ROUTING STRATEGIES FOR DUAL-HOP TDA-MAC: TRADE-OFF BETWEEN NETWORK THROUGHPUT AND RELIABILITY

Nils Morozs*, Paul D. Mitchell, Yuriy Zakharov

Department of Electronic Engineering, University of York, York YO10 5DD, UK

* Corresponding author: Nils Morozs, nils.morozs@york.ac.uk, +44 1904 322395

Abstract: *This paper investigates the use of underwater acoustic sensor networks (UASNs) for large scale monitoring of the ocean environment. The slow propagation of acoustic waves is a fundamental challenge in implementing reliable networking protocols due to the limited amount of control signalling that is achievable due to the long propagation delays in UASNs. Sequential Dual-Hop Transmit Delay Allocation MAC (SDH-TDA-MAC) is a Medium Access Control (MAC) protocol that mitigates these physical constraints by incorporating long propagation delays into the transmission schedules to provide high network throughput in dual-hop UASNs. In this paper, we take a cross-layer approach to designing a routing protocol tailored to SDH-TDA-MAC. We present and evaluate the minimum delay and fewest relays routing strategies with optional routing redundancy, to offer a trade-off between achieving high network throughput and reliable packet delivery.*

Keywords: *Medium Access Control, Routing, Sensor Network, Underwater Acoustic Network*

1. INTRODUCTION

The use of wireless sensor networks (WSNs) for remote monitoring of the ocean environment is becoming an increasingly popular research subject, owing to the modern developments in underwater acoustic modem technologies [1][2][3]. Acoustic waves are the preferred practical medium for underwater communications, since they exhibit significantly better propagation characteristics compared with electromagnetic and optical waves. However, acoustic communications are fundamentally limited by the low sound propagation speed and low usable frequency bandwidth [4]. These severe physical constraints necessitate the design of networking protocols dedicated to underwater acoustic sensor networks (UASNs).

Much of the well-established research on Medium Access Control (MAC) in UASNs focuses on Time Division Multiple Access (TDMA) based protocols that aim to schedule packet transmissions in a way that mitigates the negative effect of long propagation delays on the network performance, e.g. by exploiting large differences in propagation delays and/or topology sparsity for spatial reuse of the channel airtime [5][6]. For example, in [7] we proposed the Transmit

Delay Allocation MAC (TDA-MAC) protocol that leverages the knowledge of the propagation delays in a centralised UASN to achieve high throughput without clock synchronisation at the sensor nodes. In [8] we proposed Sequential Dual-Hop TDA-MAC (SDH-TDA-MAC), extending the TDA-MAC approach to dual-hop UASNs, which introduced the problem of routing, i.e. choosing which sensor nodes act as relays to optimise a particular performance objective, e.g. throughput, reliability, energy fairness etc.

Routing in WSNs is a well-established research field with many solutions available for different network architectures, and for specific performance objectives [9]. In this paper, we take a cross-layer approach to design routing strategies that are specifically tailored to dual-hop TDA-MAC applied to UASNs, i.e. a combined design of the MAC and the network layer. We believe that cross-layer protocol design is key for achieving efficient network operation under the severe constraints imposed by the long propagation delays in UASNs. The purpose of this paper is to provide an insight into the performance of several dual-hop routing strategies in the context of two performance metrics: network throughput and packet delivery ratio. The routing strategies presented in this paper incorporate both relay node selection to maximise the throughput, and routing redundancy to increase the network reliability, similar to flooding protocols [10] but designed specifically for dual-hop TDA-MAC [8].

The rest of the paper is organised as follows: Section 2 describes the SDH-TDA-MAC protocol; Section 3 presents details of several routing strategies for SDH-TDA-MAC; Section 4 evaluates the proposed routing strategies in simulation; finally, Section 5 concludes the paper.

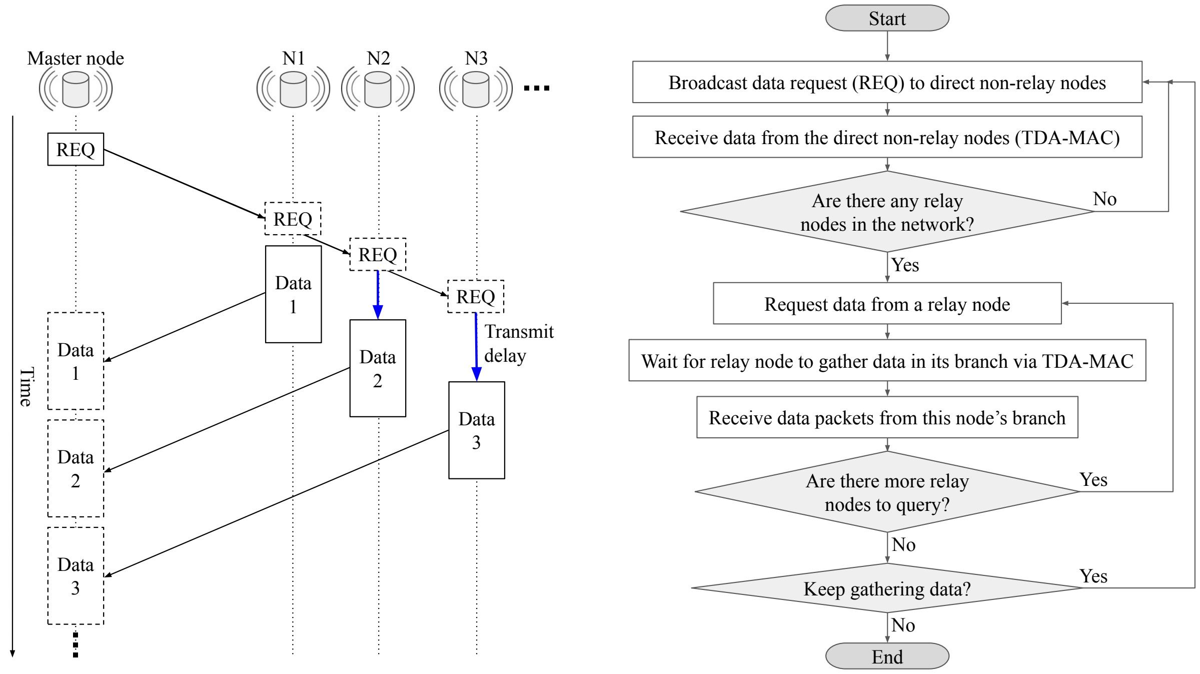
2. DUAL-HOP TDA-MAC

In [7], we proposed the TDA-MAC protocol for centralised scheduling of data transmissions from sensor nodes connected to a single gateway node. Its main advantage over other MAC protocols found in the literature is that it can achieve network throughputs close to the channel capacity without clock synchronisation at the sensor nodes. Therefore, it shows great potential as a practical solution for efficient data gathering in UASNs. A practical application of TDA-MAC was successfully demonstrated in sea trials with a small underwater sensor network in July 2018 in Fort William, UK [11]. Figure 1a shows an illustrative example of the packet flow in TDA-MAC. The gateway (master) node broadcasts a data request (REQ) packet that is received by every sensor node at a different time (due to the differences in propagation delays of the acoustic links). Each sensor node then waits for a specific (individually assigned) amount of time before transmitting their data packet back to the gateway node as shown in Figure 1a.

In [8], we extended the TDA-MAC protocol to dual-hop networks, i.e. where nodes that do not have a direct link with the gateway node are connected via another sensor node that acts as a relay. Figure 1b shows the flowchart of the SDH-TDA-MAC protocol. There, the single-hop TDA-MAC protocol depicted in Figure 1a is first used at the gateway node for all directly connected sensor nodes, and then at every relay node to gather data packets within their respective network branch sequentially. This approach was shown to achieve high network throughput by leveraging the many-to-one connections in dual-hop UASNs.

3. DUAL-HOP ROUTING STRATEGIES

In addition to scheduling, dual-hop TDA-MAC also needs to incorporate a routing procedure, i.e. choosing the dual-hop links between sensor nodes to deliver packets to the gateway node.



(a) TDA-MAC packet flow *(b) SDH-TDA-MAC protocol at the gateway node [8]*

Figure 1: Sequential Dual-Hop TDA-MAC (SDH-TDA-MAC) scheduling. The gateway node first uses TDA-MAC to gather data packets from directly connected non-relay sensor nodes. It then gathers data from every relay node sequentially, instructing it to gather data within its network branch using TDA-MAC.

In this section we present several routing strategies, expanding on our previous work in SDH-TDA-MAC in [8]. In particular, we investigate routing in terms of two key metrics: network goodput and robustness against link fading, typical in the underwater acoustic environment.

3.1. Minimum Delay Routing

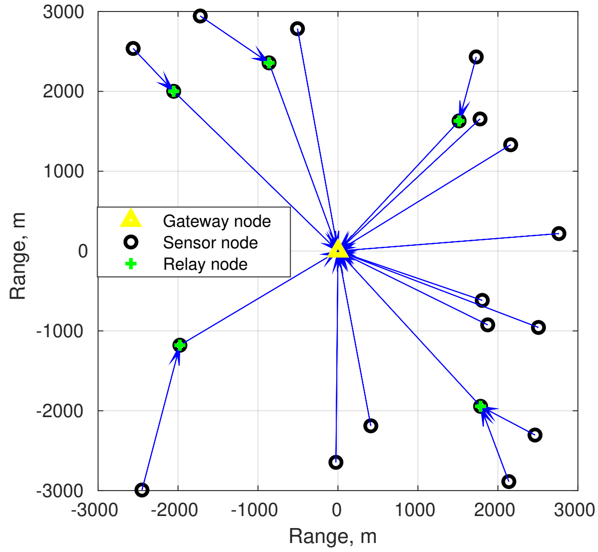
A simple and reliable approach to routing in WSNs is minimum delay routing. In most cases it is equivalent to shortest path routing, where a sensor node that requires a multi-hop route to the destination chooses the relay nodes by minimising the total propagation delay across all hops.

Let $\boldsymbol{C}$ and $\boldsymbol{T}_\mathrm{p}$ be $N \times N$ connectivity and propagation delay matrices respectively, established during the network discovery and setup stage, and then periodically updated based on received data packets, e.g. as described in [7]. This process is sufficient to maintain an accurate topology estimate of a quasi-stationary underwater sensor network. $N = 1 + N_\mathrm{sn}$ is the total number of nodes, including one gateway node and N_sn sensor nodes. $\boldsymbol{C}$ is a binary matrix, whose elements are $C[i,j] = 1$ if there is a link between nodes i and j, and $C[i,j] = 0$ otherwise. $T_\mathrm{p}[i,j]$ is the propagation delay from node i to node j.

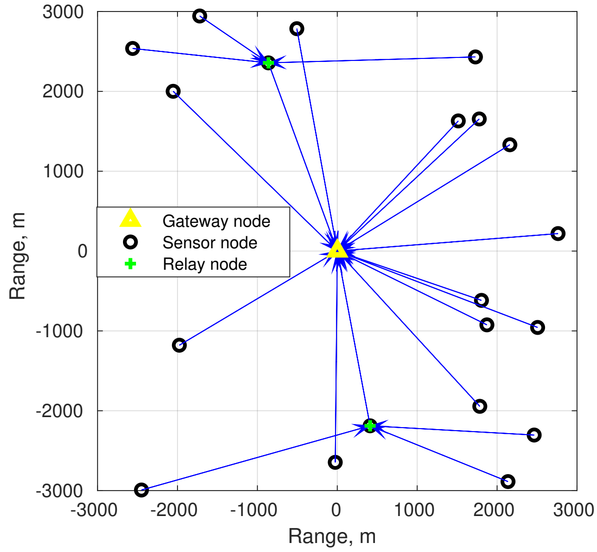
We can identify the set of sensor nodes $M_\text{dual-hop}$, that do not have a direct link with the gateway node and, therefore, require a dual-hop connection, as follows:

$$M_\text{dual-hop} = \big\{ n \,|\, n \in [2,N],\, C[1,n] = 0 \big\} \tag{1}$$

For every sensor node i that requires a dual-hop connection, a relay node r_i is found that min-



(a) *Minimum delay routing*



(b) *Fewest relays routing*

Figure 2: Dual-hop routing strategies in a UASN comprising a surface gateway node and 20 sensor nodes at approximately 500 m depth with 3 km communication range.

imises the total propagation delay across two hops (sensor-relay and relay-gateway nodes):

$$\forall i \in M_{\text{dual-hop}},\ r_i = \underset{j\in[2,N]}{\operatorname{argmin}} \left\{T_{\text{p}}[j,i] + T_{\text{p}}[1,j]\right\},\ \text{s.t. } C[1,j] = 1, C[j,i] = 1 \tag{2}$$

If there are no other sensor nodes that can serve as a relay, i.e. there is no node j that satisfies both $C[1,j] = 1$ and $C[j,i] = 1$ conditions, node i does not have dual-hop connectivity.

For an arbitrary multi-hop network, minimum delay routing can be achieved by the well-established Dijsktra's algorithm [12] which finds the shortest path tree topology, such as that shown in the 20-node example in Figure 2a. However, in the specific case of a dual-hop network topology, this process is significantly simpler, since an optimal relay node can be found by a single evaluation of (2) for every sensor node requiring a dual-hop connection.

3.2. Fewest Relays Routing

The disadvantage of the minimum delay routing approach is that it does not take into account the network throughput performance. The key feature of the SDH-TDA-MAC protocol described in Section 2 is the exploitation of many-to-one connections to achieve high throughput, whereas every relay branch of the network topology is processed sequentially, increasing the idle time caused by the dual-hop round trip delays and thus reducing the throughput.

Therefore, to maximise the throughput of the SDH-TDA-MAC protocol, the routing strategy should minimise the number of relay nodes, hereafter referred to as "fewest relays" routing. The aim of the routing algorithm is to find the smallest set of nodes M_{relays} such that:

$$\forall i \in M_{\text{dual-hop}},\ \exists j \in M_{\text{relays}},\ C[1,j] = 1, C[j,i] = 1, \tag{3}$$

i.e. the smallest subset of relay nodes that covers all sensor nodes requiring a dual-hop connection.

This is a set cover problem [13]. Every potential relay node j can be represented by a set of nodes directly linked to it $M_C^j = \{i \,|\, C[j,i] = 1\}$. The optimal set of relay nodes $M_{\text{relays}} = \{a, b, ...\}$ is determined by finding the smallest collection of node sets $\mathcal{S} = \{M_C^a, M_C^b ...\}$ such that their union contains all nodes in $M_{\text{dual-hop}}$:

$$M_{\text{dual-hop}} \subseteq \bigcup_{M_C^j \in \mathcal{S}} M_C^j, \tag{4}$$

i.e. this is a problem of finding the set cover $\mathcal{S}$ of $M_{\text{dual-hop}}$ that uses the fewest sets M_C^j.

The set cover problem is NP-hard [13]; therefore, a computationally efficient method of finding the optimal set of relays M_{relays} does not exist. Instead, it can be found by a heuristic approximation algorithm that does not guarantee an optimal solution but efficiently finds good suboptimal solutions. Our implementation of such a heuristic algorithm is outside of the scope of this paper, but any existing general approximation algorithm for the set cover problem can be used to solve this problem, e.g. see [14], [15].

Figure 2b gives an example of the fewest relays routing solution found by our algorithm for the 20 node UASN. This routing strategy is more suitable for SDH-TDA-MAC, since there are only 3 sequential instances of TDA-MAC required to cover the whole network (1 gateway + 2 relays), compared with 6 TDA-MAC instances (1 gateway + 5 relays) using minimum delay routing shown in Figure 2a.

3.3. ROUTING REDUNDANCY

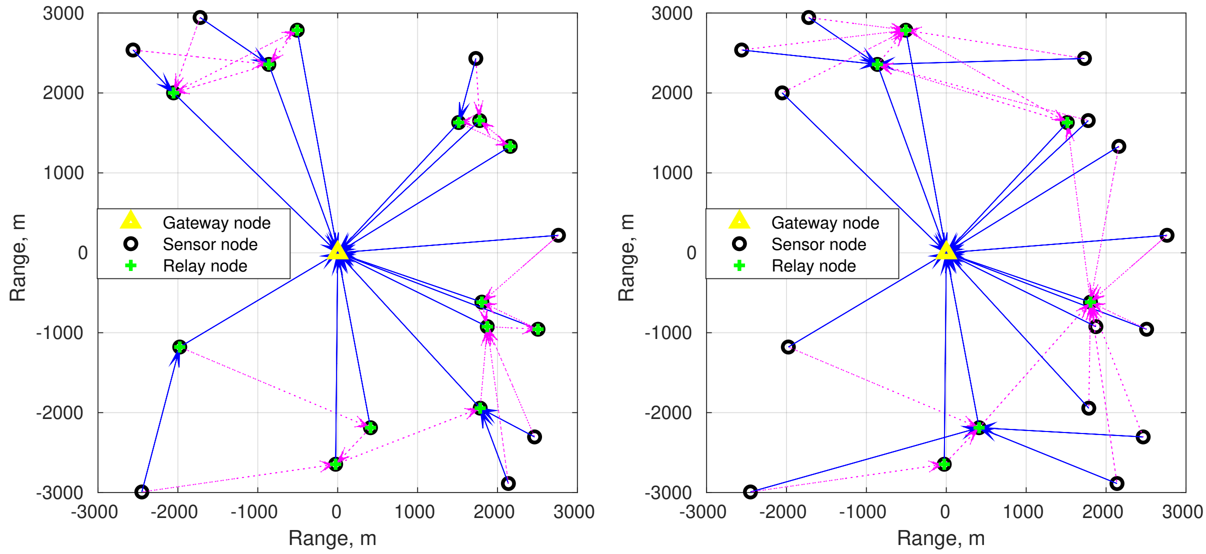
Although the fewest relays routing strategy increases the network throughput, it makes it less robust against random link fading typical for the underwater acoustic environment. For example, if a link between the gateway node and a relay node fails, e.g. due to signal path obstruction, excessive noise, interference, Doppler shift, multipath fading etc., all packets from this relay node's branch will be lost. To combat this issue, in [8] we proposed a routing diversity approach that is backward compatible with the SDH-TDA-MAC protocol, and where every node has multiple unique routes for its packets to reach the gateway node. Figure 3 shows an example of adding double redundancy to the two routing strategies from Figure 2. Every sensor node has two unique routes to the gateway, while the SDH-TDA-MAC protocol is identical to the original one described in Section 2.

The routing diversity approach, such as that shown in Figure 3 is implemented by repeating the routing procedure for every additional level of redundancy with extra constraints [8]:

- Every node (including directly connected nodes) must choose an extra destination different from the one already in use.
- Existing links cannot be used in reverse (i.e. if node j is a relay for node i, node i cannot be a relay for node j).

4. SIMULATION RESULTS

This section presents the empirical evaluation results of the routing strategies discussed in this paper using an event-driven Matlab network simulator running the SDH-TDA-MAC protocol [8]. 100 sensor nodes are spread over a 6×6 km area at 470-490 m depth, similarly to the 20 node example shown in Figures 2 and 3. The gateway node is located at the centre of the coverage area at 10 m depth. The connection range is fixed at 2.5 km, which on average yields



(a) Minimum delay routing

(b) Fewest relays routing

Figure 3: Dual-hop routing with double redundancy in a UASN comprising a surface gateway node and 20 sensor nodes at approx. 500 m depth with 3 km communication range. Every sensor node has two unique routes to send data to the gateway node.

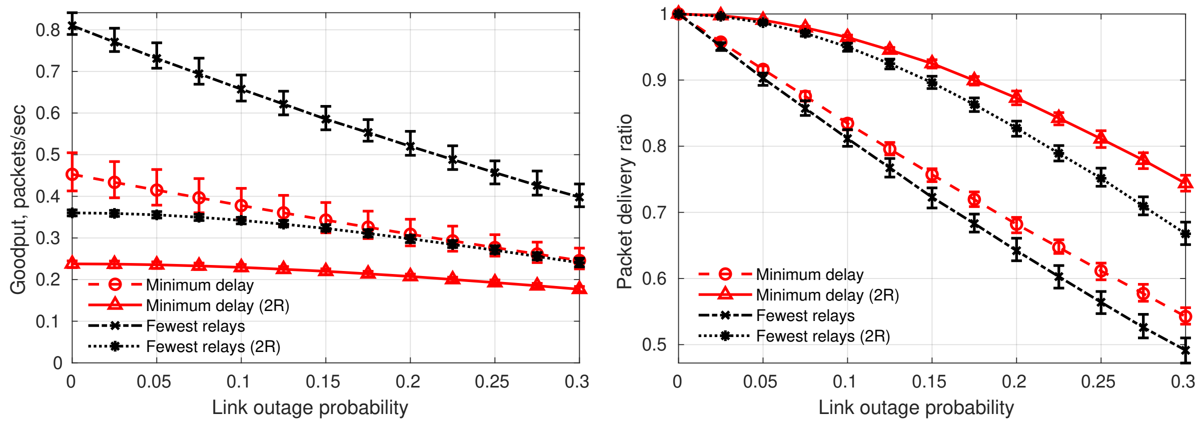
a 52/48% split among directly connected nodes and nodes connected via dual-hop links. All datapoints in the plots show an average of 50 simulations with different random seeds and node locations, with the error bars representing the 5th and 95th percentiles.

The network is simulated at a range of link outage probabilities to assess its robustness against random link fading. Link fading was modelled using a classical two-state Markov process [16] to approximate large-scale underwater acoustic link fading often observed in practice, where link outage may last for tens of seconds or minutes due to changes in the channel caused by node movement or external factors, such as noise. In the two-state Markov model both the duration of random link outage and the duration of normal link operation are exponentially distributed [17]. We fix the mean link outage duration at $\tau_{\text{outage}} = 30$ s, whereas the mean duration of the normal link operation is calculated as follows [17]:

$$\tau_{\text{normal}} = \frac{1 - p_{\text{outage}}}{p_{\text{outage}}} \tau_{\text{outage}} \tag{5}$$

where p_{outage} is the probability of link outage.

Figure 4 shows that the fewest relays routing strategy achieves a significant 79% increase in the network goodput (i.e. different data packets received at the gateway node) compared with minimum delay routing. However, it is less robust against random link fading compared with the latter that uses more relay nodes thus increasing the routing diversity. Introducing the double routing redundancy dramatically improves the network reliability, but at the cost of reducing the network goodput due to duplicate transmissions. For example, at 0.1 link outage probability the proportion of failed packet deliveries (one minus the packet delivery ratio) is reduced by a factor of 4, while the network goodput is reduced by 40% and 48% for minimum delay and fewest relays routing, respectively. This again shows that there is a trade-off between the network throughput and reliability. If maximising the network goodput is the primary concern, fewest relays routing with no redundancy is the best strategy, whereas if reliable packet delivery is more important than supporting high traffic loads, minimum delay routing with double redundancy is a far better strategy. The strategy that strikes a balance between the network



(a) Goodput at the gateway node

(b) Packet delivery ratio

Figure 4: Trade-off between the network goodput and reliability achieved using the minimum delay and fewest relays routing strategies, with and without double redundancy (2R).

throughput and reliability is the fewest relays routing protocol with double redundancy, which combines the throughput maximising relay selection approach with routing redundancy for increased resilience against random link fading.

Another valuable metric to consider in future work on this topic is load balancing, i.e. designing routing strategies suitable for SDH-TDA-MAC that spread the transmission load more evenly among the sensor nodes, e.g. to maximise the network lifetime limited by the available battery energy at the underwater sensor nodes. For example, this could involve a dynamically changing network topology with different sensor nodes working as relays, based on the gateway node's knowledge of the channel state information received from the sensor nodes.

5. Conclusion

The routing strategies investigated in this paper provide new insights into the performance of the SDH-TDA-MAC protocol applied to UASNs with random link fading. Fewest relays routing maximises the network throughput, whereas minimum delay routing provides more robust packet delivery. Introducing the routing redundancy, where each sensor node has more than one unique path for its packet to reach the destination, dramatically increases the network reliability, but reduces the network goodput due to duplicate packet transmissions. Depending on the application-specific network criteria, e.g. high throughput vs reliable packet delivery, the routing strategies presented in this paper provide a range of options to achieve this trade-off.

Acknowledgements

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) through the USMART (EP/P017975/1) and Full-Duplex (EP/R003297/1) projects.

REFERENCES

[1] **H. S. Dol, P. Casari, T. van der Zwan, and R. Otnes.** Software-defined underwater acoustic modems: Historical review and the NILUS approach. *IEEE Journal of Oceanic Engineering*, 42(3):722–737, 2017.

[2] **B. Sherlock, J. A. Neasham, and C. C. Tsimenidis.** Spread-spectrum techniques for bio-friendly underwater acoustic communications. *IEEE Access*, 6:4506–4520, 2018.

[3] **Y. Zakharov, Y. Fei, P. Mitchell, N. Morozs, B. Henson, L. Shen, and T. Tozer.** Low-complexity UAC modem and data packet structure. In *Proceedings of Underwater Communications and Networking Conference (UComms'18)*, 2018.

[4] **J. Heidemann, M. Stojanovic, and M. Zorzi.** Underwater sensor networks: applications, advances and challenges. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 370(1958):158–175, 2012.

[5] **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.

[6] **R. Diamant, G. N. Shirazi, and L. Lampe.** Robust spatial reuse scheduling in underwater acoustic communication networks. *IEEE J. Oceanic. Eng.*, 39(1):32–46, 2014.

[7] **N. Morozs, P.D. Mitchell, and Y. Zakharov.** TDA-MAC: TDMA without clock synchronization in underwater acoustic networks. *IEEE Access*, 6:1091–1108, 2018.

[8] **N. Morozs, P.D. Mitchell, and Y. Zakharov.** Dual-hop TDA-MAC with route diversity for robust data gathering in underwater acoustic sensor networks. Submitted to *IEEE J. Oceanic. Eng.*, 2019.

[9] **J. N. Al-Karaki and A. E. Kamal.** Routing techniques in wireless sensor networks: a survey. *IEEE Wireless Communications*, 11(6):6–28, 2004.

[10] **R. Otnes, J. Locke, A. Komulainen, S. Blouin, D. Clark, H. Austad, and J. Eastwood.** Dflood network protocol over commercial modems. In *Proceedings of the Underwater Communications and Networking Conference (UComms'18)*, 2018.

[11] **N. Morozs, et al.** Robust TDA-MAC for practical underwater sensor network deployment: Lessons from USMART sea trials. In *Proceedings of ACM WUWNet'18*, 2018.

[12] **E. W. Dijkstra.** A note on two problems in connexion with graphs. *Numerische Mathematik*, 1(1):269–271, 1959.

[13] **U. Feige.** A threshold of ln N for approximating set cover. *J. ACM*, 45(4):634–652, 1998.

[14] **D.S. Hochbaum.** Approximation algorithms for the set covering and vertex cover problems. *SIAM J. Comput.*, 11:555–556, 1980.

[15] **P. Slavík.** A tight analysis of the greedy algorithm for set cover. *Journal of Algorithms*, 25(2):237 – 254, 1997.

[16] **M. Zorzi, R. R. Rao, and L. B. Milstein.** On the accuracy of a first-order Markov model for data transmission on fading channels. In *Proceedings of the IEEE International Conference on Universal Personal Communications (ICUPC'95)*, pages 211–215, 1995.

[17] **E. N. Gilbert.** Capacity of a burst-noise channel. *The Bell System Technical Journal*, 39(5):1253–1265, 1960.