slot every TDMA frame. Finally, vessel 1 moved to point 1D in
Figure 7 in which no acoustic line-of-sight to the other network nodes existed. Hence, this topology (Topology 6 in Figure 8) included an island scenario. According to the HSR-TDMA schedule, the time slot of node 1 is shared equally between nodes 2, 3 and 4, while giving node 1 the chance to regain its time slot in every second TDMA frame. Thus, nodes 2 and 3 were expected to transmit 14 times in every 6 TDMA frames and node 4 would have 7 slots available in every 6 TDMA frames.

The above-described sequence of topologies was repeated for transmission with a conventional TDMA MAC (see [27] for details) to enable a comparison with the HSR-TDMA MAC protocol. We note that the same spreading factor ($L_{\text{spread}} = 15$) was applied for both protocols. In case of conventional TDMA, spreading allows reliable communication under worst-case channel conditions. HSR-TDMA makes opportunistic use of this for the purpose of collision resolution if the channel quality permits, i.e., if the link is not noise limited.

2) Sea Trial Results: We now present the measured performance results from the sea trial, comparing conventional TDMA and the proposed HSR-TDMA protocol.

Figure 9 shows the availability achieved with the HSR-TDMA protocol for nodes 1 to 4 in the six different topologies described above and illustrated in Figure 8. Availability was measured by counting the number of available slots for transmission for each node according to the present connectivity matrix. Note that the availability for TDMA is $1/4$ for all nodes regardless of the topology. We observe that, depending on the topology, substantial increases of network availability are achieved with HSR-TDMA compared to conventional TDMA. For example, in Topology 3 (see Figure 8) nodes 1, 3 and 4 have even hop-distance to each other and thus benefit from threefold spatial reuse. In Topology 4 all nodes are able to transmit in about two time slots per TDMA frame. In Topology 6, node 1 disappeared from the connection list of all nodes, which was detected by other nodes which successfully reused its time slot.

In Figure 10, the average availability results from Figure 9 are shown for each topology and compared with the expected average availability according to (8) and assuming connectivity matrix $C$ according to Figure 8. A good match between measurements and expected results can be observed, with the measured availability results being consistently slightly above the analytical values. This small bias is due to the flickering effect due to low SNR and SINR conditions during the trial, which resulted in temporarily sparser connectivity matrix $C$ with potentially larger spatial reuse. The effect of network topology changes on availability is highlighted in Figure 11, which shows availability on a per-TDMA frame basis for the duration of the trial. We observe notable fluctuations during fixed vessel configurations, and the transitions between vessel configurations are clearly visible. While the former emphasizes on the time-variant nature of UWAC network topologies even in a seemingly static scenario, the latter demonstrates the ability of the proposed protocol to track topology changes.

Next, Figure 12 shows the average outage rate for the different topologies. (We neglect the contribution of node 1 to the average outage rate in the sixth topology since it was disconnected from the network.) It can be seen that in all cases outage rates are relatively high, which is a result of the harbor’s regulations, which limited the transmitted power, and the high level of ambient noise in the harbor. When comparing TDMA and HSR-TDMA, we observe a notable degradation in outage rate for topologies with large spatial reuse gain, i.e., topologies 3 and 4, and for
Topology 5 due to the near-far problem at node 2 whose detection and mitigation requires some transition time.

The effective gain due to the use of HSR-TDMA compared to conventional TDMA is manifest in Figure 13, which presents the measured average STR for the different topologies. While TDMA and HSR-TDMA STRs are almost identical for the first topology, for which the HSR-TDMA schedule essentially falls back to conventional TDMA, the STR is greatly improved by the proposed protocol for the other topologies. The greatest improvements are obtained for the third topology structure, where three nodes can transmit simultaneously in three out of four slots.

V. CONCLUSION

In this paper, we have presented a novel TDMA protocol suitable for UWAC networks. We have focussed on applications that require high-traffic broadcast communication. To improve network throughput, the proposed protocol applies spatial reuse TDMA. It also makes use of DSSS signaling in UWAC systems, which enables the integration of CDMA leading to a hybrid MAC scheme. Robustness to topology changes and a certain level of fairness is achieved by imposing a skeleton TDMA schedule. We have derived analytical expressions for availability, reliability, and STR afforded by the new protocol. Numerical performance results obtained for synthetic and real-life UWAC transmission scenarios have demonstrated that the proposed protocol consistently and significantly outperforms the conventional TDMA protocol. Future directions of this work include the study of different fairness measures for MAC in broadcast UWAC networks where throughput is of interest, taking flow constraints into account.

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Fig. 1. Example of a 10-node topology and the use of TDMA slots with the HSR-TDMA protocol. Distances for results in Section IV-A3a:
\[ d_{1,2} = 2288 \text{ m}, \quad d_{2,3} = 2042 \text{ m}, \quad d_{2,4} = 2045 \text{ m}, \quad d_{4,5} = 2076 \text{ m}, \quad d_{5,6} = 2073 \text{ m}, \quad d_{5,7} = 2279 \text{ m}, \quad d_{5,8} = 2105 \text{ m}, \quad d_{6,7} = 2073 \text{ m}, \]
\[ d_{6,9} = 2105 \text{ m}, \quad d_{8,9} = 2249 \text{ m}, \quad d_{9,10} = 2165 \text{ m}. \]

Fig. 2. Convergence parameters \( b_1 \) and \( b_2 \) vs. transmission range

Fig. 3. Per-node STR for the topology from Figure 1.
Fig. 4. Average outage probability $\frac{1}{N_{\text{nodes}}} \sum_{S=1}^{N_{\text{nodes}}} (1 - \rho_{\text{Suc},S})$ for 100 random networks with $N_{\text{nodes}} = 3, \ldots, 10$ nodes. Note that HSR-TDMA with orthogonal CDMA has the same outage probability as conventional TDMA.

Fig. 5. STR $\rho$ from (18) for 100 random networks with $N_{\text{nodes}} = 3, \ldots, 10$ nodes. "Optimal TDMA" refers to the exact solution of (1) using a graph coloring approach (see Section II-C1).
Fig. 6. Average collision rate $\nu(t)$ for $N_{\text{nodes}} = 10$ and $b_1 = b_2 = 2$.

Fig. 7. Satellite picture of the sea trial location (picture taken from Google maps on September 29, 2009.) The different locations of the vessels (and thus network nodes) for creating the different topologies shown in Figure 8 are marked.
Fig. 8. Topologies tested during the sea trial corresponding to vessel locations shown in Figure 7.

Fig. 9. Measured availability $N_i/N_{\text{nodes}}$ (in percent) for the HSR-TDMA protocol, for $i = 1, \ldots, N_{\text{nodes}} = 4$ and the six sea trial topologies illustrated in Figure 8.
Fig. 10. Measured and computed average availability \( \frac{1}{N_{\text{nodes}}} \sum_{i=1}^{N_{\text{nodes}}} N_i/N_{\text{nodes}} \) (in percent, \( N_{\text{nodes}} = 4 \)) for the HSR-TDMA protocol and the six sea trial topologies illustrated in Figure 8.

Fig. 11. Measured availability (in percent) per time frame for the HSR-TDMA protocol during the sea trial. Vertical dashed lines indicate the times when the topology change occurred.
Fig. 12. Measured average outage probability \( \frac{1}{N_{\text{nodes}}} \sum_{S=1}^{N_{\text{nodes}}} (1 - \rho_{\text{suc},S}) \) \( (N_{\text{nodes}} = 4) \) for the six sea trial topologies illustrated in Figure 8.

Fig. 13. Measured STR \( \rho \) for the six sea trial topologies illustrated in Figure 8.