SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Reprint Series **CMRE-PR-2019-027**

An adaptive cross-layer routing protocol for underwater acoustic networks

Roberto Petroccia, Konstantinos Pelekanakis, Joao Alves, Stefano Fioravanti, Stephane Blouin, Sean Pecknold

May 2019

Originally presented at:

2018 Fourth Underwater Communications and Networking Conference (UComms), Lerici, Italy, 28-30 August 2018, doi: 10.1109/UComms.2018.8493225

About CMRE

The Centre for Maritime Research and Experimentation (CMRE) is a world-class NATO scientific research and experimentation facility located in La Spezia, Italy.

The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

NOTE: The CMRE Reprint series reprints papers and articles published by CMRE authors in the open literature as an effort to widely disseminate CMRE products. Users are encouraged to cite the original article where possible.

An Adaptive Cross-layer Routing Protocol for Underwater Acoustic Networks

Roberto Petroccia,* Konstantinos Pelekanakis,* João Alves,* Stefano Fioravanti,*
Stephane Blouin† and Sean Pecknold†

* NATO STO Centre for Maritime Research and Experimentation Viale S. Bartolomeo 400, 19126 La Spezia, Italy
email: {roberto.petroccia; konstantinos.pelekanakis; joao.alves; stefano.fioravanti}@cmre.nato.int

† Defence Research and Development Canada (DRDC), Dartmouth, Nova Scotia, B2Y 3Z7, Canada
email: {Stephane.Blouin; Sean.Pecknold}@drdc-rddc.gc.ca

***Abstract*—This short paper presents an adaptive cross-layer routing protocol for Underwater Acoustic Networks (UANs). The proposed solution, termed NADIR for Network Aware aDaptIve Routing, is fully distributed and self-adaptive. It supports the use of multiple coded modulation schemes and the usage of cross-layer information to interact with the physical layer. Link quality information is exploited along with energy and topological data in order to select the relay node to use. The protocol performance has been evaluated considering a challenging networking scenario, *i.e.*, a polar environment, with very long propagation delays and a high probability of packet errors. The results show that the use of an adaptive strategy offers better network performance in terms of packet delivery and energy consumption in the presence of unreliable channels.**

***Index Terms*—Underwater communications, underwater networks, adaptive routing, cross-layer routing.**

I. Introduction

Underwater wireless networks have attracted increased research interest in recent years, opening to the possibility to observe and explore the vast underwater domain [1]. Most underwater applications require the coverage of large areas where the deployed nodes cannot directly communicate with each other. Appropriate routes must be found to exchange data among the nodes or to deliver the intended information to a common collection point (sink). In the underwater domain, acoustics is the main technology used so far for communications, since radio and optical signals are greatly attenuated. Nonetheless, acoustic solutions suffer from sound speed variability, channel gain fluctuations, low bit rate and many other impairments [2], which complicate the implementation of robust and reliable networks. To mitigate all these impairments various strategies have been proposed exploring the combination of acoustic and optical communications to route packets [3]. Acoustic waves are typically used for long-range low-bitrate data transmissions, while optical signals are used for short-range high-bitrate data delivery [4]–[6]. The development of software-defined acoustic modems [7]–[10] has been also considered to enhance the reliability and performance of acoustic communications. In this case, the objective is to enable the possibility to switch among multiple modulation and coding schemes and/or to explore various frequencies and bandwidths depending on the channel conditions. In [11], a reinforcement learning approach is considered to identify the multi-hop routes that provide an overall minimum delay or highest degree of reliability through an underwater network. The presence of a static network is assumed and the energy consumption is not considered as a key metric. In [12], the use of multiple non-overlapping communication modalities for acoustic transmission is explored considering also power consumption and topology variations. The full knowledge of two-hop neighbours is assumed.

This short paper proposes a distributed and adaptive cross-layer routing protocol for UANs, with the support for multiple coded modulation schemes over the same acoustic medium. The NADIR protocol can work in the presence of both static and mobile devices and uses energy consumption as one of the key metrics to determine how to route packets in the network. Cross-layer information is exchanged with the physical layer to obtain link quality and energy consumption data. As a test case, the performance of the NADIR protocol was evaluated through simulation, considering a monitoring network deployed in a polar environment. An acoustic channel model and three physical layer schemes designed for this environment (both described in [10]) were considered. These three schemes open the possibility to explore different link qualities, bit rates and communication ranges. The protocol performance was compared with that of the EFlood protocol [13] (that was enhanced with the support for multiple communication schemes). The collected results show that the usage of an adaptive strategy leads to better network performance (in terms of packet delivery, energy consumption, end-to-end delay and network robustness[1]) with respect to static ones.

The remainder of the paper is organised as follows. Section II describes the NADIR protocol in details. The simulation scenarios and the collected results are detailed in Section III. Finally, Section IV concludes the paper.

II. NADIR protocol

The protocol operates in two phases. When the network is deployed, the nodes start exchanging control messages to

[1]The network robustness is defined as the minimum number of nodes that needs to be removed from the network to make it disconnected.

obtain relevant information such as number of hops, supported communication schemes or interfaces, presence of mobile nodes and link quality data to reach the neighbour nodes (Phase 1). An approach similar to the one used by the DIVE protocol [14] is implemented with a built-in mechanism to cope with unreliable channels. When this initial phase is completed, the actual network operations start with packets being routed in the network (Phase 2). During the second phase, control information is sent periodically to inform about any changes occurring on the estimated number of hops and on the quality of the links. This information can be sent appended to regular data messages or using dedicated control packets. Furthermore, each node transmits its residual available energy to the neighbours. This information is then used to select the best relay node.

The NADIR protocol is designed to work in the presence of mobile nodes. Data provided by these nodes is treated differently since the motion of mobile platforms would introduce continuous changes in the estimated hop counts and quality of the links. Each node keeps track of the presence and of the messages provided by mobile nodes but it does not use this data to update its routing information. The selection of static nodes as relays is therefore preferred and mobile nodes can be selected with a given probability[2].

The NADIR protocol makes use of four factors to route packets in the neighbourhood:

1) the estimated number of hops from the neighbour node to the intended destination;
2) the quality of the link to reach the neighbour node. In this paper the quality of the link is obtained as a cross-layer information computed by the physical layer, according to information received by the other nodes. It is provided in the form of a Packet Error Rate (PER) measurement, which depends on the message length, the considered waveform and the addressed link.
3) the energy required to transmit the information to the neighbour node (depending on the selected modulation scheme);
4) the residual energy of the neighbour node.

The transmitting node (x), computes for each neighbour node (y) and for each supported modulation scheme (m) a score to reach the intended destination (D). The following formula is used:

$$\begin{aligned}\text{Score}_{y,m,D} = &(\text{normalised\_hops}_{y,m,D} \times \text{hops\_weight})\\ &+ (\text{normalised\_link\_quality}_{x,y,m} \times \text{link\_quality\_weight})\\ &+ (\text{normalised\_energy}_{x,y,m} \times \text{pkt\_energy\_weight})\\ &+ (\text{normalised\_residual\_energy}_{y} \times \text{residual\_energy\_weight})\end{aligned}$$

The node y and modulation scheme m with the highest score are selected to relay the packet. Each of the considered factors is normalised to a value between $[0, 1]$, the higher the value the better is the relay node and modulation scheme. A weight is also applied to each factor with the sum of all the weights equal to one. Giving more weight to the number of hops, shorter routes will be selected, while giving more weight to the link quality, more reliable links will be preferred, even if incurring in longer routes. The energy required to transmit the information to the neighbour node is considered as a key factor. When multiple modulation and coding schemes are used[3], the trade-offs between robustness and throughput can be explored. This selection will result in a different transmission time and energy consumption for the considered packet. Finally, the use of the node residual energy as a scoring factor is to avoid selecting always the same node that will then fast run out of battery. This is particularly important for the nodes around the sink that will have to forward the packets coming from all the other nodes of the network. In this way, nodes can share the transmission load and therefore minimise the presence of a connectivity hole around the sink.

III. Performance Evaluation and Comparison

Both NADIR and EFlood were implemented using the SUNSET software [15], which can be freely downloaded from [16]. The EFlood protocol was enhanced with the support for multiple communications schemes. Every new incoming packet is broadcasted in the network selecting randomly the physical layer scheme to employ.

A. Performance metrics

Key metrics were established to compare the performance of the two routing solutions, considering reliability and robustness in delivering data to the sink along with delays and overhead introduced in the communications. The considered metrics are presented in what follows:

- **Goodput**, defined as the number of useful information bits delivered in the network per unit of time, excluding protocol overhead bits and retransmitted data packets. The goodput represents the end-to-end achievable bit rate.
- **End-to-end delay**, defined as the average time between data packet generation and data packet reception at the intended destination.
- **Overhead per bit**, defined as the average number of overhead bits transmitted in the network for each of the data bits correctly delivered in the network.
- **Energy per bit consumption**, defined as the average amount of energy required to correctly deliver one bit of data to the final destination.

B. Simulation scenarios and settings

The deployment of a monitoring network in harsh polar environment was considered as the test case scenario. A network of up to 21 nodes was (virtually) deployed in the Baffin Bay (Southwest coast of Greenland), covering an area of 100×240 km^2 with average distance between two adjacent nodes of 42 km.

Node 1 was the sink (being the one closer to land), while nodes 5 and 18 were two Autonomous Underwater Vehicles (AUVs). These AUVs were used to enlarge the monitored

[2]For the experiments in this paper, a large number of static nodes was deployed thus allowing to set this probability to a low value (0.15).

[3]This could be extended to the case of a multi-modal system with multiple communications interfaces, *e.g.*, acoustic and optical links.

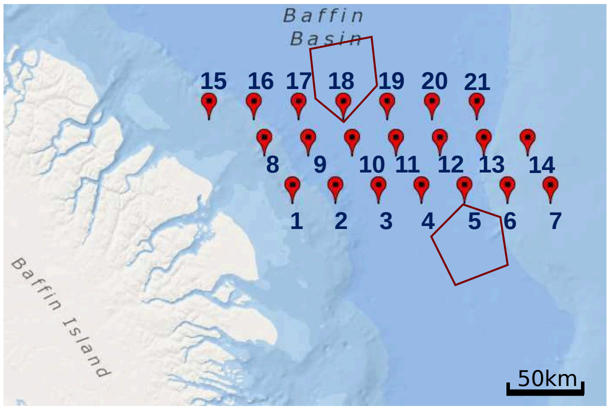


Figure 1: Baffin Bay network topology. AUVs moving areas are depicted with the red polygons.

region in the South and the North of the deployment area. They were covering a distance up to $60-80$ km south/north of their original position at a speed of 3 knots, following a random way-point mobility pattern[4]. Four different network sizes (N) were considered: $N = 9, 13, 17, 21$. The sink and the AUVs were always part of the network while different sets of nodes were cumulatively added to build the considered scenarios. All nodes were generating data (*e.g.*, environmental measurements and status reports) to be delivered to the sink. Similarly the sink was generating messages to be sent to the network nodes (*e.g.*, commands, mission updates). Two different packet sizes were considered, a short control message of 8 bytes and a larger data packet of 32 bytes.

To model the underwater acoustic channel the results presented in [10] were used. In that work, thee physical (PHY) layer schemes, *i.e.*, FH-BFSK (FSK), BPSK-OFDM (BPSK) and TCM-OFDM (TCM), were considered, enabling to explore different communication ranges, link qualities and transmission rates in the polar environment. The HMS-AT650 [18] transducer was considered, offering a bandwidth of 400 Hz at a centre frequency of 650 Hz and requiring 42 W acoustic power (60% efficiency) for a source level of 185 dB re 1μPa@1m. Table I shows some of the physical layer parameters. A high power consumption is reported in reception mode since an array of 96 elements was used.

Table I: PHY layer parameters.

Freq. (Hz)	Band. (Hz)	bit rate (bps)			Power consump. (W)		
		FSK	BPSK	TCM	TX	RX	Idle
650	400	1.8	21.4	96.2	42	20	0.133

One of the requirements considered for the addressed scenario was to guarantee connectivity and continuous network operation of one year. Given the high channel unreliability, an additional quality of service requirement was introduced to ensure an effective data delivery in the network. Only scenarios where the employed protocols are able to deliver at least 90% of the generated packets were considered. All the results presented in the following Section satisfy the packet delivery and network lifetime requirements.

The SUNSET carrier sensing ALOHA protocol [19] was used at the MAC layer with acknowledgement packets (ACKs). The MAC protocol was also exchanging cross-layer information with NADIR to add the required control data in piggybacking to ACK messages. The EFlood protocol, requiring broadcast transmissions, was not using any acknowledgement message. To increase its robustness, each node was transmitting multiple replicas of the same packet. The number of replicas was computed based on the average quality of the links between the node and its neighbourhood. Using this approach an increase in the data delivery up to 20% was obtained by EFlood with respect to the case of no replicas.

For the considered network configurations, all three schemes were supported by each node. It is not possible to send or receive in parallel with two schemes from the same node. It is instead possible to listen simultaneously to all supported modulation and coding schemes. Various weights were used by the NADIR protocol, empirically tuned depending on the network size, to provide the better tradeoff between goodput, energy consumption and robustness[5].

C. Simulation results

Figure 2 shows the performance comparison between the NADIR and EFlood protocols when the goodput metric is considered. The additional metrics are then reported in Figure 3. When only the TCM scheme is used the network is always disconnected, while for the BPSK case it is connected when $N \geq 13$.

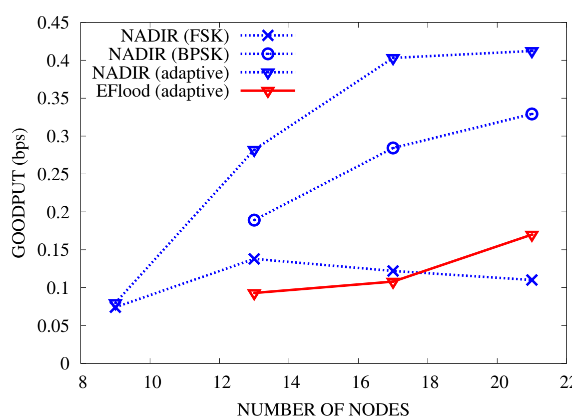
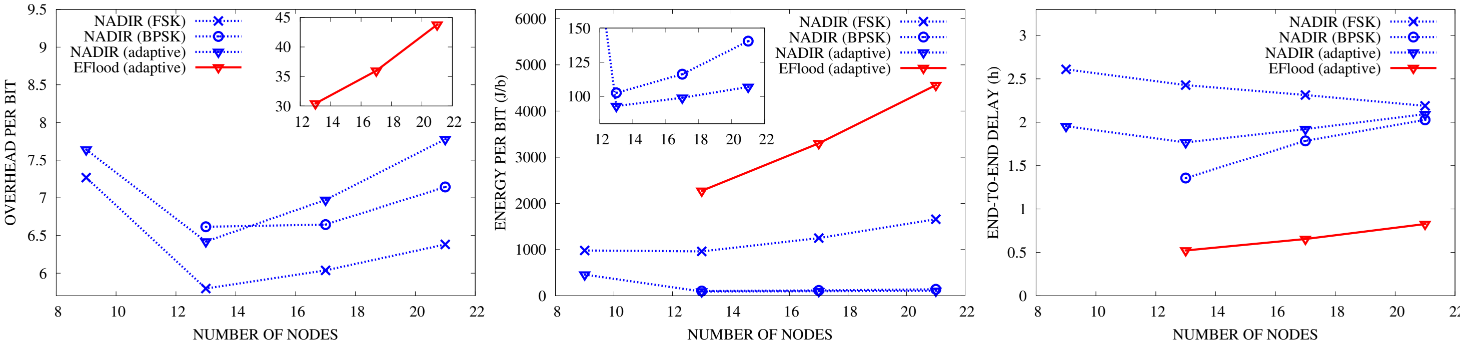


Figure 2: Goodput, performance comparison.

For NADIR the results when using single modulation schemes and the adaptive strategy (selecting among multiple schemes) are reported. For EFlood instead only the adaptive case is presented since it enables to meet the packet delivery and network lifetime requirements (when $N \geq 13$). When the FSK scheme is considered a very long packet collision

[4]In order to properly navigate, each AUV triggers a ranging request every 3 hours. All the nodes receiving the request reply according to the NETLBL protocol [17] to compute the two-way-time-of-flight measurements.

[5]hops_weight $\in [0.2, 0.3]$; link_quality_weight $\in [0.2, 0.3]$; pkt_energy_weight $\in [0.25, 0.35]$; residual_energy_weight $\in [0.1, 0.15]$. Values are set at the beginning of the simulation and do not vary over time.



(a) Overhead per bit. (b) Energy per bit consumption. (c) End-to-end latency.

Figure 3: Performance comparison among the considered protocols.

window is experienced which leads to many errors in the message delivery, especially in the presence of multiple duplicate transmissions. Using faster schemes the reliability of the links reduces. Without implementing any acknowledgement mechanism a significant reduction in the delivered data is experienced.

Increasing the number of nodes results in more and better links available in the network. For both protocols, this results in improving the robustness of the network and the achievable goodput (Figure 2). Although NADIR requires the exchange of control information to perform "smarter" PHY scheme selection, better goodput performance can be obtained with respect to EFlood. The use of BPSK results in better performance with respect to the FSK scheme, since it reduces the transmission time and the occupation of the channel by one order of magnitude. This enables the delivery of more bits and the reduction of energy consumption even if the overhead per bit is higher. More retransmissions and longer routes are in fact required by BPSK with respect to FSK, due to the lower reliability of the links. When using the adaptive approach all three modulation schemes are employed. Table II shows the average percentage of usage of each modulation scheme for the NADIR protocol.

Table II: Percentage of usage of each modulation scheme by the NADIR adaptive strategy.

Network size	FSK	BPSK	TCM
9	50%	44%	6%
13	13%	63%	24%
17	3%	63%	34%
21	1%	62%	37%

Similarly to EFlood, the use of the adaptive approach with NADIR always results in a higher goodput (Figure 2) with respect to the single schemes. When using NADIR the average overhead per bit is reduced by several times with respect to EFlood while the average energy per bit consumption is reduced by up to more than one order of magnitude. Slower and more reliable links are preferred by NADIR when the network is sparse. This results in less bits delivered, a higher overhead per bit (Figure 3a) and a larger energy per bit consumption (Figure 3b). When faster and less reliable links are available, these are preferred. Although a larger number of retransmissions is experienced, the channel occupation and the energy per bit are reduced by up to two orders of magnitude. This results in both a higher goodput and a lower energy per bit consumption. The use of the node energy budget as one of the key metrics for the relay selection provides an even distribution of the load. When $N = 21$, each node makes use, on average, of up to 3.1 different relay nodes, due to the reduction in their energy budget over time. Depending on the different configurations, the selection of the PHY layer scheme to use is always a trade-off between the capability of data delivery and energy consumption, as also expressed in NADIR selection strategy.

When more nodes are deployed, more data are pushed into the channel. Increasing the number of nodes also increases the number of potential interferers. Nodes start finding the channel busy more often, thus delaying their transmissions. For the FSK scheme the end-to-end delay (Figure 3c) is mainly affected by the long transmission time and the backoff delay when the channel is found busy. When considering faster schemes, the transmission time is reduced but the number of failures in the message delivery increases. For each failure the transmitting node has to wait the acknowledgement timeout before starting the backoff delay. EFlood achieves an end-to-end delay up to four times shorter than NADIR, since no packet retransmissions are performed at the MAC layer. This comes at the cost of a significant reduction in the number of delivered messages.

IV. Conclusions

In this paper the NADIR protocol was presented to adaptively select the relay node and physical layer scheme to use when routing packets in the network. The proposed solution is fully distributed, self adaptive and explicitly supports the presence of mobile nodes. The use of cross-layer information from the PHY is considered in support of the routing selection strategy. Three different modulation and coding schemes were selected resulting in different link qualities, bit rates and communication ranges. The protocol performance was evaluated in a harsh polar environment, with very long propagation delays and an unreliable acoustic channel. The collected results show that NADIR outperforms the EFlood in terms of goodput, energy consumption and introduced overhead. Additionally, the adaptive strategy results in a better trade-off between packet delivery, network robustness and energy consumption.

Acknowledgements

The authors would like to acknowledge and thank Dale Green and Yannis Fountzoulas for their valuable support to this work. This work was co-funded by Defence Research and Development Canada (DRDC) and NATO Allied Command Transformation (ACT) Future Solutions Branch under the Autonomous Security Network Programme.

References

[1] J. Heidemann, M. Stojanovic, and M. Zorzi, "Underwater sensor networks: Applications, advances, and challenges," *Royal Society*, vol. 370, no. 1958, pp. 158–175, May 2012.

[2] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 84–89, January 2009.

[3] F. Campagnaro, R. Francescon, P. Casari, R. Diamant, and M. Zorzi, "Multimodal Underwater Networks: Recent Advances and a Look Ahead," in *Proceedings of the 12th ACM International Conference on Underwater Networks and Systems - WUWNet'17*. Halifax, NS, Canada: ACM Press, November, 6–8 2017.

[4] T. Hu and Y. Fei, "MURAO: A Multi-level Routing Protocol for Acoustic-Optical Hybrid Underwater Wireless Sensor Networks," in *Proceedings of the 9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, ser. SECON'12, Seoul, Korea, June 18–21 2012.

[5] F. Campagnaro, F. Guerra, P. Casari, R. Diamant, and M. Zorzi, "Implementation of a Multi-modal Acoustic-Optical Underwater Network Protocol Stack," in *Proceedings of MTS/IEEE OCEANS 2016*, Shanghai, China, April 10–13 2016.

[6] P. Gjanci, C. Petrioli, S. Basagni, C. A. Phillips, B. Ladislau, and D. Turgut, "Path Finding for Maximum Value of Information in Multi-Modal Underwater Wireless Sensor Networks," *IEEE Transactions on Mobile Computing*, vol. 17, no. 2, pp. 404–418, February 2018.

[7] R. Petroccia, G. Cario, M. Lupia, V. Djapic, and C. Petrioli, "First in-field Experiments with a "Bilingual" Underwater Acoustic Modem supporting the JANUS Standard," in *Proceedings of MTS/IEEE OCEANS 2015*, Genova, Italy, May 18–21 2015.

[8] 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*, vol. 42, no. 3, pp. 722–737, July 2017.

[9] E. Demirors, G. Sklivanitis, G. E. Santagati, T. Melodia, and S. N. Batalama, "A High-Rate Software-Defined Underwater Acoustic Modem with Real-Time Adaptation Capabilities," *IEEE Access*, vol. PP, no. 99, March 2018.

[10] K. Pelekanakis, D. Green, Y. Fountzoulas, R. Petroccia, S. Fioravanti, J. Alves, and S. Blouin, "A modem design for underwater acoustic networking in the high north," in *submitted to the 4th IEEE OES International Conference on Underwater Communications and Networking*, ser. UComms18, Lerici, Italy, August 28–30 2018.

[11] S. Basagni, V. Di Valerio, P. Gjanci, and C. Petrioli, "Finding MARLIN:Exploiting multi-modal communications for reliable and low-latency underwater networking," in *Proceedings of the IEEE International Conference on Computer Communications*, ser. INFOCOM'17, Atlanta, GA, USA, May 1–4 2017.

[12] R. Diamant, P. Casari, F. Campagnaro, O. Kebkal, V. Kebkal, and M. Zorzi, "Fair and throughput-optimal routing in multimodal underwater networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 1738–1754, March 2018.

[13] J. Alves, R. Petroccia, and J. R. Potter, "MPR: multi-point relay protocol for underwater acoustic networks," in *Proceedings of the 9th ACM International Conference on Underwater Networks and Systems*, ser. WUWNet'14, Rome, Italy, November 12–14 2014.

[14] R. Petroccia, "A distributed ID assignment and topology discovery protocol for underwater acoustic networks," in *Proceedings of the 3rd IEEE OES International Conference on Underwater Communications and Networking*, ser. UComms16, Lerici, Italy, August 30 – September 1 2016.

[15] C. Petrioli, R. Petroccia, J. R. Potter, and D. Spaccini, "The SUNSET framework for simulation, emulation and at-sea testing of underwater wireless sensor networks," *Ad Hoc Networks*, vol. 34, pp. 224–238, 2015.

[16] SENSES Lab, "SUNSET: Sapienza University Networking framework for underwater Simulation, Emulation and real-life Testing," http://reti.dsi.uniroma1.it/UWSN_Group/index.php?page=sunset, Last time accessed: June 2018.

[17] J. Śliwka, R. Petroccia, A. Munafò, and V. Djapic, "Experimental evaluation of Net-LBL: an acoustic network-based navigation system," in *Proceedings of MTS/IEEE OCEANS 2017*, June, 19–22 2017, pp. 1–9.

[18] Falmouth Scientific Inc., "HMS-AT650 Underwater Transducer, note = Last time accessed: June 2018, howpublished=https://www.oceanologyinternational.com/__novadocuments/245657?v=636016667424830000."

[19] S. Basagni, C. Petrioli, R. Petroccia, and M. Stojanovic, "Optimized packet size selection in underwater WSN communications," *IEEE Journal of Oceanic Engineering*, vol. 37, no. 3, pp. 321–337, July 2012.

Document Data Sheet

Security Classification		Project No.
Document Serial No.	**Date of Issue**	**Total Pages**
CMRE-PR-2019-027	May 2019	5 pp.

Author(s)

Roberto Petroccia, Konstantinos Pelekanakis, Joao Alves, Stefano Fioravanti, Stephane Blouin, Sean Pecknold

Title

An adaptive cross-layer routing protocol for underwater acoustic networks

Abstract

This short paper presents an adaptive cross-layer routing protocol for Underwater Acoustic Networks (UANs). The proposed solution, termed NADIR for Network Aware aDaptIve Routing, is fully distributed and self-adaptive. It supports the use of multiple coded modulation schemes and the usage of crosslayer information to interact with the physical layer. Link quality information is exploited along with energy and topological data in order to select the relay node to use. The protocol performance has been evaluated considering a challenging networking scenario, i.e., a polar environment, with very long propagation delays and a high probability of packet errors. The results show that the use of an adaptive strategy offers better network performance in terms of packet delivery and energy consumption in the presence of unreliable channels.

Keywords

Underwater communications, underwater networks, adaptive routing, cross-layer routing

Issuing Organization

NATO Science and Technology Organization
Centre for Maritime Research and Experimentation

Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
STO CMRE
Unit 31318, Box 19, APO AE 09613-1318]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@cmre.nato.int