A Hybrid Spatial Reuse MAC Protocol for Ad-Hoc Underwater Acoustic Communication Network

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Abstract—We present a medium access control (MAC) protocol for underwater acoustic ad-hoc network that reuses the spatial domain of the network to improve network throughput. Conventional protocols for high traffic networks use a network-wide time division multiple access (TDMA) scheme in which only a single node transmits at each time. In the proposed protocol, selected additional nodes can transmit simultaneously to the assigned node, thus improving the efficiency of the MAC protocol. By tracking the time-varying network topology, our protocol, named Hybrid Spatial Reuse TDMA (HSR-TDMA), adaptively optimizes the set of active nodes and overcomes problems of underwater acoustic communication networks such as the near-far problem, flickering, and formation of islands. Both the conventional TDMA protocol and the proposed protocol were tested in a sea trial at the Haifa harbor in Israel. The results show that the new protocol greatly increases the availability of nodes to transmit messages, which leads to an improved overall network throughput in high traffic networks.

I. INTRODUCTION

Underwater communication is becoming popular as a research area due to the many applications that require underwater communication such as oceanography data collection, ocean exploration, underwater navigation and control over Autonomous Underwater Vehicles (AUV). Long communication ranges are only possible through the use of acoustic waves since radio frequency communication does not propagate well underwater. UnderWater Acoustic Communication (UWAC) is governed by several factors such as long delay spread, fast time varying channel, long propagation delay and limited signal bandwidth [1]. These factors pose engineering challenges that are very different from those experienced in radio frequency wireless networks such as high collision rate and high latency.

The time-varying topology structure and high outage rate makes centralized UWAC network control difficult and ad-hoc MAC protocols are required [4]. The narrow bandwidth available for UWAC [3] and the design constrains of the acoustic transducers [5], motivates focusing on solutions in the time domain or in the code domain.

In this work we regard applications such as sharing navigation information, command and control and safety ‘alive’ messages for diver’s security. We note that for these applications high traffic network is required since most packets are broadcast. Surprisingly, although such applications are commonly used, there hasn’t been much study on the problem of availability in UWAC network design. In fact, most existing protocols focus on reliability and latency issues for low traffic networks and the need to establish fast secure links [2]. Our main objective is to optimize the system’s throughput such that the number of received correctly packets will increase.

A commonly used MAC protocol for contention-free UWAC networks is the Time Division Multiple Access (TDMA) protocol [4], where the time is slotted to TDMA cycles and each node is assigned to a unique time slot in which only it is allowed to transmit. Although reliable, the TDMA’s throughput is low and latency is high since the TDMA’s cycle duration is generally large for even short communication range.

The most commonly used collision-avoidance protocols are the handshake type protocols [7]. Before transmitting, the node sends a Request To Send (RTS) message to the destination node and transmits only upon the reception of a Clear To Send (CTS) message. Handshake protocols achieve high reliability. Still, they do not allow simultaneous transmissions from different nodes, much like the TDMA protocol, resulting in low network availability. Furthermore, for high traffic networks the TDMA scheme will achieve better results since the network is fully used.

In [9] a hybrid Aloha-CDMA MAC protocol is described. In this protocol header packets are sent in a random fashion (i.e., Aloha) before the transmission of the data packets in a CDMA fashion. The transmitter optimizes its pseudo-random sequences length and transmitted power to minimize Mutual Access Interference (MAI). Unlike the scenario presented in [9] where all transmissions are unicast, we cannot assume separate destinations for different sources and this analysis does not hold for our case.

In this paper we continue the line of research introduced at [8]. This protocol augments the network’s throughput when clustering the network is possible without the need for handshaking. Each node is assigned to a cluster such that the communication between the cluster’s nodes is based on TDMA and adjacent clusters uses orthogonal modulation symbols in a CDMA fashion. Using multiple access to the channel, the availability dramatically increases. However, temporal topology changes might result sensitivity to false cluster assignments and high MAI may occur. In addition, when the number of nodes in a cluster is not the same, the full spatial reuse is
not exploited.

Our protocol is a hybrid protocol in the sense that it combines the TDMA and CDMA techniques at the same time regardless of the node’s location in the network. Although we assume that in certain topology structure the network can be clustered, differently from [8], we use mesh-type protocol. Mesh-type protocols usually provide lower bound on system’s throughput even when the network’s topology structure is unknown, and allow general and robust solutions. To the best of our knowledge this is the only protocol that exploits the spatial reuse of the network in a mesh-type fashion, suitable for ad-hoc networks. Although hybrid TDMA-CDMA for UWAC was introduced first at [8], this is the first attempt to combine the two protocols in the time domain.

The remaining of this paper is organized as follows. Section II describes our protocol and its solution to the UWAC challenges. In Section III we present results from sea trial comparing our protocol to the commonly used TDMA protocol. Finally, conclusions are drawn in Section IV.

II. THE HSR-TDMA PROTOCOL

The core idea of the HSR-TDMA protocol is to rely on the TDMA’s protocol as a basic common protocol for all nodes in order to a-priori set a designated node, defined as the slot node, for each time slot while adaptively identifying the available nodes that can transmit at the same slot without resulting collisions. These nodes are defined as joining nodes for this time slot, while the rest of the network nodes are defined as receiving nodes. The classification of the network’s nodes is performed in an ad-hoc fashion, based on a shared time-varying connectivity matrix which updates whenever a change in the network’s topology occurs. By combining TDMA and CDMA in a mesh-type, we simply reuse the topology structure of the net. Since the protocol reuses the spatial domain of the network, we define it as Hybrid Spatial Reuse Time Division Multiple Access (HSR-TDMA) protocol.

The basic assumptions of the HSR-TDMA protocol are: 1) The network’s connectivity matrix, \( C \), is slow time varying and 2) Up until a certain limit, each node can decode parallel transmissions from its neighbors. Since current systems use DSSS for TDMA protocols as well as for point-to-point applications [9], there is no time or bandwidth overhead for the HSR-TDMA protocol. However, as we describe later, higher MAI exists.

We derive \( C \) for each node in an ad-hoc fashion using each node’s connection list, CL, which is a list of all nodes connected directly to node \( p \). Each node creates an adaptive CL by identifying the source of each received packet. The CL is intensively shared by including it in every outgoing packet. Assuming multi-hop relays, each node can extract the most recent available CL of each node and track topology changes in the network. We define the \( i,j \) element of \( C \), \( c_{i,j} \), to be ‘1’ when a connection exists between nodes \( i \) and \( j \) and ‘0’ otherwise. \( C \) is used to calculate a minimal hop-distance matrix, \( H \), such that its elements, \( h_{i,j} \), are the minimal number of hops required for transmitting a packet from node \( i \) to node \( j \). Using Minimal Spanning Tree (MST) techniques, such as DIJKSTRA algorithm [10] over \( C \), \( H \) is efficiently created.

In each time slot, a pre-determined slot node transmits regardless of the current network’s topology. Assuming the orthogonality of the node’s transmissions to be limited only by the half duplex nature of the physical layer, the adaptive classification of the network’s nodes in each time slot to joining nodes and receiving nodes is based on their hop-distance, derived from \( H \), to the slot node. Nodes with even hop-distance to the slot node are nominees to join its transmissions, while nodes with odd hop-distance to the slot node are set to be receiving nodes. Since the slot node is replaced in a deterministic order in every time slot, fairness is achieved.

In cases where nodes with even hop-distance to the slot node are neighbors (see for example nodes 6 and 7 in Figure 1), due to the half duplex constrain, only one of these nodes can be a joining node. Therefore, each ‘nominee’ joining node, ‘competes’ in every time slot against the others using a monotonic one to one function, \( W_i[n], n = 1, 2, \ldots N_{nodes} \), where \( N_{nodes} \) are the number of nodes in the network and \( t \) is the current TDMA cycle number. For a ‘nominee’ joining node \( n \), a slot node \( s \), and for a set \( K \) such that \( k < K, k \neq n \) if \( c_{n,k} = 1 \) and \( h_{n,k} = h_{k,s} \), the decision is performed according to the following set of rules:

1) If \( h_{n,s} \mod 2 = 0, \text{rank}(K) = 0 \), then \( n \) is a joining node.
2) If \( h_{n,s} \mod 2 = 0, \text{rank}(K) > 0 \), and \( W_i[n] > W_i[k] \), than \( n \) is a joining node.

In order to achieve fairness, \( W \) must be as random as possible, such that for the next comparison a different node will be selected. In this manner, for each selection of slot node the optimal solution is achieved in terms of availability.

A. Algorithm for the HSR-TDMA protocol

To summarize the steps of the HSR-TDMA protocol the algorithm run by node \( p \) is presented in this subsection. Start by initializing the network’s connectivity matrix, \( C \), such that all elements are equal to 1 and a counting vector \( V \), such that all elements are equal to the a-priori value \( b[0] \). At time slot \( j \) execute the following:

1) If \( p = j \) transmit in this time slot and stop.
2) Calculate unique random weight vector, \( W \).
3) For each node \( i, i \neq j \) run steps 4-7.
4) Create hop-distance matrix \( H \) using \( C \).
5) If \( h_{i,j} \) is odd stop.
6) Set \( n \in N \) such that \( c_{n,i} = 1, h_{n,j} = h_{i,j} \).
7) If \( W_i < W_n \) stop, otherwise set \( i \in Y \).
8) If \( p \notin Y \) than stop.
9) Set \( m \in M, M \in Y \) such that \( h_{m,j} = h_{p,j} \pm 2 \).
10) Set \( q \in Q \) if \( c_{q,m} = 0, c_{q,p} = c_{m,q} = 1 \).
11) Set \( q \in Q \) if \( c_{q,p} = 0, c_{q,m} = c_{p,q} = 1 \).
12) If \( Q \neq \emptyset \) include \( m \in X \).
13) If \( W_p < W_x, x \in X \) than stop.
14) Transmit in this time slot.
B. Example for the HSR-TDMA protocol

Let us examine the complex topology structure appears in Figure 1. In most time slots, several nodes were picked as 'joining nodes', enlarging the overall availability relatively to simple TDMA by decreasing the average delay time of a node between adjacent transmissions. In fact, only when bottleneck nodes, such as nodes 2 and 5, were involved, less than five nodes transmitted in the same time slot. From Figure 1 we also observe that the neighbor nodes 6 and 7 are in equal hop-distance to each of the network's nodes. Thus, only one of them can join the 'slot node' transmissions at each time. The average transmission slot number for each node was 4.2 greater than in the TDMA protocol. An interesting observation is that the HSR-TDMA protocol’s performance improves as the topological structure is more complex, i.e., the connectivity matrix is more sparse, since the reuse of the network’s spatial domain increases.

C. Quality measure for high traffic networks

For high traffic communication network, reliability and availability are both of high importance. However, like in the simple TDMA case, there exist a tradeoff between the two measures. We observe that in high traffic network system the secure transmission of one single packet is not as important as the delivery of as many packets as possible. Therefore, we are interested in a measure that reflects the number of properly received packets in each node for a certain amount of time. Such measure can be the system’s throughput.

Since each node transmits at least one packet whenever possible, the number of transmitted packets from node $i$ is

$$N_i = \rho_{\text{availability},i} \cdot \frac{T}{T_{\text{slot}}}, \quad (1)$$

where $\rho_{\text{availability},i} = \frac{N_{\text{slot},i}(T) \cdot T_{\text{slot}}}{T}$, $N_{\text{slot},i}(T)$ is the number of time slots assigned to node $i$ at the time interval $T$ and $T_{\text{slot}}$ is the duration of a time slot (where we assume all time slots to be equal). The average number of received packets is

$$\bar{N}_i = N_i \cdot (1 - \rho_{\text{outage},i}(T)), \quad (2)$$

where $\rho_{\text{outage},i}(T)$ is the average outage rate of node $i$. Since all messages were broadcast messages,

$$\rho_{\text{outage},i}(T) = \frac{E[N_{\text{error},i}(T)]}{N_{\text{node}} - 1}, \quad (3)$$

where $E[N_{\text{error},i}(T)]$ is the average number of nodes that failed to receive messages from node $i$ in time interval $T$.

From (1) and (2) and for a fixed $T$ and $T_{\text{slot}}$, the throughput is

$$\rho = \frac{1}{N_{\text{node}}} \sum_{i=1}^{N_{\text{node}}} (1 - \rho_{\text{outage},i}) \cdot \rho_{\text{availability},i} \cdot \frac{T}{T_{\text{slot}}}, \quad (4)$$

Note that $\rho$ is normalized such that performance are better for larger values.

Assuming a full $C$, i.e., all nodes are connected to each other, a maximum can be derived to (4). Consider a perfect CDMA system and $n$ transmissions in each time slot. Due to the half duplex nature of the UWAC sensors, only $N_{\text{node}} - n$ can detect the ongoing messages in each time slot. Thus,

$$\rho = \frac{N_{\text{node}} - n}{N_{\text{node}}} \cdot \frac{n}{N_{\text{node}}} \cdot \frac{T}{T_{\text{slot}}}. \quad (5)$$

Maximum $\rho$ is achieved for $n = \frac{N_{\text{node}}}{2}$. Thus, despite the half duplex communication, better performance are achieved when $\frac{N_{\text{node}}}{2}$ nodes transmit together.

In [6] we presented such a protocol for the case of full $C$. However, for sparse $C$ this analysis does not hold and it is more complex. We leave maximization analysis for the general $C$ for future work.

D. Flickering and islands in the HSR-TDMA protocol

The stability of the HSR-TDMA protocol is based on the existence of unique connectivity matrix for all network’s nodes. However, when a link is unstable due to low SINR, node’s movements or channel time-varying distortions, fast time-varying topology changes occur and the topological information of each of the network’s nodes will not be unique. This situation is sometimes referred as the ‘flickering’ problem.

We account for the ‘flickering’ problem by setting an adaptive value $b[t]$ for each TDMA cycle, $t$, such that only when $b[t]$ adjacent packets arrive from a neighbor node, the connection list will include it. The value of $b[t]$ determines the convergence rate of the protocol when topology change occur. The value $b[t]$ marks our belief in the quality of the link connection. We suggest an adaptive ad-hoc estimation of $b(p,q)[t]$ performed at node $p$ for a neighbor node $q$ such that its value is determined by the temporal link’s packet error rate,

$$1 - P_{\text{packet}}(d_{p,q}) \cdot b(p,q)[t] > T_h, \quad (6)$$

where $T_h$ is an empiric threshold value and $P_{\text{packet}}(d_{p,q})$ is the evaluated packet error rate. Thus, $b(p,q)[t]$ can be associated with the evaluation of $d_{p,q}$.

Due to node movements or time domain changes in the underwater acoustic channel characteristics, a node can be erased from the connectivity matrix, i.e., there exists no node

![Fig. 1. Analysis results of HSR-TDMA protocol for complex topology structure.](image-url)
that receives its transmissions. Such node is also called *island node* since no node receives the isolated node’s transmissions. The detection of an *island node* is performed by looking for unconnected nodes in $C$. We reuse the *island node’s* time slot by dividing its slot between the network’s nodes. Upon detecting the *island* node, a new node will be declared as the *slot node* (instead of the *island node*) in a periodic fashion, and the rest of the networks nodes will adapt their transmissions accordingly. In order to allow the *island node* a chance to re-connect to the network’s node (for example, by relocation), at every second TDMA cycle, no node will acquire the *island node’s* time slot at the cost of reducing the availability.

### E. Mutual Access Interference in the HSR-TDMA protocol

Since propagation loss and absorption loss are both a function of the transmission range, scenarios where lower than required SINR values are possible when nodes are moving or when range differences are large. We are most concerned about strong MAI created by nodes at different transmission range. This scenario is referred to as the ‘Near-Far’ problem [9], since large range differences between separate nodes might cause this effect.

We define the receiver node in a ‘Near-Far’ situation as the *center node*, the closer nodes (which transmissions causes the interference) as the *interfering nodes* and the farther nodes which transmissions are blocked as the *jammed nodes*. Although the network’s connectivity matrix is generally a symmetric matrix, high value MAI might defect this symmetry. Thus, the identities of the *center node*, *interfering nodes* and *jammed nodes* can be detected by detecting long-term asymmetric components of $C$.

To avoid high MAI, only one of the *interfering nodes* and *jammed nodes* can be allowed to transmit in every time slot. This decision can easily be made using the ‘flickering’ weights mechanism. Note that after avoiding the ‘Near-Far’ situation, $C$ becomes symmetric again and a periodic ‘Near-Far’ situation will occur if no memory process exists. Thus, the new transmission order, achieved by the ‘Near-Far’ avoidance, stays fixed unless a topological change that affects the connection between the relevant nodes occurs.

### III. Sea trial for the HSR-TDMA protocol

In May 2009, a sea trial was conducted in the Haifa harbor in order to validate our assumptions and to better understand the network behavior. The trial included 4 vessels, each performed as an individual node in the network. Each node calculated its location based on a GPS device placed on each of the vessels, and produced periodic broadcast navigational messages.

In order to compare the proposed MAC protocol to the TDMA protocol, the trial included two phases. First, an implementation of a TDMA-based MAC was tested for each topology, then a real-time model of the HSR-TDMA MAC protocol replaced the TDMA protocol and the trial repeated for each topology. The sea trial lasted for more than 12 hours, 5.5 hours for the testing of each MAC protocol.

Due to harbor’s regulations, each node transmitted at the minimal power required to reach its farthest neighbor at SNR of 10dB. However, since the harbor’s ambient noise was far greater than expected, SNR values were low. Therefore, packet error probability rates were high and reliability was low. However, this was not a major problem since we are interested in comparison of the HSR-TDMA protocol to the TDMA protocol. Furthermore, more interesting issues occurred due to the low reliability that enabled insight to the HSR-TDMA protocol’s process facing “flickering”, “islands” and “Near-Far”.

The 4 vessels were placed in various locations inside the harbor and the transducers were located in fixed 3m depth. In order to check the network performance in various topologies, the vessels moved throughout the trial between the harbor docks. During the trial, six different topology structure, shown in Figure 2, were tested. In part V, ‘Near-Far’ situation existed between nodes 1 and 4 since $d_{1,2}$ was 1000m where $d_{4,2}$ was 300m. Part IV included an *‘island’* scenario were node 1 was disconnected from the rest of the network’s nodes.

We measured the proposed MAC protocol performance by using two separate measures: availability and reliability using (1) and (3). The normalized availability values for each node per topology structure for the HSR-TDMA protocol are shown in Figure 3. The difference between the normalized availability values for each node, result from the different connection lists in each topology structure. Note that the TDMA’s normalized availability was fixed on $\frac{1}{4}$. Due to the substantial increase of the normalized availability value in the proposed protocol, the number of transmitted messages in the second phase of the trial was much higher. In fact the number of transmitted messages increased from an overall 1260 transmitted messages in the first phase of the trial to almost twice in the second phase: 2164 transmitted messages.

The average outage rate, $\rho_{\text{outage}}$, for each topology part was calculated as an average of $P_{\text{error},i}$ for each node. The outage results for both methods are shown in Figure 4, where we neglect the contribution of node 1 to the average outage rate in the sixth part of the sea trial since it disconnected from the network. Note that in both cases, the outage rate was
The HSR-TDMA protocol’s reliability significantly decreased compared to the TDMA. This is due to the MAI in the relaying nodes and the much greater number of packets to relay in the HSR-TDMA protocol. In addition, topology changes do not affect the TDMA protocol’s reliability, whereas, the HSR-TDMA protocol adapts itself slowly to topology changes resulting in higher packet error rates until convergence is reached and $C$ is unique for all nodes.

In order to compare the two protocols considering both availability and reliability, we use our throughput quality measure (4). The system’s throughput for both methods in each topology part is presented in Figure 5. The throughput is almost the same for the first topology structure where the proposed method backslides to the TDMA protocol. However, the throughput of the proposed protocol was greatly improved than the TDMA protocol for the other every topology structures. The best results are obtained for the third topology structure where the maximal network’s spatial diversity exists.

IV. CONCLUSION

In this paper we presented a novel hybrid TDMA-CDMA MAC protocol, suitable for the Underwater Acoustic Channel. We argued that if both high availability and reliability are required, the throughput measure is suitable. Thus, to maximize throughput we formalized collision-avoidance MAC protocol with maximum available time slots for transmissions for each node. We showed that our protocol reuses the spatial domain of the network while maintaining the TDMA reliability in steady state. A sea trial comparing the proposed protocol with the classic TDMA protocol for a number of topology scenarios was performed, showing a number of advantages of our protocol to high traffic underwater acoustic communication network. Future directions of this work includes analysis of a general topology structure to derive the best protocol achieving optimal throughput for the case of high traffic network and the comparison of such protocol to cluster-based protocols.

REFERENCES