Optimized Incremental Cooperative Communication for Underwater Acoustic Sensor Networks

Veerapu Goutham*, V.P. Harigovindan†
Department of Electronics and Communication Engineering
National Institute of Technology Puducherry, Karaikal, India 609609.
Email: *gouthamveerapu@gmail.com, †hari.nitpy.ac.in

***Abstract*—In this article, we present incremental cooperative communication (ICC) for underwater acoustic sensor networks (UANs). This method uses adjacent active sensor nodes during the retransmission of DPs. Subsequently, a mathematical model to calculate the energy efficiency (EE) for ICC in UANs by examining the influences of distance-dependent usable bandwidth, ambient noises, and acoustic spreading is presented. Numerical and simulation results show that ICC significantly improves EE compared to the existing techniques over considerable distances between transceiving nodes. We later frame an optimization problem to optimize transmission power and packet size to improve EE over transmission distance further. The results confirm that the optimized can further increase the EE of UANs.**

***Index Terms*—EE, Genetic algorithm, Incremental cooperative communication, Underwater acoustic sensor network.**

I. Introduction

The underwater acoustic sensor network (UASN) has recently started playing an important part in addressing various issues and challenges, such as the search and survey missions, prediction of natural disturbances, pollution control, and many more. In many of these applications, sensors are used to collect information from the seafloor and transmit it to the buoy above the sea surface. Then the sensed information is transmitted to the earth station by the buoy either through satellite channels or RF signals [1], [2]. Although RF signals have significant bandwidth, they attenuate very quickly within a few meters or tens of meters due to the conductivity of the saltwater [1], [3]–[5]. However, optical signals require an accurate line of sight (LoS) with the detector. LoS is very difficult to maintain as the sensor nodes are highly dynamic due to sea currents. So, most underwater network applications rely on acoustic signals to enable communications between sensor nodes. As a result, acoustic signals are widely chosen for UASN, resulting in reduced bandwidths and increased propagation delays compared to the terrestrial wireless networks.

Energy efficiency (EE) is considered key performance metrics in UANs because the sensor nodes' lifetime depends largely on the batteries. Furthermore, it is challenging to replace or recharge the batteries if they drained due to the power consumption of the transmitter and receiver circuit [6]. Limiting the transmissions by a node is one of the feasible strategies for improving EE. As a result, cooperative communication is a prominent method that improves EE by using spatially diverse links. This scheme uses adjacent active sensor nodes to retransmit packets. The authors in [7] proposed an incremental relay technique for UANs. In which relay nodes are used incrementally at the time of packet retransmissions. This scheme achieves high throughput at the cost of increased energy consumption (EC) by additional relay nodes. The authors of [8] proposed an opportunistic cooperative routing protocol for UANs. In this scheme, the authors found the best relay node based on a fuzzy logic relay selection scheme. The authors of [9] have proposed a cooperative routing protocol for UANs. However, the majority of the published work on cooperative communications in the UANs focuses mainly on simulation analysis. Mathematical modeling for computing the EE of UANs is rarely investigated. In this paper:

1) We introduce an mathematical model to calculate EE of incremental cooperative communication (ICC) for UANs by considering the impacts of acoustic fading, ambient noises and underwater channel conditions. ICC uses adjacent active sensor nodes during the retransmission of DPs (DPs).
2) The numerical and simulation results show that the ICC scheme achieves improved performance over the direct communication scheme in EE when the transmission distance is higher.
3) We then frame an optimization problem to maximize EE by jointly optimizing transmission power and packet size. The results show that ICC significantly improved EE with the Genetic Algorithm Optimization Technique, leading to an energy-efficient ICC scheme for UANs.

II. System Model

A. Physical layer model of UANs

In this subsection, we introduce the physical layer model for calculating the SNR in UANs [10]. The transmission losses (TL) consists of spreading and absorption losses. $TL(d,f) = (1000d)^{\kappa}\ a(f)^{d}$, gives the TL between transceiving nodes, where κ is the spreading factor, d is the gap between transceiving nodes in Km, and $a(f)$ is the absorption coefficient in dB/Km for f in KHz, which is given by,

$$10\log_{10} a(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + \frac{2.75}{10^4}f^2 + 0.003. \quad (1)$$

Ambient noises in UANs includes turbulence $N_t(f)$, shipping $N_s(f)$, waves $N_w(f)$ and thermal noise $N_{th}(f)$. The

978-0-7381-1151-3/20/$31.00 ©2020 IEEE

power spectral density (psd) models of these noises are given by [10], [11],

$$\begin{aligned}
\log_{10} N_t(f) &= 1.7 - 3\log_{10} f, \\
\log_{10} N_s(f) &= 4 + 2(s - 0.5) + 2.6\log_{10} f \\
&\quad -6\log_{10}(f + 0.03), \\
\log_{10} N_w(f) &= 5 + 0.75w^{0.5} + 2\log_{10} f \\
&\quad -4\log_{10}(f + 0.4), \\
\log_{10} N_{th}(f) &= -1.5 + 2\log_{10} f,
\end{aligned} \tag{2}$$

Here w is wind speed, and s is the shipping activity. The aggregate of four noise components gives the complete psd of ambient noise $(N(f))$ present in the sea. The approximate power spectral density (psd) of ambient noise present in sea is given by, $10\log_{10}(N(f)) = 50 - 18\log_{10}(f)$. Accordingly, the SNR between transceiving nodes ($\Gamma(d, f)$) is expressed as [10], [12],

$$\Gamma(d, f) = \frac{\frac{S(f)\ \Delta f}{TL(d,f)}}{N(f)\Delta f} = \frac{S(f)}{TL(d, f)N(f)}, \tag{3}$$

where $S(f)$ denotes source psd of the transmitted signal, which is expressed as $S(f) = SL$ for $f \in B(d)$, and 0 otherwise. $B(d)$ represents distance-dependent usable bandwidth. Therefore, the total transmission power is given by, $P(d) = SL\ B(d)$. From [10], $B(d) = Bd^{-Q}$ and $P(d) = Pd^T$. Here B and P are bandwidth and power coefficients respectively, Q and T are positive constants. In UANs, noise and path losses are primarily dependent on the signal frequency of f and the transmission distance.

The communication links between nodes in UANs are described by Rayleigh fading channel due to the multi-path propagation of acoustic signals. The path gains achieved by the different paths are assumed to be statistically i.i.d communication channels [13]. We also assumed the quadrature amplitude modulation method with modulation level $b = log_2 M$ bits/symbol. Accordingly, the closed-form approximation to calculate the symbol error rate (SER) of a Rayleigh fading channel link between transceiving nodes is provided in [14].

$$SER \approx 2(1 - 2^{\frac{-b}{2}})\left(1 - \sqrt{\frac{3\Gamma(d, f)}{2(2^b - 1) + 3\Gamma(d, f)}}\right). \tag{4}$$

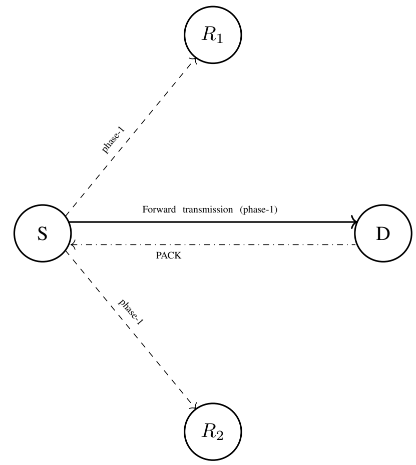
The sensor node divides the gathered information into several DPs, each with a packet length χ bits. The DP consists of header bits, payload bits and trailer bits. The PER of a link between transceiving nodes is given by,

$$PER = 1 - (1 - SER)^{\frac{\chi}{b}}, \tag{5}$$

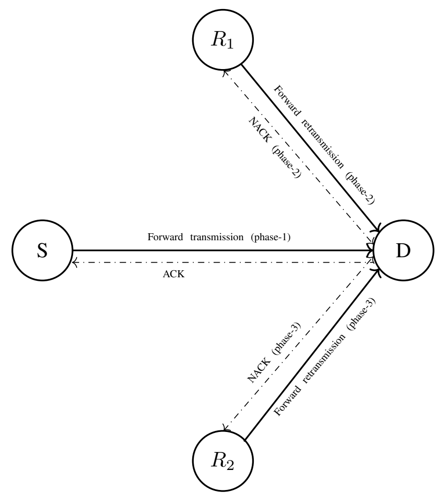
where $(1 - SER)^{\frac{\chi}{b}}$ is the success probability for transmitting $\frac{\chi}{b}$ symbols between the transceiving nodes.

B. Incremental cooperative communication

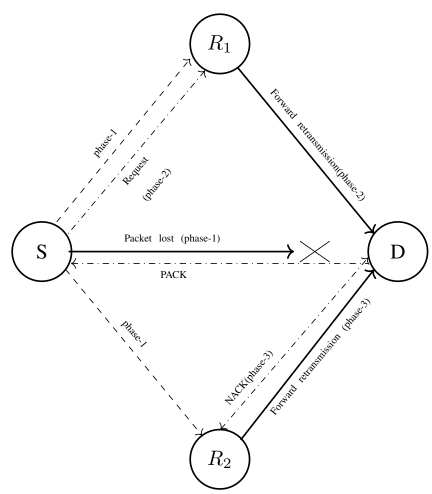
We assume a general UASN system model consists of the source node (S), the relay nodes (R_1 and R_2) and the destination node (D) as shown in Fig. 1. Here, two different



(a) Case 1: Packet transmission with successful decoding at the destination node



(b) Case 2: Packet retransmission when destination node decoded incorrectly



(c) Case 3: Packet retransmission when source node timeout timer expires

Fig. 1: Incremental Cooperative Communication

transmission schemes were considered, namely direct communication (DC) and ICC. In the DC scheme, node S transmits symbols directly to the node D through S-D channel link in each orthogonal resource slots. In the event of any incorrect packet reception, node S itself retransmits the symbols after receiving a negative acknowledgement (NACK) from node D. However, the DC scheme will be inefficient when there are any connection failures between the source and the destination nodes due to deep fading.

The illustration of the ICC protocol is shown in Fig. 1. At first, the S node transmits the control packets whenever the data has to be forwarded. The nodes that receive the control packets can provide the depth data as an acknowledgement. As a result, the S node will select the R_1, R_2 and D nodes based on the received information. The node with the lowest depth (or nearest to the sea surface) is chosen as a D node. Nodes which are nearer to the centre are chosen as R_1, and R_2 nodes. The best possible EE for cooperative relaying strategy is obtained when the relay nodes are precisely at the centre between transceiving nodes [13], [15]. Later, the S node transmits the DPs and the addresses of R_1, R_2, and D nodes. In phase-1, the R_1, and R_2 nodes will also receive DPs other than the D node shown in fig.1. If the D node receives the DP accurately, it transmits a positive acknowledgement (PACK) to the S node as shown in Fig. 1a. Otherwise, D sends a NACK to R_1, and R_1 retransmits the DP in phase-2. If this transmission is also received with errors, then the NACK will be sent to R_2 for packet transmission from the D node in the next phase, as shown in Fig. 1b. If all S, R_1, and R_2 are unsuccessful, the D node drops the DP. Here, PACK will be sent to the S node by the D node after the successful receipt of the DP from any of the relay nodes. In some cases, the S node will not get the PACK due to connection failure between the S and D nodes, which will result in the timer being expired at the source node. The S node itself permits the R_1 node to forward the DP, as shown in Fig. 1c in this condition. Therefore this scheme is advantageous in connection failures between the S and D nodes.

C. Mathamatical modelling for the calculation of EE in UANs

EE is defined as the overall amount of EC by the successful transmission of the information bits. This is the ratio of successfully transmitted message bits to the overall EC. Here, we presented an mathamatical model to calculate the EE of both DC and ICC schemes.

1) Direct Communication: The DC scheme's overall EC is the o aggregate of EC by the S and D nodes to transmit and receive the DP. It is given by,

$$E_{DC} = (P_{tx} + P_{rx})\,\frac{\chi}{R_b}, \tag{6}$$

where P_{tx} is the transmitting node, P_{rx} are the transmitting and receiving node power consumption, χ is the packet size and R_b is the data rate achieved in UANs. Therefore, the EE of the DC scheme can be obtained by,

$$\eta_{DC} = \frac{\chi_p(1 - PER_{DC})}{E_{DC}}, \tag{7}$$

where χ_p is payload of the DP and PER_{DC} is the total PER of the DC scheme. PER_{DC} is given by,

$$PER_{DC} = 1 - (1 - SER_{sd})^{\frac{\chi}{b}}, \tag{8}$$

where $(1 - P_{S_{sd}})^{\frac{\chi}{b}}$ denotes the success probability for transmitting $\frac{\chi}{b}$ symbols from S to D nodes. $1 - (1 - P_{S_{sd}})^{\frac{\chi}{b}}$ gives failure probability for transmitting a DP from nodes S to D.

2) Incremental Cooperative Communication: The ICC scheme's overall EC is the aggregate of EC by the nodes S, R_1, R_2 and D for transmission and receipt of the DP. Therefore, the overall EC in the ICC can be obtained by [16],

$$\begin{aligned}E_{ICC}=&\{[P_{tx}+3P_{rx}]\,(1-PER_{sd})+\\&[2P_{tx}+4P_{rx}]PER_{sd}(1-PER_{sr_1})(1-PER_{r_1d})\\&+[2P_{tx}+5P_{rx}]\,PER_{sd}PER_{sr_1}\,(1-PER_{sr_2})\\&(1-PER_{r_2d})+[3P_{tx}+6P_{rx}]\,PER_{sd}\\&(1-PER_{sr_1})PER_{r_1d}(1-PER_{sr_2})(1-PER_{r_2d})\\&+[P_{tx}+3P_{rx}]\,PER_{sd}PER_{sr_1}PER_{sr_2}\}\times\frac{\chi}{R_b}.\end{aligned} \tag{9}$$

The initial term in (9) is the EC for the successful transmission of the packet through the $(S-D)$ channel link. The second term is the EC for failed transmission of the packet over $(S-D)$ and successful transmission of the packet over the S-D via relay $(S-R_1-D)$ channel link. The third and fourth terms are EC for an failed transmission of the packet over $(S-D)$, $(S-R_1-D)$ channel links, and successful transmission of the packet over $(S-R_2-D)$ channel link. The fifth term is the EC for the failed transmission of the packet over $(S-D)$, $(S-R_1)$, $(S-R_2)$ paths. Therefore, the EE of ICC scheme can be calculated by,

$$\eta_{ICC} = \frac{\chi_p(1 - PER_{ICC})}{E_{ICC}}, \tag{10}$$

where the total PER of the ICC scheme (PER_{ICC}) is given by,

$$\begin{aligned}PER_{ICC} \;=\;& PER_{sd}PER_{sr_1}PER_{sr_2}\\&+PER_{sd}\,(1-PER_{sr_1})\,PER_{r_1d}PER_{sr_2}\\&+PER_{sd}PER_{sr_1}\,(1-PER_{sr_2})\,PER_{r_2d}\\&+PER_{sd}\,(1-PER_{sr_1})\,PER_{r_1d}\\&(1-PER_{sr_2})\,PER_{r_2d}.\end{aligned} \tag{11}$$

The first term in (11) is the failed transmission of packets over $(S-D)$, $(S-R_1)$ and $(S-R_2)$ channel links. The second term is the failed transmission of packets over $(S-D)$, $(S-R_1-D)$ and $(S-R_2)$ channel links. The third term is the failed transmission of packets over $(S-D)$,$(S-R_1)$ and $(S-R_2-D)$ channel links. The fourth term is the failed transmission of packets over $(S-D)$, $(S-R_1-D)$, $(S-R_2-D)$ channel links.

D. Optimization problem for EE maximization

Packet size and transmission power are vital constraints in UANs to boost the EE performance. On the one hand, large packets are prone to packet errors than small-sized packets. In contrast, the small-sized packets are more flexible to packet errors. Particularly sending small-sized packets could be a good option for avoiding bit errors. Small packets result in added frames after the packet fragmentation, increasing the packet overhead and EC. On the other hand, packets transmitting with high powers reduce errors but increase the network's EC. To this end, we use the Genetic algorithm optimization method to optimize the EE by optimizing the packet size and transmission power over transmission distance. In which, packet size and transmission power varies between $[10 - 64000\ Kb]$ and $[\ 1mW - 10W\ ]$ respectively. Using the expressions of the EE η_{ICC} from (9), we can frame the optimization problem as:

$$\underset{X, P_{tx}}{\text{maximize}} \quad \eta_{ICC} \tag{12a}$$

$$\text{subject to} \quad X \in [10\ ,\ 64000Kb)\ , \tag{12b}$$

$$P_{tx} \in [1mW, 10W] \tag{12c}$$

III. Results and Discussion

Here, we have provided numerical outcomes for EE analysis using MATLAB® R2018b and the outcomes are crosschecked with ns-3 simulations. We taken an assumption that the distances between R_1-D and R_2-D channel links are $0.5{*}rsd$ and $0.75{*}rsd$, respectively. The parameters used for mathematical and simulation analysis are reflected in Table-II [17], [18].

TABLE I: Parameters used for performance review

System parameter	Value
Bandwidth coefficient (B)	19.76 $dB\ re\ \mu kHz$
Bandwidth exponent (Q)	0.59 $dB\ re\ \frac{kHz}{km}$
Transmit power consumption (P_{tx})	5 W
Receive power consumption (P_{rx})	1.3 W
Bit rate	13900 b/s
Payload size L_p	20 $bytes$
Packet size L	1280 $bytes$
Frequency f	10 KHz
κ (Spreading factor)	1.5 for practical spreading
Depth in Km	0.5
Wind speed (w)	6.67 m/s (average wind speed)
Shipping activity (s)	0.5 (average value)
Noise model	ns3::UanNoiseModelDefault
Propagation model	ns3::UanPropModelThorp
PER model	ns3::UanPhyPerCommonModes
Energy model	ns3::AcousticModemEnergyModelHelper
mobility model	ns3::ConstantPositionMobilityModel

Figure 2 illustrates the change of EE to the gap between the S-D link. The ICC and DC schemes' energy efficiencies decrease as the increase in gap between the S-D link. The primary reason for this is the respective channel links SNRs drop with the distance rise. Another significant note from Fig. 2 is that due to the extra EC by the relay nodes in ICC, the ICC scheme works less than the DC for smaller gap between the S-D link. The ICC scheme significantly improved the EE compared to the DC scheme for higher gap between the S-D link. The SNR of the ICC scheme raised significantly as opposed to the DC scheme with the packet transmission over multiple spatially diverse links. Indicating that threshold separation between the transceiving nodes is critical in deducting the optimal transmission regime concerning the gap between the transceiving nodes.

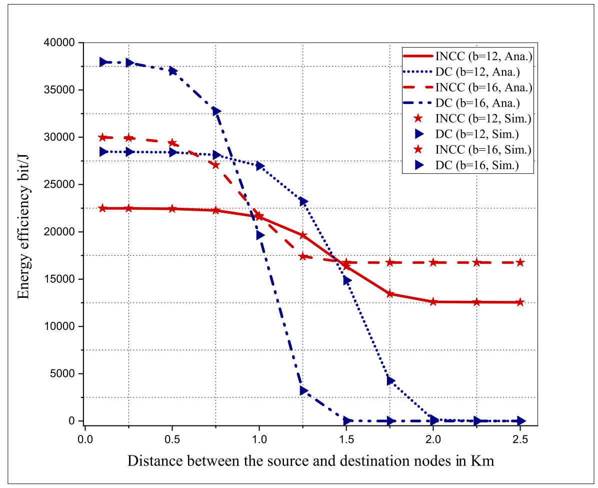


Fig. 2: EE versus the distance separation between source and destination nodes

TABLE II: Optimization outcomes using GA

Distance	EE Kbits/J		Transmission power	Packet size (Kb)
	ICC	Optimized ICC		
100	29.968	92.358	0.0377	20.930
500	29.406	76.529	0.2	70.642
1000	21.703	70.984	0.0112	18.470
1500	16.750	68.864	0.0419	17.661
2000	16.747	64.841	0.1217	5.7371
2500	16.744	40.817	1.0509	3.2029

Table II shows the ICC scheme's optimum EE simultaneously with respective optimal transmission power and packet size. ICC scheme with joint optimal transmission power and packet size notably enhances the EE, as reflected in the Tables II. It is evident that the Genetic algorithm optimally allocating the transmission power from 1 mW to 10 W and packet size (χ) from 10 Kb to 64000 Kb to optimize the EE.

IV. Conclusion

We have presented a mathematical model to estimate the EE of DC and ICC schemes in UANs in this paper. It is clear from the results that ICC can function superior to the DC scheme regarding the EE in UANs. It also confirms the presence of a threshold gap between the transceiving nodes, which is fundamental in determining the transmission gap's ideal transmission regime. An optimization problem is constructed to optimize ICC EE by collectively optimizing packet size and transmission power. The outcomes show that this algorithm further improves the EE of the ICC scheme. With this work, we deduce that ICC with an optimization algorithm can greatly increase the EE of UANs.

ACKNOWLEDGMENT

This work is supported by Science Engineering Research Board, Department of Science and Technology, Government of India, under Mathematical Research Impact Centric Support scheme with file number MTR/2019/001228.

REFERENCES

[1] R. W. L. Coutinho, A. Boukerche, L. F. M. Vieira, and A. A. F. Loureiro, "Underwater wireless sensor networks: A new challenge for topology control-based systems," *ACM Computing Surveys*, vol. 51, no. 1, pp. 19:1–19:36, Jan. 2018. [Online]. Available: http://doi.acm.org/10.1145/3154834

[2] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," *Ad Hoc Networks*, vol. 3, no. 3, pp. 257–279, 2005.

[3] H. Kaushal and G. Kaddoum, "Underwater Optical Wireless Communication," *IEEE Access*, vol. 4, pp. 1518–1547, 2016.

[4] H. Yan, Z. J. Shi, and J.-H. Cui, *DBR: Depth-Based Routing for Underwater Sensor Networks*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 72–86. [Online]. Available: https://doi.org/10.1007/978-3-540-79549-0_7

[5] A. Darehshoorzadeh and A. Boukerche, "Underwater sensor networks: a new challenge for opportunistic routing protocols," *IEEE Communications Magazine*, vol. 53, no. 11, pp. 98–107, November 2015.

[6] N. Abughalieh, K. Steenhaut, A. Nowé, and A. Anpalagan, "Turbo codes for multi-hop wireless sensor networks with decode-and-forward mechanism," *EURASIP Journal on Wireless Communications and Networking*, vol. 2014, no. 1, p. 204, Nov 2014.

[7] H. Nasir, N. Javaid, M. Sher, U. Qasim, Z. A. Khan, N. Alrajeh, and I. A. Niaz, "Exploiting outage and error probability of cooperative incremental relaying in underwater wireless sensor networks," *Sensors*, vol. 16, no. 7, 2016. [Online]. Available: https://www.mdpi.com/1424-8220/16/7/1076

[8] M. A. Rahman, Y. Lee, and I. Koo, "Eecor: An energy-efficient cooperative opportunistic routing protocol for underwater acoustic sensor networks," *IEEE Access*, vol. 5, pp. 14 119–14 132, 2017.

[9] K. Pervaiz, A. Wahid, M. Sajid, M. Khizar, Z. A. Khan, U. Qasim, and N. Javaid, "Deac: Depth and energy aware cooperative routing protocol for underwater wireless sensor networks," in *2016 10th International Conference on Complex, Intelligent, and Software Intensive Systems (CISIS)*, 2016, pp. 150–158.

[10] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," in *Proceedings of the 1st ACM International Workshop on Underwater Networks*, ser. WUWNet '06. New York, NY, USA: ACM, 2006, pp. 41–47.

[11] Y. Li, Y. Zhang, H. Zhou, and T. Jiang, "To relay or not to relay: Open distance and optimal deployment for linear underwater acoustic networks," *IEEE Trans. Commun.*, vol. 66, no. 9, pp. 3797–3808, Sep. 2018.

[12] H. U. Yildiz, V. C. Gungor, and B. Tavli, "Packet size optimization for lifetime maximization in underwater acoustic sensor networks," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 2, pp. 719–729, Feb 2019.

[13] S. Wang and J. Nie, "Energy efficiency optimization of cooperative communication in wireless sensor networks," *Eurasip Journal on Wireless Communications and Networking*, vol. 2010, 2010.

[14] A. Goldsmith, *Wireless communications*. Cambridge, New York: Cambridge University Press, 2005.

[15] K. S. Geethu and A. V. Babu, "Minimizing the Total Energy Consumption in Multi-hop UWASNs," *Wireless Personal Communications*, vol. 83, no. 4, pp. 2693–2709, 2015.

[16] V. Goutham and V. P. Harigovindan, "Modeling and analysis of hybrid arq scheme for incremental cooperative communication in underwater acoustic sensor networks," *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, Jun 2020.

[17] M. Uysal, E. Panayirci, and H. Nouri, "Information theoretical performance analysis and optimisation of cooperative underwater acoustic communication systems," *IET Communications*, vol. 10, no. 7, pp. 812–823, 2016.

[18] Evologics, "Underwater acoustic modem," https://evologics.de/acoustic-modems, August 2020.