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Efficient Data Communication in Underwater Sensor Network Based on H-Leach Algorithm

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ABSTRACT

Underwater wireless sensor networks (UWSNs) have emerged as an enabling technology for aquatic monitoring. However, data delivery in UWSNs is challenging, due to the harsh aquatic environment and characteristics of the underwater acoustic channel. In recent years, underwater nodes with multi- modal communication capabilities have been proposed to create communication diversity and improve data delivery in UWSNs. Nevertheless, less attention has been devoted to the design of networking protocols leveraging multi-modal communication ca-pabilities of underwater nodes. In this paper, we propose a novel stochastic model for the study of opportunistic routing (OR) in multi-modal UWSNs. We also design two candidate set selection heuristics, named OMUS-E and OMUS-D, for the joint selection of the most suitable acoustic modem for data transmission and next-hop forwarder candidate nodes at each hop, aimed to reduce the energy consumption and improve the network data delivery ratio in multi-modal UWSNs, respectively. Numerical results showed that both proposed heuristics reduced the energy consumption by 65%, 70%, and 75% as compared to the DBR, Hydro Cast, and GEDAR classical related work protocols, while maintaining a similar data delivery ratio. Furthermore, the proposed solutions outperformed the CAPTAIN routing protocol in terms of data delivery ratio, while maintaining comparable energy consumption.

INTRODUCTION

THE demand for oceanographic data and underwater mon- itoring is growing exponentially. However, traditional approaches for underwater data collection are costly and logistically challenging as they rely on ship missions for data sampling or on the use of underwater sensor devices interconnected by cables or without any underwater communi- cation capabilities. In recent years, underwater wireless sensor networks (UWSNs) have emerged as an enabling technology for real-time, autonomous, and large-scale data collection from underwater environments [1]. However, reliable and energy- efficient data collection in UWSN is daunting due to the harshness of the underwater environment and unique char- acteristics of the underwater acoustic channel. First of all, the performance of UWSN applications is affected by the low and spatio-temporal variability underwater sound prop- agation speed, which depends on the temperature, pressure, and salinity of water [2], [3]. Second, underwater acoustic communication will suffer from multipath propagation, due to signal refraction and different propagation speeds at different depths. Third, spreading loss is a function of distance and frequency. Moreover, underwater acoustic communication.

In this regard, opportunistic routing (OR) protocols have been proposed to tackle poor and variable quality of the underwater acoustic channel and improve data delivery in UWSNs [5]–[11]. OR protocols select a subset of neighboring nodes, rather a single neighbor, as next-hop forwarder candi- date nodes, which will work collaboratively to advance the packet towards the destination. At each hop, selected next- hop forwarder candidate nodes are assigned data forwarding priorities. Thus, a candidate node will forward the received data when all the higher priority candidate nodes failed to do so [12], [13]. Therefore, a data packet will be lost only if none of the candidate nodes receives it. Nevertheless, the performance of OR is yet limited by the constraints of traditional physical layer of underwater sensor networks.

In recent years, programmable acoustic modems [14], [15], adaptive modulation [16], and multi-modal communi- cation [17]–[19] are gaining momentum in UWSNs. These approaches are aimed at creating communication diversity on underwater sensor nodes to cope with the high acoustic channel dynamics. Programmable acoustic modems can adjust physical layer operating parameters, in an on-the-fly manner, to reactively tackle extreme short-term channel variabilities and fast dynamics of underwater wireless communication. Communication diversity is also achieved by using multi-modal communication, i.e., optical-acoustic [17], [19] or multiple acoustic modems and physical layers with different settings [18], such as centered frequency, transmission power, bandwidth, bit rates, and communication range. Hence, the most suitable acoustic modem is used for given data transmis- sion, according to observed channel characteristics and link qualities.

Although significant progress has been made at the physical-layer of programmable acoustic modems and multi-modal UWSNs, less attention has been devoted to the design of net- working protocols that consider such communication diversityin UWSNs. This paper is aimed at filling this gap by proposingand designing an analytical framework for the study of OR in multi-modal UWSNs. The proposed stochastic modeling will assist researchers and practitioners to study and understand thefundamental building blocks towards the design of OR pro- tocols for multi-modal UWSNs. In addition, we propose two heuristics for the next-hop forwarder candidate nodes selectionin scenarios of multi-modal UWSN applications. Specifically, our main contributions are summarized as follows:

We devise a stochastic model for the joint problem of selecting the most suitable acoustic modem and next- hop forwarder candidate nodes, at each hop, in multi-modal UWSNs. The proposed analytical framework models the joint selection of the acoustic modem and next-hop forwarder candidate nodes, anypath nature of OR paths given the combination of next-hop nodes at each hop, the traffic load at each node based on the selected acoustic modem and candidate forwarder priorities on the sender nodes, and common metrics for performance evaluation, such as packet delivery ratio, delay, and energy consumption. The presented model also takes into consideration the unique characteristicsof the underwater acoustic channel and environment in order to have more representative modeling.

We propose two novel heuristics, named OMUS-E and OMUS-D, for next-hop forwarder candidate nodes selection in OR for multi-modal UWSN applications, intended to reduce energy consumption and improve data delivery, respectively. The OMUS-E candidate set selection heuristic considers the characteristics of the underwater acoustic modems used by the sensor nodes, andthe energy consumption for transmission and reception, when determining the acoustic modem to be used and the next-hop forwarder nodes. The OMUS-D candidate set selection heuristic considers the link quality achieved by each possible acoustic modem and the aggregated data delivery probability at each hop, when selectingthe acoustic modem and next-hop forwarder candidate nodes.

We demonstrate the potential of the proposed OMUS-E and OMUS-D heuristics through extensive numerical evaluations. Obtained results showed that both proposedheuristics reduced the energy consumption by 65%, 70%, and 75% compared to the DBR, HydroCast, and GEDAR classical related work protocols, while main- taining a similar data delivery ratio. Furthermore, the proposed solutions outperformed the CAPTAIN routing protocol in terms of data delivery ratio, while main- taining comparable energy consumption. Finally, the OMUS-E and OMUS-D candidate set selection heuris- tics contributed to balance the energy consumption of multi-modal underwater sensor nodes.

The remainder of this paper is organized as follows. Sec- tion II discusses the related work. Section III discusses the addressed research problem in detail. Section IV reviews someof the concepts and theories used in the proposed stochastic model. Section V presents the proposed stochastic modeling and the candidate set selection procedure that explores multi- modal and opportunistic routing data delivery. Section VI shows the performance evaluation of the proposed candidate set selection algorithm. Finally, Section VII presents the final remarks and discusses future work.

RELATED WORK

In this section, we discuss related work that has been proposed to improve data delivery either by employing multi-modal communication or opportunistic routing.

Multi-modal communication has gained increased momen- tum to improve data delivery in underwater networks. Diamant et al. [20] proposed the optimal multi-modal routing (OMR) protocol for fair resource utilization and increased throughput in UWSNs. The OMR protocol considers the backlog of packets at a node and decides the number of bits the node will transmit to its next-hop nodes, through each available communication technology. Basagni et al. [18] developed the MARLIN-Q routing protocol, which uses the Q-learning algorithm for selecting the best acoustic modem and next-hop node, at a node with a data packet to transmit, basedon the packet’s class of service, i.e., reliable or urgent. Ac- cordingly, the MARLIN-Q routing protocol implements a costfunction that considers the acoustic channel quality, the packettransmission, and the propagation delay, aimed to reduce data delivery delay and packet loss.

Câmara Júnior et al. [19] proposed the CAPTAIN proto- col for data collection in optical-acoustic underwater sensor networks. Their proposed protocol divides the underwater network into clusters of sensor nodes, where a cluster headerin each cluster is responsible for collecting data from cluster members and aggregates collected data before transmitting it towards the sink at the sea surface. Cluster headers are elected by a defined score value calculated from the fraction of the number of neighbors the node has when it uses optical and acoustic communication and its residual energy. Cluster head-ers are responsible for collecting data from cluster members, and route the aggregated data to the sink through a route tree constructed with the sink as the root.

Gjanci et al. [21] designed an optimized-based approachfor determining autonomous underwater vehicle (AUV) paths to maximize the value of information of collected data from all underwater nodes, in which acoustic communication isused by the nodes to send short control packets to the AUV and optical communication is used by the nodes to transfer data to the AUV. Han et al. [17] proposed an optical-acoustic communication approach for real-time video streaming from AUV networks, in which acoustic communication is used to assist the alignment of AUVs and to send control signals, suchas topology control and acknowledgments, whereas optical communication is used to transmit high-resolution videos between aligned AUVs.

Opportunistic routing protocols

Opportunistic routing protocols were proposed to improve data delivery in traditional single-modem underwater sensor networks. Yan et al. [5] proposed the depth-based routing(DBR) protocol. The DBR protocol uses the depth informationof the nodes, obtained from pressure sensors, to route data upwards, towards surface sonobuoys (sinks). To do so, a sendernode includes its depth information within the packet header before broadcasting it. Upon a data packet reception, a node will compare its depth with the sender's depth included withinthe packet header, and will coordinately continue forwarding the packet if it is closer to the surface than the performance of the DBR protocol. The authors considered the peculiar characteristics of UWSNs, such as nodes' deployment and mobility, and acoustic channel quality, as well as thebuilding blocks of the DBR protocol (e.g., depth-based routingand packet holding time) while devising important UWSN performance metrics, such as end-to-end delay, data delivery probability and energy consumption.

Noh et al. [7] designed the HydroCast routing protocol, which proposed a heuristic for selecting next-hop candidate nodes within each others' proximity, intended to reduce the hidden terminal problem. This protocol proposed a void- handling mechanism to cope with the local minimal problem of geographic routing. Coutinho et al. [8], [9] proposed the GEDAR routing protocol, which considered location infor- mation and multi-sink architectures for data routing deci- sions. Moreover, the GEDAR protocol uses a nodes' depth adjustment-based topology control procedure for handling voidnodes and the communication void region problem [22]. The authors recently proposed the PCR routing protocol [23], which explored transmission power control at each node aimed at improving energy efficiency, and the EnOR routing protocol [10], which addressed the problem of immutable data forwarding priorities assigned to candidate nodes. This problem of non-rotation of data forwarding priorities led tothe overuse of a few neighboring nodes, which will quickly drain their batteries and result in network partitions.

Discussions and Novelty

In the literature, the design trends of multi-modal un- derwater network architectures and OR protocols have been following independent paths. To the best of our knowledge, there is a lack of works designing OR protocols for multi- modal UWSNs and, therefore, we advocate for the design of OR in multi-modal UWSNs. In this paper, we proposea stochastic model for the problem of joint selection of the most suitable acoustic modem and next-hop candidate nodes, for data transmission at each hop. To do so, we considerthe unique characteristics of multiple acoustic modems, un- derwater acoustic communication, underwater noise, OR data delivery, and energy costs. Moreover, we propose the OMUS-Eand OMUS-D heuristics for the joint selection of the acoustic modem and candidate set at each hop, intended to reduce the energy consumption and improving the network data delivery ratio, respectively.

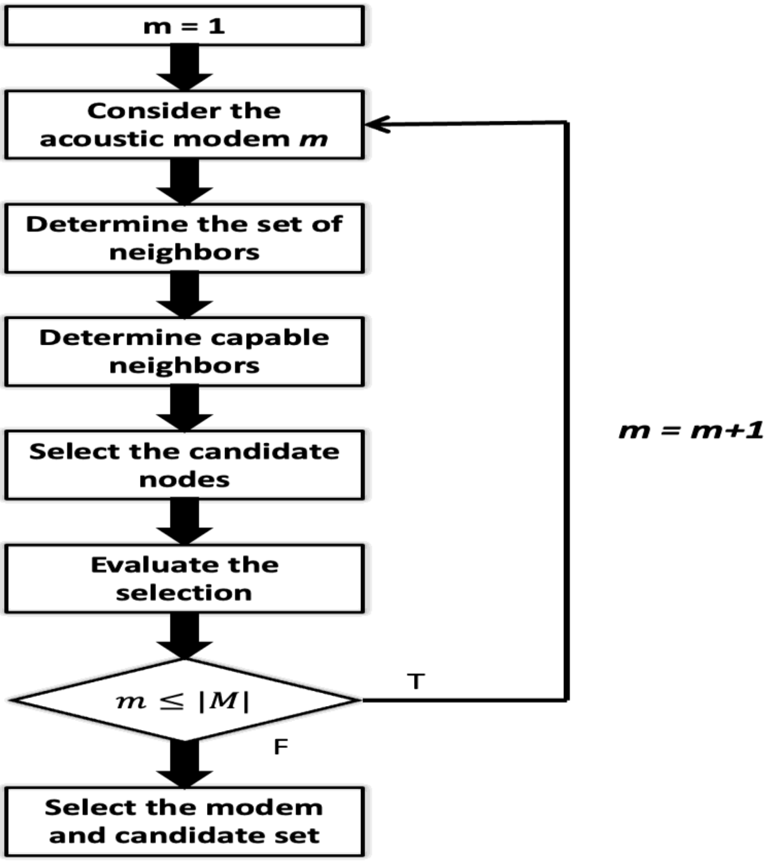
PROBLEM STATEMENT

This paper tackles the design of OR protocols for multi- modal UWSNs. More specifically, it sheds light on the chal- lenging problem of jointly selecting the most suitable acousticmodem and next-hop forwarder nodes, at each underwatersensor node. Fig. 1 depicts the overall steps to be performedat each multi-modal underwater node. These steps are detailedin the following.

First of all, each node is equipped with multiple acoustic modems with different settings. A node with a data packetto transmit will first determine its neighboring nodes, consid- ering each acoustic modem m it is equipped with of neighbors will depend on the communication range and acoustic link quality, which are based on the characteristics and configuration of the used acoustic modems. After that, thesubset of neighbors that can forward the packet towards the destination is determined. A neighbor can forward a received packet towards the destination if it satisfies a specified criterion given by the OR protocol, such as packet progress, which accounts for the geographical advancement of the packet towards the destination location.

Subsequently, a candidate set selection procedure imple- mented by the employed OR protocol determines the set of neighbor nodes that will collaboratively work to continue ad- vancing the packet towards the destination. The set of selected neighbors is called next-hop forwarder candidate nodes. The first step in the candidate set selection procedure is to rank the neighbors that can forward the packet. Herein, we use the normalized packet advancement (NADV) [24] to rank the nodes, which normalizes the progress a neighbor makes by the cost, in terms of link quality, to reach the neighbor. Different metrics can be used in candidate set selection procedures, such as link quality, latency, and residual energy.

The daunting challenge consists of the design of OR pro- tocols to take advantage of multi-modal communications to improve reliability and energy efficiency in UWSNs. In this paper, we propose the OMUS-E and OMUS-D to select which capable neighboring nodes will be the next-hop forwarder candidate nodes for a given sender node. In the OMUS-E heuristic, a capable node is chosen if it contributes to reducing the energy consumption of the candidate set, i.e., set of next- hop forwarder nodes. In the OMUS-D heuristic, the data delivery is the criteria used to add a capable node in the candidate set. Finally, the acoustic modem and corresponding candidate set that lead to the lower energy cost and higher data delivery probability are selected when the OMUS-E.



Preliminaries

In this section, we describe the underwater acoustic channel model considered in the proposed model. Moreover, we revise the model used to estimate the delivery probability of a transmitted *m* bit packet over a link using frequency f kHz, between two nodes distant of d m.

A representative modeling of underwater acoustic commu- nication and the environment is one of the main challenges when devising analytical models for performance evaluation of UWSNs. Morozs et al. [3] discussed three common approaches used in the literature to study the performance of UWSN protocols and applications. The first approach consists of the use of the basic range-based model, which assigns fixed con- nectivity and interference based on the communication range. The second approach consists of the use of the analytical transmission loss model, in which mathematical expressions are used for estimating distance-related spreading loss and frequency-related absorption loss. Finally, the third approach consists of the use of specialized channel modeling software; for example ray/beam tracing is used to predict the acoustic pressure field in a specific underwater environment.

Herein, we use the analytical transmission loss model, commonly referred to as the Urick model [25], as it presents a low computational complexity while maintaining a suitable degree of realism by modeling frequency-related signal ab- sorption, distance-related signal spreading loss, and natural and human-made underwater noise. It is worth mentioningthat the Urick underwater acoustic channel model is one of the underwater acoustic channel models implemented in the ns-3 and DESERT simulators and used in [5]–[8], [17], [19], [21], [23], [26], [27].

$10 \log N_t(f) = 17 - 30 \log f$
$10 \log N_s(f) = 40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03)$ $10 \log N_w(f) = 50 + 7.52^{1/2} + 20 \log f - 40 \log(f + 0.4)$
$10 \log N_{th}(f) = -15 + 20 \log f.$ (4)

A review of the packet delivery probability

We use the following model to estimate the packet delivery probability between two underwater acoustic sensor nodes.In terms of modulation, recent works (e.g., [16]) have pro- posed the use of adaptive modulation to cope with observed environmental conditions and improve bit error rate (BER)and throughput. Herein, we assume the use of the BinaryPhase Shift Keying (BPSK) modulation, where each symbol carries a bit. This choice is motivated by the fact that the BPSK modulation scheme is widely used in state-of-the-art acoustic modems and related works, such as [5]–[11], [15], [18]–[20]. In a non-fading Additive White Gaussian Noise (AWGN) channel, the bit error rate can be determined as

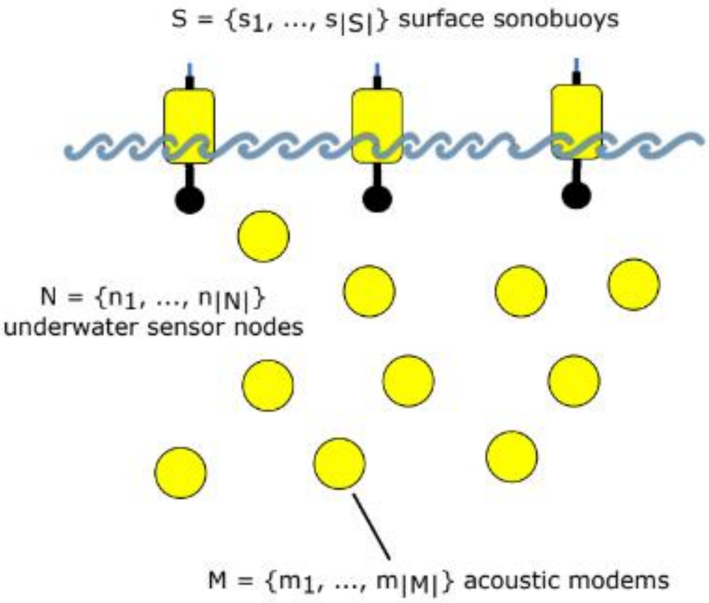


Fig. 2. Multi-modal UWSN architecture.

Network architecture modeling

We assume an underwater sensor network architecture com-posed of non-mobile sensor nodes deployed underwater and sink nodes deployed at the surface, as illustrated in Fig. 2. Thistypical multi-sink scenario can be used in many underwater variables and marine life monitoring in a certain area of interest.

Network model*:* We define V = $N \cup S$ as the set of nodes composed of $N = \{n_1, \ldots, n_{|N|}\}$ underwater sensor nodes∈and $S \{= s_1, \ldots, s_{|S|}\}$surface sonobuoys (sinks). We assume random deployment of underwater sensor nodes in a 3D area of interest, m∈deled by a uniform distribution. Eachnode n_i N will be located at X_i, Y_i and Z_i Cartesian coordinates, and each sink s S will be deployed at the surface, i.e., depth equals to 0, in a preplanned manner at the location X_s, Y_s and Z_s. Underwater sensor nodes are responsible for underwater monitoring and periodic report datacollected from surface sonobuoys. The opportunistic routing protocol is used to determine the next-hop forwarder nodes at each hop, for multi-hop data routing from underwater nodes to surface sonobuoys.

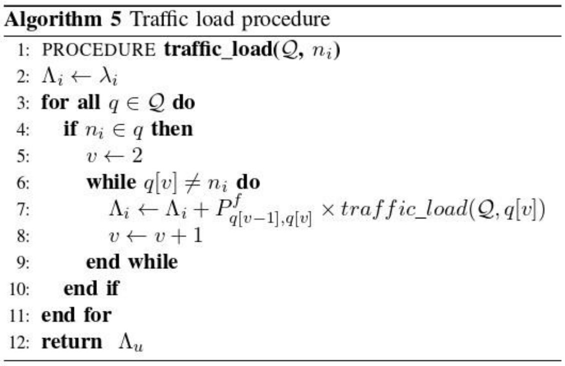
Classical UWSN routing protocols, such as DBR [5] and HydroCast [7], used pressure information, instead of geographic location, for data routing decisions. However, the use of location information is fundamental for georeferenced or target detection and tracking underwater monitoring appli- cations (e.g., [30], [31]), and should be leveraged for the design of networking protocols in UWSNs. In this regard, localization services (e.g., [32], [33]) can be used to estimate underwater nodes' positions. Moreover, these positions need only be estimated once as a non-mobile UWSN architectureis assumed.

B. *Opportunistic routing modeling*

In this section, we model the main procedures implemented by opportunistic routing protocols, as well as the problem of selecting the appropriate modem during data transmission, at each hop, in a multi-modal underwater sensor network. In gen- eral, an opportunistic routing protocol implements two main procedures: *i)* a next-hop forwarder candidate set selection procedure and *ii)* a next-hop forwarder candidates’ transmis- sion coordination procedure. The authors in [13] provided a detailed discussion of the main principles and techniques used by state-of-the-art opportunistic routing protocols for underwater sensor networks.

***The candidate set selection procedure**:* This procedure is responsible for choosing the next-hop forwarder candidate nodes at each hop, which is a subset of neighboring nodes that will work collaboratively to continue forwarding the data packet towards the destination. The candidate set selection procedure uses a fitness function (e.g., distance, packet ad- vancement, link quality or residual energy) to measure the suitability of each neighbor as potential next-hop forwarder candidate node, and determines the next-hop forwarder can- didate set; that is, the subset of the neighboring nodes that will be chosen as next-hop forwarder nodes. Furthermore, the candidate set selection procedure is responsible for assigning forwarding priorities to each candidate node, based on the used fitness function.

***The candidates’ transmission coordination procedure**:* This procedure controls the data forwarding at next-hop for- warder candidate nodes. A underwater sensor node with a data packet to send will determine the next-hop forwarder candidate nodes and broadcast the data packet to them. Upon the reception, the candidate node will schedule the transmission of the incoming data packet. The time a candidate node will wait before forwarding the packet will be given according to its assigned forwarding priority. Accordingly, a candidate node with higher forwarding priority has a lower waiting time. The candidate nodes should cooperate to reduce the number of redundant data transmissions. Therefore, a candidate node that received the data packet will continue forwarding it only if the candidate nodes with higher forwarding priority failed in to do so. Candidate nodes suppress scheduled data transmissions whenever they hear that the same packet has been transmitted by a higher priority candidate node. This implicit acknowledgment is used to reduce the number ofredundant packet transmissions



Algorithm 5 Traffic load procedure

```
PROCEDURE traffic_load($\mathcal{Q}$, $n_i$)
$\Lambda_i \leftarrow \lambda_i$
for all $q \in \mathcal{Q}$ do
    if $n_i \in q$ then
        $v \leftarrow 2$
        while $q[v] \neq n_i$ do
            $\Lambda_i \leftarrow \Lambda_i + P^{f}_{q[v-1],q[v]} \times traffic\_load(\mathcal{Q}, q[v])$
            $v \leftarrow v + 1$
        end while
    end if
end for
return $\Lambda_u$
```

.

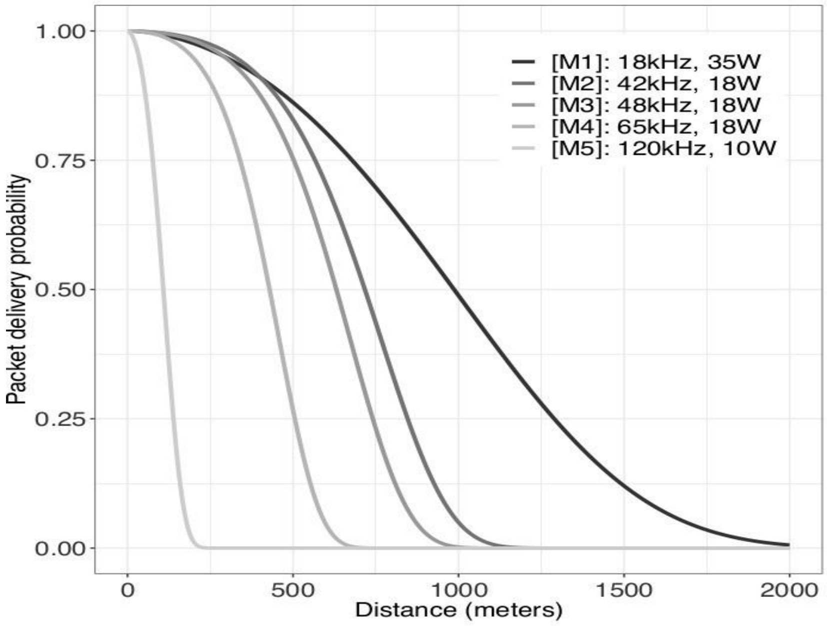
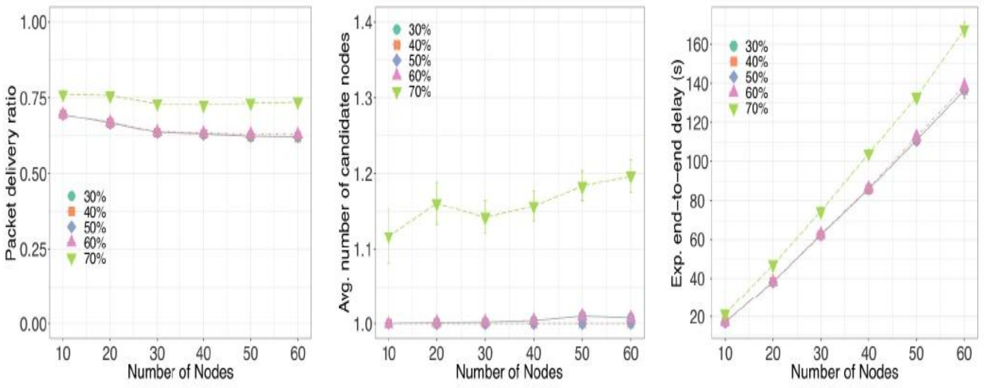


TABLE I
PARAMETERS AND TOPOLOGY PROPERTIES.

Parameter	Value	Parameter	Value
Number of sonobuoy	4	Depth threshold DBR	50 m
Network size	10 to 60 nodes	Packet size	8 KBytes
Sensor field	1500 m × 1500 m × 500 m	Shipping (s)	0
Packet generation rate (λ)	0.05 s	Wind (w)	0
A_0	5 dB		

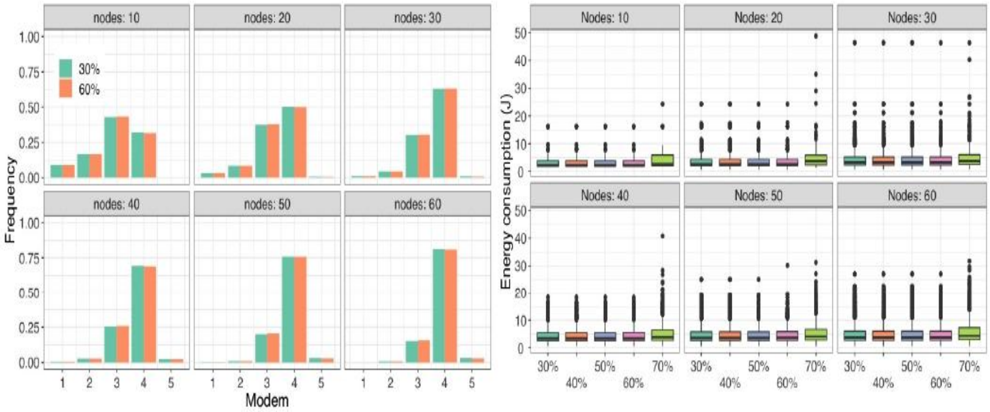
TABLE II
PARAMETERS AND TOPOLOGY PROPERTIES.

Identifier	Modem	Range	Frequency	Data Rate	Transmission Power	Reception Power
[M1]	S2C R 18/34	$R_{m_1} = 860\,\text{m}$	$f_{m_1} = 18\,\text{kHz}$	$b_{m_1} = 13900\,\text{bps}$	$e_{T_1} = 35\,\text{W}$	$e_{R_1} = 0.8\,\text{W}$
[M2]	S2C R 42/65	$R_{m_2} = 660\,\text{m}$	$f_{m_2} = 42\,\text{kHz}$	$b_{m_2} = 31200\,\text{bps}$	$e_{T_2} = 18\,\text{W}$	$e_{R_2} = 0.8\,\text{W}$
[M3]	S2C R 48/78	$R_{m_3} = 580\,\text{m}$	$f_{m_3} = 48\,\text{kHz}$	$b_{m_3} = 31200\,\text{bps}$	$e_{T_3} = 18\,\text{W}$	$e_{R_3} = 1.1\,\text{W}$
[M4]	S2C R 42/65	$R_{m_4} = 400\,\text{m}$	$f_{m_4} = 65\,\text{kHz}$	$b_{m_4} = 31200\,\text{bps}$	$e_{T_4} = 18\,\text{W}$	$e_{R_4} = 1.4\,\text{W}$
[M5]	S2C M HS	$R_{m_5} = 100\,\text{m}$	$f_{m_5} = 120\,\text{kHz}$	$b_{m_5} = 62500\,\text{bps}$	$e_{T_5} = 10\,\text{W}$	$e_{R_4} = 0.8\,\text{W}$



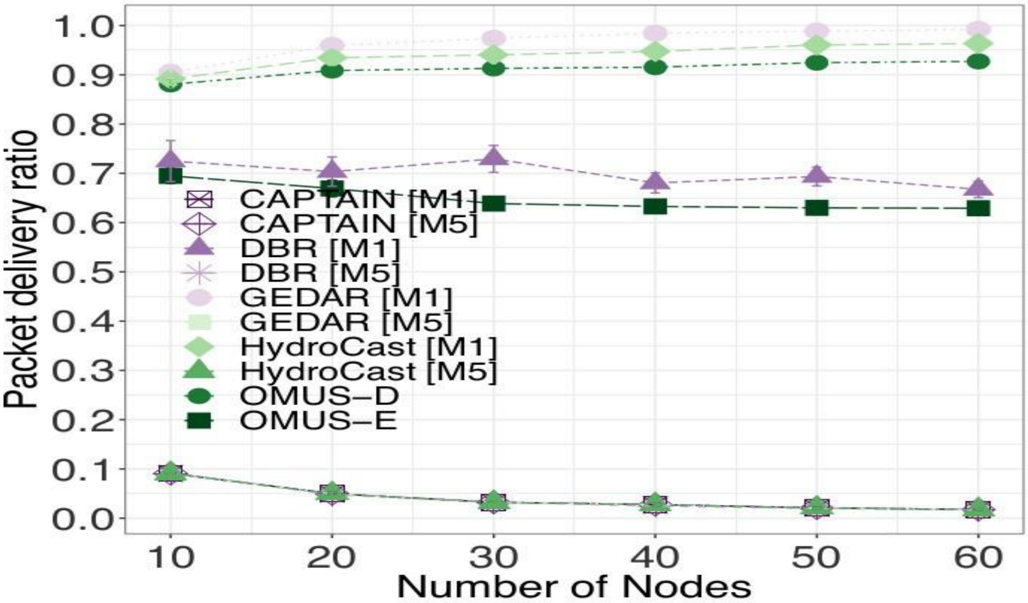
(a) (b) (c)

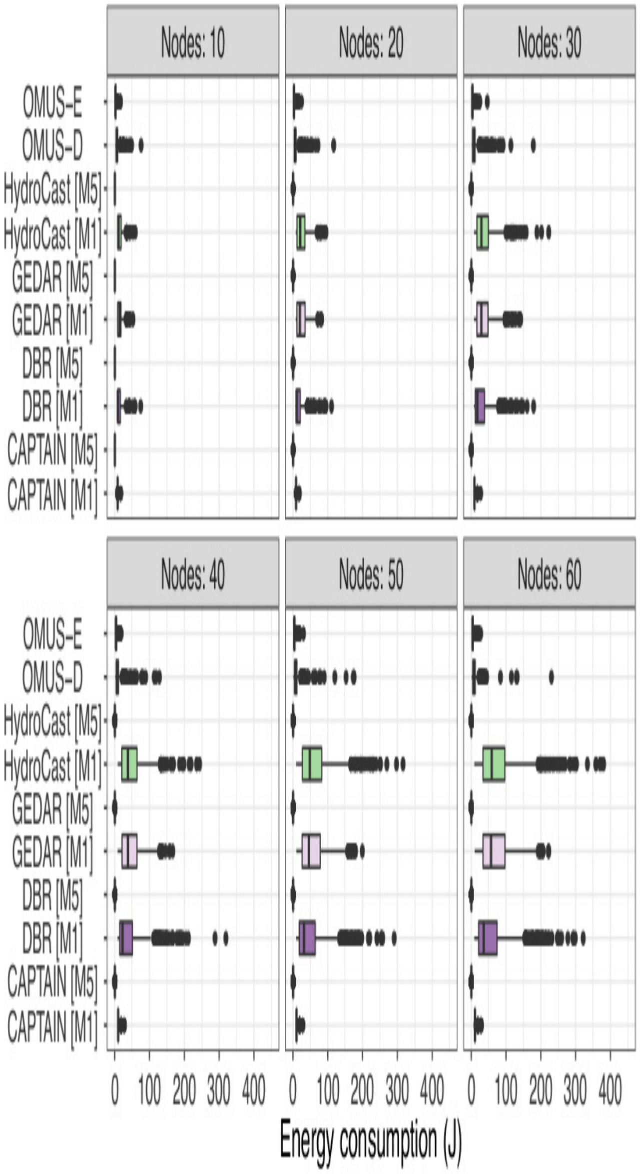
Fig. 5. Numerical results: a) Packet delivery ratio. b) Avg. number of candidate nodes. c) Expected end-to-end delay.

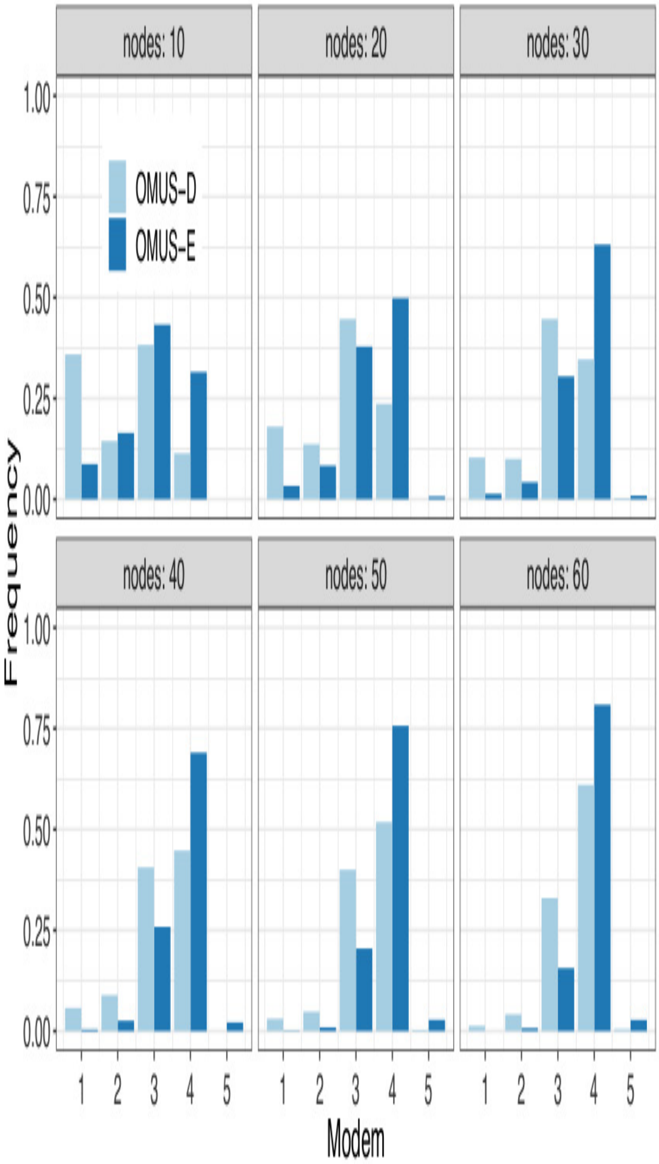


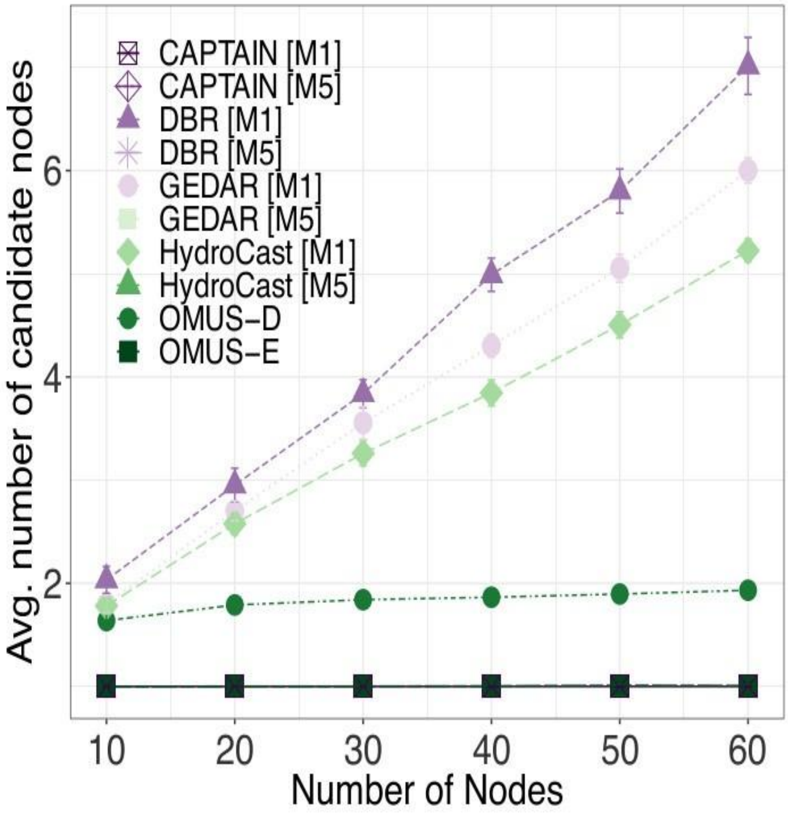
(a) (b)

Fig. 6. Numerical results: a) Used acoustic modem. b) Average energy consumption.


Packet delivery ratio
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10
20
30
40
50
60
Number of Nodes
CAPTAIN [M1]
CAPTAIN [M5]
DBR [M1]
DBR [M5]
GEDAR [M1]
GEDAR [M5]
HydroCast [M1]
HydroCast [M5]
OMUS–D
OMUS–E


Nodes: 10
Nodes: 20
Nodes: 30
Nodes: 40
Nodes: 50
Nodes: 60
OMUS-E
OMUS-D
HydroCast [M5]
HydroCast [M1]
GEDAR [M5]
GEDAR [M1]
DBR [M5]
DBR [M1]
CAPTAIN [M5]
CAPTAIN [M1]
0
100
200
300
400
Energy consumption (J)


nodes: 10
nodes: 20
nodes: 30
nodes: 40
nodes: 50
nodes: 60
Frequency
1.00
0.75
0.50
0.25
0.00
OMUS-D
OMUS-E
1
2
3
4
5
Modem



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