Target Detection Using Underwater Acoustic Networking

Nils Morozs*, Paul D. Mitchell, Yuriy Zakharov
School of Physics, Engineering & Technology
University of York
York, YO10 5DD, United Kingdom
*nils.morozs@york.ac.uk

***Abstract*—This paper presents a feasibility study for simultaneous underwater acoustic communication (UAC) and target detection using a network of underwater nodes. It can be achieved via anomaly detection in the estimated channel impulse response (CIR) of regular packet transmissions in the network. Such a network could serve as the first step in detecting and localising possible targets, which could then be followed up by the deployment of a sonar-equipped AUV to scan the identified area in more detail. The MAC layer based on Spatial Reuse TDMA (STDMA) fits the traffic requirements of such a network significantly better than contention-based MAC protocols. An enhancement of STDMA packet scheduling that utilises interference cancellation (IC) capabilities at the receivers can further increase the network throughput and, thus, the target detection performance. The simulation study shows that such an approach is feasible from the point of view of network throughput and the probability of the target "crossing" an active acoustic path. Further work includes the integration of a more detailed acoustic environment model, and the development of a Network and Application Layer to deliver the detection information through the network and to enable target tracking.**

***Index Terms*—Network Protocols, Underwater Surveillance, Underwater Acoustic Network**

I. Introduction

Underwater monitoring and surveillance are crucial tasks for countries with a coastline [1]–[3]. They involve the detection, classification, localisation and tracking of targets underwater, such as autonomous underwater or surface vehicles (AUV/ASV), marine mammals, sharks, divers, surface vessels and submarines [1].

Typical approaches to underwater target detection involve the use of dedicated sensor systems, e.g. monostatic/multistatic sonar [4], passive acoustic sensors [5] or visual/infrared cameras [1]. A disadvantage of these systems is that, after a possible target detection, an underwater node then needs to communicate this to a station on shore, which requires a separate communication system, using: (a) subsea cables; (b) tether to the surface + radio link; or (c) most practically, underwater acoustic communications (UAC) [6].

In this paper, we consider an alternative way of detecting underwater targets – simultaneous UAC and target detection using a network of underwater nodes. It can be achieved via anomaly detection in the estimated channel impulse response (CIR) for every data transmission from a given source, e.g. detecting significant signal paths appearing or disappearing. It is similar to the idea of multistatic sonar [4], but instead of dedicated sonar transmissions, regular data transmissions from the network nodes are "reused" for the target detection purpose.

In particular, we focus on developing a network protocol for such a *cooperative underwater surveillance network (COUSIN)* and evaluating the target detection performance of this network for a range of target speeds, sizes and detection sensitivities.

An essential element of any network protocol stack is Medium Access Control (MAC) [7]. It is responsible for coordinating transmissions from multiple nodes to provide adequate throughput, packet delivery and latency performance to meet the requirements of the given application. This is especially challenging in the underwater acoustic domain due to the extremely slow propagation of acoustic waves (typically between 1450–1550 m/s) and low available bandwidth (typically in the order of several kHz) [6], [8].

Many existing MAC protocols designed for UASNs are based on the idea of *contention*: the nodes attempt to access a shared channel dynamically, on demand, based on a particular set of rules [9]. These channel access rules are based on one or a combination of three principles: (a) *random access* (ALOHA) [10]); (b) *channel reservation* (e.g. using Request-to-Send (RTS) / Clear-to-Send (CTS) handshakes [11], [12]; (c) *Carrier sensing* (the "listen-before-talk" principle) [13]. Contention-based MAC protocols work well in scenarios with low traffic loads and random packet generation times (such that the probability of two or more nodes transmitting at the same time is low) [7]. However, the long propagation delays of acoustic signals render them inefficient in high throughput UASN applications due to the increased number of collisions, limited carrier sensing accuracy and high latency incurred by retransmission management.

A different class of MAC protocols is based on the principle of Time Division Multiple Access (TDMA), where the nodes are scheduled to transmit their data packets in particular time slots such that the packets arrive at the intended receivers without collisions, e.g., [14]–[16]. Schedule-based MAC schemes do not involve contention for communication resources, thus removing the need for control signalling in order to establish collision-free links. Therefore, they are capable of achieving high throughput by scheduling the transmissions in a way that

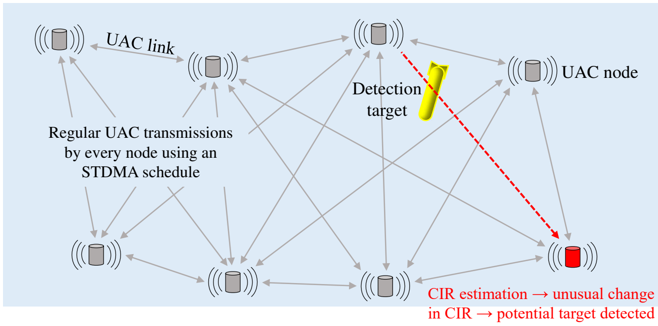


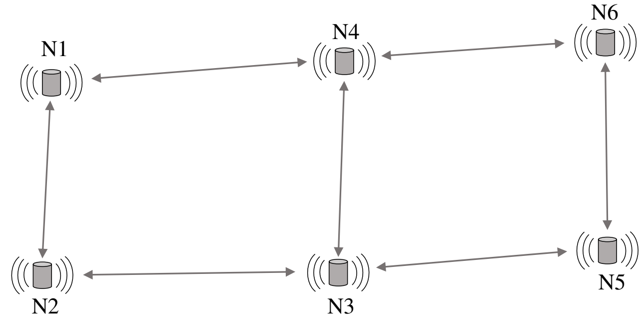
Fig. 1. Target detection using a network of UAC nodes performing channel impulse response (CIR) estimation on every reception.

results in a stream of data packets separated by guard intervals at the intended receivers. TDMA requires a synchronised clock reference among the network nodes, which is more challenging to provide in underwater acoustic networks, compared with terrestrial systems [6]. However, a relatively coarse clock synchronisation is sufficient since the typical duration of a TDMA slot incorporates long propagation delays in the network [17] – in the order of hundreds of milliseconds or multiple seconds; therefore, potential clock drift can be accounted for by a relatively small increase in the guard interval. In this paper, we propose a solution based on TDMA; in particular, enhanced versions of TDMA that incorporate spatial reuse of time slots and/or interference cancellation (IC) capabilities at the receiver to increase the network throughput and thus improve the target detection performance.

The rest of the paper is organised as follows: Section II describes the proposed system setup for target detection using UAC; Section III describes the MAC protocols; Section IV presents the results of the simulation study; finally, Section V gives conclusions and directions for further work.

II. System Setup

The proposed system setup is depicted in Fig. 1. A number of UAC nodes are deployed in the area of interest, e.g. along a sea coast, or in a river estuary, harbour, etc. Every node regularly broadcasts a data packet, which is received by a number of other nodes within its acoustic connection range. For every packet reception, all receiving nodes estimate the CIR and compare it with the CIRs measured during previous transmissions from the same source node. If they detect an anomaly in the CIR, e.g. a new strong reflection or an obstruction of a direct signal path, this could signify the presence of a target in the water. Due to the highly time-varying, rich multipath structure of UAC channels, it would be impossible to ascertain that a given CIR anomaly is indeed caused by a target in the water. Therefore, such a network would work as the first step in detecting and localising possible targets, which could then be followed up by the deployment of a sonar-equipped AUV to scan the identified area in more detail.



STDMA schedule (4 slots per frame)

Slot 1	*Slot 2*	*Slot 3*	*Slot 4*
N1, N5	N2, N6	N3	N4

Spatial reuse of TDMA slot

STDMA + IC schedule (3 slots per frame → +33% throughput)

Slot 1	*Slot 2*	*Slot 3*
N1, N5	N2, N4	N3, N6

Fig. 2. Spatial reuse of time slots in a sparsely connected network using STDMA and STDMA with interference cancellation (STDMA+IC), where each node has the capability to receive two packets simultaneously via multi-user IC at the PHY layer.

III. STDMA Medium Access Control Layer

The most suitable type of MAC protocol to support a periodic traffic pattern, such as that produced by the target detection network described above, is Time Division Multiple Access (TDMA). An enhancement of the standard TDMA approach often employed in underwater acoustic networks (UANs) is to exploit their topology sparsity for collision-free spatial reuse of time slots – Spatial TDMA (STDMA) [18]. This increases the network throughput allowing each node to transmit more frequently.

Fig. 2 shows an illustrative example of a sparsely connected network comprising six nodes. All nodes have a coarsely synchronised time reference and follow a common transmission schedule, where each node has been allocated a particular time slot for its transmission. The duration of a single time slot τ_{slot} is set as follows:

$$\tau_{\text{slot}} = \tau_{\text{packet}} + \hat{\tau}_{\text{prop}} + \tau_{\text{guard}}, \tag{1}$$

where τ_{packet} is the duration of a packet transmission, $\hat{\tau}_{\text{prop}}$ is the maximum propagation delay in the network, and τ_{guard} is an additional guard interval to account for the channel delay spread, potential clock drift etc. This slot duration provides collision-free TDMA channel access, where transmissions from any two interfering nodes are separated in time, such that they never collide at a common receiver. Every node is allocated one time slot per frame. In STDMA, sparse connectivity among the network nodes is exploited to allow more than one node to transmit in the same time slot. In this example, N1 and N5 can transmit simultaneously without interference as they do not have any common receivers (i.e. they are separated by more than two hops). The same applies to N2 and N6.

As a result, it is possible to derive a 4-slot STDMA frame (shown in Fig. 2) where every node gets a collision-free slot for transmission. This frame pattern is then repeated in time, such that every node gets an opportunity to transmit every four slots. For quasi-static network deployments, such as the target detection network considered in this paper, the schedule can be derived by a centralised node (e.g. control station on shore connected to an acoustic gateway node) and distributed to all nodes at the start of its operation, periodically repeating the network discovery and schedule setup to incorporate potential changes in the node connectivity, e.g. as proposed in [19].

The spatial reuse of time slots can be further enhanced by using interference cancellation (IC) capabilities at the receivers which allow the nodes to receive multiple packets simultaneously by performing multi-user IC at the physical layer [20]. For example, if the nodes are able to demodulate and decode two packets in parallel, a three slot STDMA+IC schedule can be derived as shown in Fig. 2, which would increase the network throughput by 33% (each node can now transmit every three slots, instead of every four slots) and significantly increase the probability of detecting a target moving through water as shown in Fig. 1.

IV. Simulation Study

A. Simulation Setup

We simulated a large number of scenarios similar to the one shown in Fig. 3, with 20 UAC nodes arranged in two lines, e.g. installed along a coast line. The nodes are arranged as a 10×2 grid in a 5×1 km segment of a coast line with a 50 m radius random perturbation in each node's position. The detection target was placed at random locations along the horizontal axis and travelled vertically down (worst case trajectory for detection) at a fixed speed (e.g. 2 m/s).

While the target is moving across the network, the UAC nodes transmit broadcast packets using a TDMA, STDMA or STDMA+IC schedule, as described in Section III. A detection of the target is registered if, during a transmission on an acoustic link (between a particular Tx and Rx node), the target's location is within the "target-to-path detection distance" $d_{\text{t-p}}$ of the vertical plane between the transmitter and the receiver, i.e. $d_{\text{t-p}}$ represents the target's "detectability radius". Typical UAC environments are multipath-rich due to strong reflections from the sea surface and seabed; therefore, in this study we model the channel between a transmitter and receiver as a

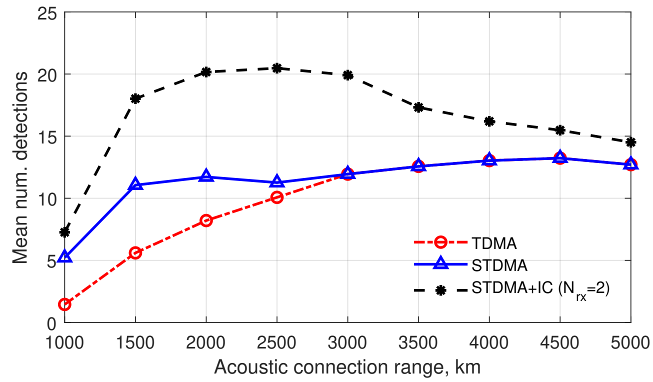
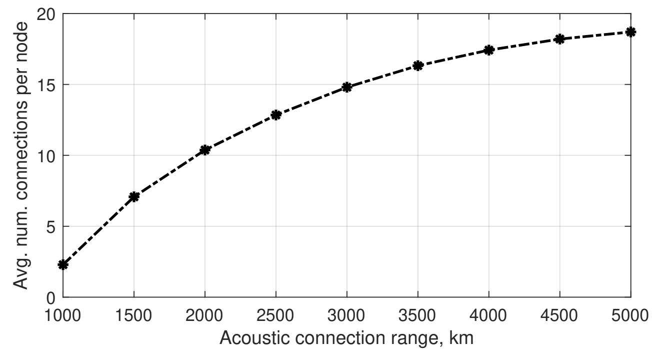
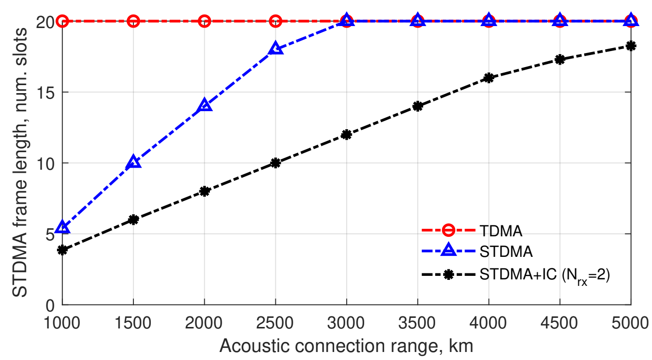


Fig. 4. Detection performance of the network at different acoustic connection ranges, using TDMA and STDMA with/without the IC capability.



(a) Average number of connections per node



(b) Average number of slots per frame

Fig. 5. Spatial reuse of time slots in STDMA is particularly effective in sparsely connected networks (at shorter acoustic connection ranges). This can be further enhanced by incorporating interference cancellation (IC) capabilities at the receivers, which enable them to demodulate and decode signals from multiple nodes in parallel (in this example – up to 2).

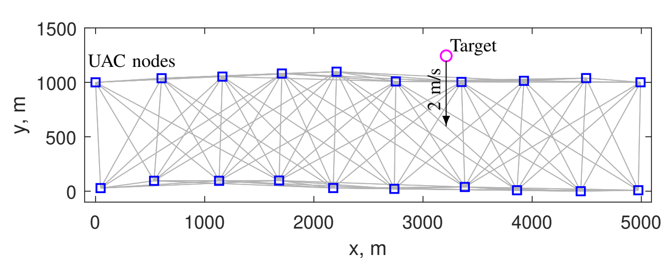
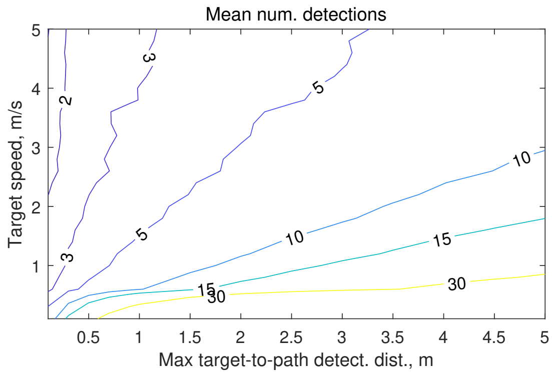


Fig. 3. Example of a simulated network topology; the target is moving on a worst-case trajectory (perpendicular to the lines of nodes) at 2 m/s.

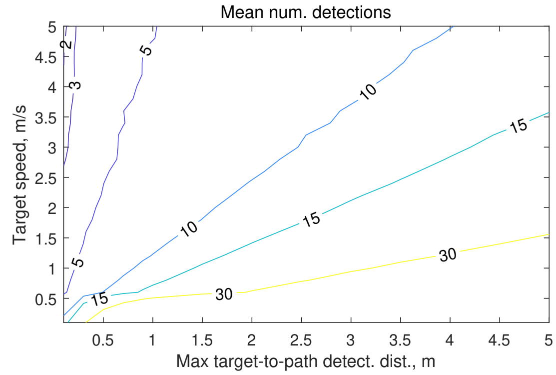
vertical plane containing many multipath components that can be used to detect a change in CIR and, therefore, detect a target. Simulations were run at a range of $d_{\text{t-p}}$ values which approximate the effect of the target size, e.g. larger $d_{\text{t-p}}$ would correlate with larger targets and vice-versa.

B. Results

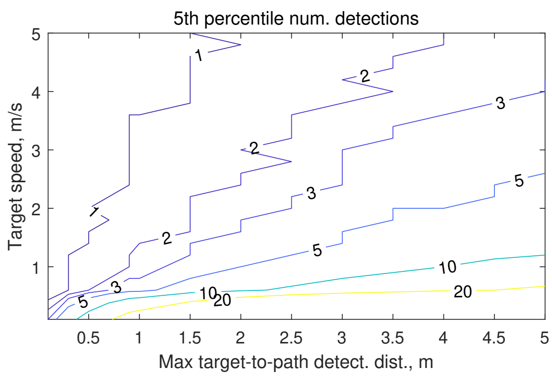
Fig. 4 shows the mean target detection performance from 1,000 simulation sets with different random seeds, comparing the TDMA, STDMA and STDMA+IC protocols at different



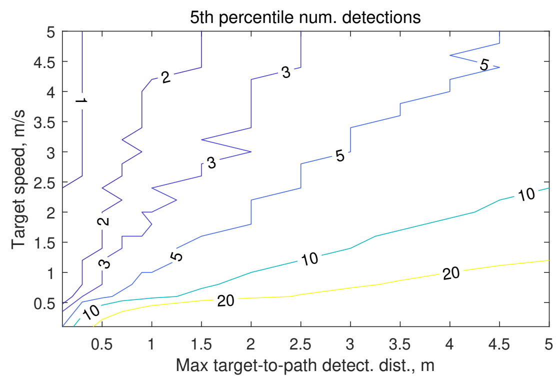
(a) STDMA; mean detection performance



(b) STDMA+IC (up to 2 parallel Rx); mean detection performance



(c) STDMA; 5th percentile detection performance



(d) STDMA+IC (up to 2 parallel Rx); 5th percentile detection performance

Fig. 6. Average detection performance at a range of target speeds and sizes (approximated as the target-to-acoustic-path distances in m).

acoustic connection ranges, for a target moving at 2 m/s and the target-to-path-detection distance $d_{\text{t-p}} = 4$ m. The acoustic connection range is defined as the maximum distance at which two nodes can communicate or interfere with each other. Fig. 5a shows how the acoustic connection range affects the sparsity of the network. The lower the range, the fewer connections each node has on average, which in turn enables greater spatial reuse of time slots in STDMA and STDMA+IC (Fig. 5b) and higher throughput. However, having fewer acoustic connections per node also means that there are fewer possible acoustic paths that can be used for target detection. To summarise: dense connectivity (longer connection range) provides more detection paths but lower throughput (less frequenct transmissions per node); but sparse connectivity (shorter connection range) provides fewer paths but higher throughput. Fig. 4 shows that for the STDMA+IC protocol, this trade-off results in an optimal operating point at around 2.5 km acoustic connection range, which enables spatial reuse of time slots (10-slot frames on average, see Fig. 5b) but also provides a sufficiently dense mesh of acoustic paths for effective target detection.

The key conclusion from Fig. 4 is that the proposed cooperative UAN approach to target detection is feasible and on average achieved many detections (up to 13 for TDMA/STDMA and up to 20 for STDMA+IC) for a target travelling on the worst case trajectory at 2 m/s (e.g. a fast AUV).

Fig. 6 shows how the detection performance of the network varies with the target speed and "size" (represented by $d_{\text{t-p}}$). The contours in Fig. 6a and Fig. 6b show the mean number of detections achieved by STDMA and STDMA+IC, respectively, at the given combination of the target speed and $d_{\text{t-p}}$, whereas Fig. 6c and Fig. 6d show the 5th percentile performance, i.e. the minimum detection performance achieved in at least 95% of the simulated scenarios. These plots provide a useful tool for network planning and performance prediction. For example, to detect small targets (e.g. $d_{\text{t-p}} = 1$ m) travelling at 2 m/s, the STDMA+IC protocol is required to provide at least 5 detections on average (Fig. 6b), whereas for larger/slower targets standard STDMA is sufficient (Fig. 6a), which reduces the signal processing complexity at the receiver.

V. Conclusions and Further Work

This paper considered an underwater acoustic target detection network where regular packet transmissions from the nodes are "reused" for the purpose of target detection via anomaly estimation in the CIR. A Monte Carlo simulation study showed that the MAC layer based on STDMA, with a potential enhancement that utilises interference cancellation (IC) capabilities at the receivers, can detect underwater targets travelling at realistic speeds (e.g. fast AUV) and having a representative "detectability radius". These results suggest that the proposed approach to underwater target detection is feasible, provided that it is possible to perform sufficiently accurate CIR estimation at the PHY layer to be able to detect the potential presence of targets in the water.

Further work includes the integration of a more detailed acoustic environment model (based on ray tracing) to simulate target detections; and the development of a Network and Application Layer to assess the reliability and latency of delivering the detection information through the network, and to enable target tracking by analysing a sequence of multiple detections.

Acknowledgement

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) through the COUSIN project grant (EP/V009591/1).

References

[1] D. S. Terracciano, L. Bazzarello, A. Caiti, R. Costanzi, and V. Manzari, "Marine robots for underwater surveillance," *Curr. Robot. Rep.*, vol. 1, pp. 159–167, 2020.

[2] C. Peckham, "An overview of maritime and port security," in *Proceedings iof IEEE HST'12*, 2012, pp. 260–265.

[3] G. Ferri, A. Munafo, A. Tesei, P. Braca, F. Meyer, K. Pelekanakis, R. Petroccia, J. Alves, C. Strode, and K. LePage, "Cooperative robotic networks for underwater surveillance: an overview," *IET Radar, Sonar & Navigation*, vol. 11, no. 12, pp. 1740–1761, 2017.

[4] L. Hu, X. Wang, and S. Wang, "Decentralized underwater target detection and localization," *IEEE Sensors J.*, vol. 21, no. 2, pp. 2385–2399, 2021.

[5] R. Otnes, J. E. Voldhaug, and S. Haavik, "On communication requirements in underwater surveillance networks," in *Proceedings of IEEE OCEANS'08*, 2008, pp. 1–7.

[6] J. Heidemann, M. Stojanovic, and M. Zorzi, "Underwater sensor networks: applications, advances and challenges," *Philos. Trans. R. Soc. A*, vol. 370, no. 1958, pp. 158–175, 2012.

[7] S. Jiang, "State-of-the-art Medium Access Control (MAC) protocols for underwater acoustic networks: A survey based on a MAC reference model," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 96–131, 2018.

[8] L. Lanbo, Z. Shengli, and C. Jun-Hong, "Prospects and problems of wireless communication for underwater sensor networks," *Wireless Communications and Mobile Computing*, vol. 8, no. 8, pp. 977–994, 2008.

[9] K. Chen, M. Ma, E. Cheng, F. Yuan, and W. Su, "A survey on MAC protocols for underwater wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1433–1447, 2014.

[10] N. Chirdchoo, W.-. Soh, and K. Chua, "Aloha-based MAC protocols with collision avoidance for underwater acoustic networks," in *Proceedings of IEEE INFOCOM'07*, May 2007, pp. 2271–2275.

[11] W. H. Liao and C. C. Huang, "SF-MAC: A spatially fair MAC protocol for underwater acoustic sensor networks," *IEEE Sens. J.*, vol. 12, no. 6, pp. 1686–1694, 2012.

[12] R. Diamant, P. Casari, F. Campagnaro, and M. Zorzi, "A handshake-based protocol exploiting the near-far effect in underwater acoustic networks," *IEEE Wireless Commun. Lett.*, vol. 5, no. 3, pp. 308–311, 2016.

[13] M. Rahman, Y. Lee, and I. Koo, "An adaptive network allocation vector timer-based carrier sense multiple access with collision avoidance medium access control protocol for underwater acoustic sensor networks," *Int. J. Dist. Sens. Netw.*, vol. 13, no. 1, 2017.

[14] P. Anjangi and M. Chitre, "Propagation-delay-aware unslotted schedules with variable packet duration for underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 42, no. 4, pp. 977–993, Oct 2017.

[15] R. Diamant and L. Lampe, "Spatial reuse time-division multiple access for broadcast ad hoc underwater acoustic communication networks," *IEEE J. Ocean. Eng.*, vol. 36, no. 2, pp. 172–185, 2011.

[16] S. Lmai, M. Chitre, C. Laot, and S. Houcke, "Throughput-efficient super-TDMA MAC transmission schedules in ad hoc linear underwater acoustic networks," *IEEE J. Ocean. Eng.*, vol. 42, no. 1, pp. 156–174, 2017.

[17] K. Kredo II, P. Djukic, and P. Mohapatra, "STUMP: Exploiting position diversity in the staggered TDMA underwater MAC protocol," in *Proceedings of IEEE INFOCOM*, 2009.

[18] R. Diamant, G. N. Shirazi, and L. Lampe, "Robust spatial reuse scheduling in underwater acoustic communication networks," *IEEE J. Ocean. Eng.*, vol. 39, no. 1, pp. 32–46, 2014.

[19] N. Morozs, B. Sherlock, B. T. Henson, J. A. Neasham, P. D. Mitchell, and Y. Zakharov, "Data gathering in UWA sensor networks: Practical considerations and lessons from sea trials," *J. Mar. Sci. Eng.*, vol. 10, no. 9, 2022.

[20] A. Pottier, P. J. Bouvet, and P. Forjonel, "Performance evaluation of Multi-User MIMO underwater acoustic communications," in *Proceedings of UComms'21*, 2021, pp. 1–5.