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A Novel Opportunistic Power Controlled Routing Protocol for Internet of Underwater Things

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Abstract

Internet of Underwater Things (IoUTs) has been proposed to autonomously monitor and collect data from aquatic environments. In these networks, the acoustic channel is currently considered as the most viable technology for underwater wireless communication among the nodes. By using acoustic modems, underwater sensor nodes are able to autonomously and collaboratively sense the area of interest and report collected data to a monitoring center through multi-hop underwater wireless communication. However, underwater wireless communication through acoustic channels is daunting, due to the limited bandwidth, multipath propagation, shadowing zones, high and variable delay, noisy environment and high energy cost. These characteristics impair data collection and shorten the IoUT lifetime. In this paper, we propose a novel power control-based opportunistic (PCR) routing protocol for IoUTs. The proposed protocol considers the neighborhood density, link quality, distance, packet advancement, and energy waste to select the suitable transmission power level at each sensor node. Accordingly, each neighboring node eligible to continue forwarding the data packet is considered as a next-hop forwarder node if its inclusion in the next-hop nodes candidate set does not increase the energy waste in the considered hop. Numerical results showed that the proposed protocol improves data delivery rate while maintaining the energy cost at levels comparable to the related work.

Keywords: Internet of Underwater Things, power control, opportunistic routing, energy efficiency

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1. Introduction

Oceans cover more than 2/3 of Earth's surface and they play a fundamental role to support life on our planet. Oceans have absorbed more than 1/4 of

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carbon dioxide (CO_2) produced by humans since 1800 and 2/3 of the heating produced by human activities since 1995 [1]. Moreover, they are one of the main sources of food and mineral resources and they serve as a transportation medium for people and goods. Despite all benefits, it is estimated that no more than 5% of the oceans' volume has been seen by human eyes [2]. The critical challenge, therefore, is how we can change this worrying reality. Overall, ship missions for ocean monitoring are expensive and might jeopardize humans life, due to extreme weather conditions, for instance. Hence, there is a growing demand for the development of aquatic monitoring technologies that can autonomously collect data from oceans and events beneath them.

In this regard, Internet of Underwater Things (IoUTs) [3], as an evolution of underwater wireless sensor networks (UWSNs) [4, 5], emerges as a cost-effective solution for increasing maritime awareness through the large-scale and real-time monitoring of aquatic environments. IoUTs will be composed of intelligent sensor nodes (floats) that will collaboratively sense the area and events of interest and them report collected data to a cloud computing system [6]. To do so, the underwater sensor nodes will be equipped with acoustic modems that will enable underwater wireless communication among them.

The development of IoUTs will empower the effective monitoring for several underwater applications, such as lake monitoring [7], earthquake and tsunamis [8], landslides and floods [9], and underwater oil exploration [10], just to name a few. However, current developments are still severely impaired by the use of underwater acoustic channels, which results in limited bandwidth, multipath propagation, shadowing zones, high and variable delay, noisy environment and high energy cost [11, 12].

Overall, opportunistic routing (OR) has been proposed to improve data delivery in different scenarios of wireless networking [13, 14, 15]. In this routing paradigm, a sender selects a subset of its neighboring nodes, instead of a single next-hop forwarder node, to continue forwarding the data packet towards the destination. The selected next-hop forwarder nodes, named of candidate nodes, work collaboratively to advance the data packet towards the destination. To do so, a forwarding priority is assigned to each node, based on determined criteria (e.g., distance [16] or the normalized packet advancement [17]).

A candidate nodes will forward a received data packet when it does not see any transmission of the same packet by a higher priority candidate node. When using an OR protocol, a packet is lost only if none of the selected next-hop nodes (candidate nodes) received it. Therefore, this routing paradigm improves data delivery and reduces the number of packet retransmissions, which in turn reduces packet collisions [18].

However, OR protocols often are not energy efficient and they will shorten the IoUTs lifetime [19, 20]. First, the overhead for the selection and coordination of candidate nodes will lead to additional energy cost. Second, redundant data transmissions will happen especially in scenarios of IoUTs, due to the challenges to coordinate the transmission of candidate nodes. Third, OR protocols tend to assign the same transmission priorities for the nodes in a candidate set, i.e., there is no rotation in the transmission priority among candidate nodes. Hence, a few central nodes will be highly demanded from a routing point of view [21].

In this paper, we explore the opportunistic routing paradigm and transmission power control to achieve energy-efficient data delivery in IoUTs. We proposed the power-based opportunistic routing protocol (PCR), which selects the suitable transmission power and candidate set at each hop based on the neighborhood density, packet advancement, link quality and energy waste that will incur. Extensive numerical results show that the PCR protocol improves the link quality among sender nodes and their next-hop candidate nodes and, consequently, the data delivery rate while maintaining the energy cost at a level comparable to the related work. The contributions of this paper are the following:

- a thorough review of opportunistic routing protocols for UWSNs,
- a deep discussion of how power control-based routing protocols have been explored for energy conservation,
- a more detailed theoretical framework for the problem formulation and description of the proposed algorithms,
- more simulation results including different network densities and opportunistic routing related performance evaluation metrics.

The remaining of this paper is organized as follows. Section 2 discusses the related work. Section 3 presents our network modeling and reviews preliminary concepts considered in this paper. Section 4 develops our proposed power control-based opportunistic routing protocol for the ocean of things. Section 5 conducts numerical experiments considering different settings of the ocean of things. Finally, Section 6 shows the final remarks and future work.

2. Related Work

In the literature, opportunistic routing has been proposed to improve the performance of data delivery in underwater sensor networks, while power control-based protocols have been proposed for energy conservation in wireless sensor networks.

2.1. Opportunistic Routing Protocols

Yan et al. [16] proposed the depth-based routing (DBR) protocol. The DBR protocol is one of the first protocols designed for underwater sensor networks to consider the depth information of the nodes. The idea is to forward data packet upwards, where they will be received by sink nodes at the sea surface. In the DBR protocol, next-hop candidate nodes are determined from the depth difference between the sender node and its neighbors. Whenever a sender node has a data packet to send, it includes its depth information within the packet and broadcasts it. Each neighboring node, upon the reception of the data packet, will check if it can advance the packet towards the sea surface and if the depth difference between itself and the sender is higher than a determined threshold.

Lee et al. [22] proposed the Hydrocast routing protocol. The Hydrocast protocol relies on the packet advancement and link quality for selecting next-hop candidate nodes and prioritizing their transmissions. Accordingly, a sender node will calculate the normalized packet advancement (NADV) [23] for each neighboring node that can advance the packet towards the surface. Hence, those nodes are clustered based on the NADV and the distance among them. The idea is to have the next-hop candidate set composed of the neighbors with high NADV and whose distance among them is lower than the communication range, to avoid the hidden terminal problem.

Wahid et al. [24] proposed the EEDB routing protocol. The EEDBR extends the DBR routing protocol to achieve energy-efficiency during the data delivery. The selection of the next-hop candidate nodes follows the principle design of the DBR routing protocol, which considers the depth difference between the sender node and the neighbors. However, a balanced energy consumption among candidate nodes is achieved by prioritizing their transmissions according to residual energy. Hence, higher is the residual energy of a candidate node, shorter will be its delay before forwarding a received data packet.

Noh et al. [25] proposed the VAPR routing protocol. The VAPR protocol resembles the Hydrocast routing protocol in the procedure for the candidate set selection. However, instead of considering the vertical progress towards the surface, the VAPR protocol relies on directional paths discovered from periodic beacons initially transmitted from surface sonobuoys. This approach helps to reduce the impact of communication void regions.

Coutinho et al. [26] proposed the GEDAR routing protocol. The GEDAR is among the first protocol to consider the location information of the nodes and to forward data directed to sonobuoys at sea surface. The GEDAR uses the normalized packet advancement to select candidate nodes at each hop. However, instead of using the depth information of the nodes, it considers the location information, which can be obtained through a localization service in the network.

In addition, Coutinho et al. [20] proposed the EnOR protocol aiming a balanced energy consumption among candidate nodes. The EnOR protocol was the first opportunistic routing protocol, designed for underwater sensor networks, that proposes to periodically rotate the transmission priority of the candidate nodes. The authors observed that current OR protocols in the literature, once they assign the transmission priorities for candidate nodes, they do not change it over time. This lead to an overuse of some of the candidate nodes, which will drain their batteries quickly. To deal with this challenge, the EnoR protocol periodically alternates the transmission priority of a set of candidate nodes, on a per-packet basis, according to their residual energy.

Jafri et al. [27] proposed an analytical model for the study of opportunistic routing protocols in underwater sensor networks. The proposed modeling allows engineers and practitioners to determine the optimal configuration for opportunistic routing protocols along different scenarios and networking settings. From the modeling, the authors proved that the selection of the proper progress threshold in depth-based OR protocols is crucial for the performance of the protocol.

2.2. Power Control Protocols

The proper transmission power control at sensor nodes has been explored in the literature to improve energy-efficiency in energy-constrained sensor networks. In fact, power control has been highlighted as one effective methodology for topology control in underwater sensor networks, aimed at improving data delivery and reducing energy costs [28].

Coutinho et al. [29] proposed the TCOR protocol for wireless sensor networks. The TCOR is an opportunistic routing protocol that explores the transmission power control to conserve energy in wireless sensor networks. Accordingly, the TCOR protocol calculates the expected energy consumption for data delivery, the given transmission power levels, and then selects the transmission power level, at each hop, that leads to reduced energy consumption.

Luo et al. [30] proposed the ENS_OR routing protocol for scenarios of 1-D wireless sensor networks. In the proposed protocol, the optimal transmission distance is calculated at each node, and the corresponding transmission power is used. To calculate the optimal transmission distance, queueing modeling is proposed and the energy consumption is estimated, based on the neighborhood density and environmental noise.

Lin et al. [31] proposed the ATPC routing protocol, which adaptively selects the transmission power at the nodes based on the link quality. In the ATPC protocol, each node maintains a neighbor table containing the proper transmission power level to communicate with the neighbors. The selected transmission power level is the minimum one that still guarantees a good link quality between the pairs of nodes. This transmission power is adjusted on a per-packet basis, from a predictive model that describes the relation between the transmission power and link qualities.

Darabkh et al. [32] proposed the BPA-CRP protocol for clustering and routing in wireless sensor networks. In the BPA-CRP protocol, the selected communication range and, consequently, the transmission power, is based on the location of the sensor node in the field. Accordingly, the sensor field is divided into layers, where the number of layers is calculated from the sensor field size, width and number of nodes. The communication range of each is node is calculated by the base station, from the location information of all nodes. A node might be able to communicate in a network level (highest communication range), two-layer level, layer level, and cluster level (shortest communication range).

2.3. Novelty of the proposed PCR protocol

As can be noticed from the related work, opportunistic routing protocols were mainly developed to improve data delivery in underwater sensor networks. However, they can lead to additional energy cost for the network, due to the overhead for the coordination of candidate nodes and redundant data packet transmissions.

On the other hand, power control has been explored in the literature to reduce energy consumption. Overall, the protocols tend to reduce the transmission power as much as possible, while guaranteeing acceptable link quality between pair of nodes. However, this reduction would decrease even more the poor quality of the underwater acoustic links.

In contrast, the PCR protocol explores the joint design of opportunistic routing and power control. Hence, it is able to further improve the link quality at each hop, by selecting the suitable transmission power level that will reduce the expected number of transmissions to deliver a data packet. Moreover, it contributes to reducing energy consumption in those hops where a node has a high neighborhood density. Due to many nodes in the vicinity, the PCR might reduce the transmission power at a node, if the link quality between the node and its candidate set nodes is enough to efficiently deliver the data.

3. Preliminaries

In this section, we model the IoUT architecture considered in this paper, as well as the transmission power level set. Moreover, we review the model used to calculate the packet delivery probability of an acoustic link between two underwater sensor nodes.

3.1. Network architecture and modeling

We consider a multi-sink IoUT network architecture as described in the following. We assume a set of underwater sensor nodes is deployed in a 3D area of interest scouted by surface sonobuoys (sinks) deployed at the sea surface. Mobility has been explored to improve the performance of wireless sensor networks [33] and underwater sensor networks [34]. However, for the sake of simplicity, we consider a non-mobile IoUT scenario, although the proposed modeling and protocol can be extended to mobile scenarios. Let's consider the set $\mathcal{N} = \{n_1, \ldots, n_{|\mathcal{N}|}\}$ of underwater sensor nodes and the set $\mathcal{S} = \{s_1, \ldots, s_{|\mathcal{S}|}\}$ of sonobuoys.

We represent the network topology using a directed graph $G = (V, E)$, where the set $V = \{\mathcal{N} \cup \mathcal{S}\}$ denotes the set of nodes and E is the set of all one-hop edges. An edge $e_{ij} \in E$ exists if and only if there exist a link between the nodes n_i and n_j. In other words, an edge between two nodes exists if the packet delivery probability between these two nodes is higher than 0. The occurrence of an edge e_{ij} will be affected by the selected transmission power level at node n_i.

3.2. Transmission power level set

We consider that each underwater sensor node can adjust its transmission power and select one among a set of discrete values. Accordingly, let's consider $P = \{p_t^1, p_t^2, \ldots, p_t^L\}$ as the set of transmission power levels. Moreover, let's define $N_i^{p_t^k}$ as the set of neighboring nodes of n_i, when n_i selects the transmission power $p_t^k \in P$ for transmitting.

In addition, we define $p_{L^{p^k_t}_{i\rightarrow j}} \in [0,1]$ as the packet delivery probability associated to each link $L^{p^k_t}_{i\rightarrow j}$ between two nodes n_i and n_j, when the transmission power level p^k_t is used. This probability is calculated from the transmission power, distance and packet size, as described in Section 3.4.

3.3. A brief review of the physical layer

In this section, we review the modeling used to convert the transmission power from $dB\mu rePa$ to the corresponding value in Watts. Furthermore, we revise the modeling used to estimate the packet delivery probability over an underwater acoustic link. This revision is based on the discussion provided by [35].

Let's define $SL^{p^k_t}_T$ to be the acoustic signal transmission level expressed in dB re μ Pa, when a node is using the corresponding transmission power level $p^k_t \in P_t$ expressed in Watts. The signal intensity at the receiver, in dB re μ Pa, will be:

$$SL^{p^k_t}_{r,d} = SL^{p^k_t}_t - TL(d,f), \tag{1}$$

where $SL^{p^k_t}_t$ can be obtained from the transmitter sensitivity TRVm expressed in dB reμPa/V at 1 m, and the used transmission power p^k_t watts, as:

$$SL^t_{p^k_t} = TVR - 20\log(p^k_t). \tag{2}$$

Finally, the signal to noise ratio at the receiver can be calculated as:

$$SNR^{p^k_t}_d = SL^{p^k_t}_{r,d} - NL(f) + DI, \tag{3}$$

where DI is the directivity index, and $NL(f)$ is the noise for the frequency f. We set DI equals to 0, since we assume omnidirectional hydrophones [36].

3.4. Successful Packet Delivery Probability

We assume that the underwater acoustic micro-modem uses the binary phase shift keying (BPSK) modulation [37, 17, 26]. Accordingly, the bit error rate (BER) of BPSK in an underwater Rayleigh fading channel can be calculated as [36]:

$$P_e(SNR^{p^k_t}_d) = \frac{1}{2}\left(1 - \sqrt{\frac{SNR^{p^k_t}_d}{1 + SNR^{p^k_t}_d}}\right), \tag{4}$$

where the signal to noise ratio $SNR^{p^k_t}_d$ is calculated by Eq. 3. The probability of a successful packet delivery of m bits over an acoustic link $L^{p^k_t}_{i\rightarrow j}$ between any two i and j underwater sensor nodes distant of d meteres, can be calculated from Eq. 4, as:

$$p_{L^{p^k_t}_{i\rightarrow j},d,m} = (1 - P_e(SNR^{p^k_t}_d))^m. \tag{5}$$

Throughout this paper, for the sake of simplicity, we use the following notation $p_{L^{p^k_t}_{i\rightarrow j}}$ to represent the successful packet delivery probability calculated by Eq. 5.

Algorithm 1 Send Beacon Procedure

```
1: $m$: a new beacon packet
2: $m.p_t \leftarrow p_t^i$
3: $m.node\_id \leftarrow id(node)$
4: $m.node\_location \leftarrow location(node)$
5: Broadcast(m, $p_t^i$)
6: if $p_t^i$ is not the maximal then
7:     Resched Send Beacon Procedure ($p_t^{i+1}$)
8: end if
```

4. The Proposed PCR Protocol

The PCR protocol is aimed to improve data delivery while reducing the energy cost in IoUTs. To do so, it explores the transmission power adjustment capability, implemented in current acoustic modems, to select the suitable level at each hop. The building blocks of the PCR protocol is detailed in the following.

4.1. Neighborhood Discovery

In order to select the next-hop candidate nodes, a transmitter node must have the information of its neighboring nodes. The proposed PCR protocol uses a beaconing procedure for neighbors discovery. The procedure implemented by the PCR protocol is presented in Algorithm 1.

A beacon message will fundamentally contain three fields: the node id, node location, and transmission power. The node id is the unique identifier used to represent the node in the network. The node location will be used to determine if the neighboring node can advance the packet towards a surface sonobuoy. This information is obtained through the use of any localization protocol proposed for underwater networks (e.g., [38, 39, 40]). The transmission power level field in the beacon message is used to inform the neighboring nodes about the transmission power that was used by the sender during the transmission of the beacon.

Algorithm 1 is used for the beacon transmissions. First, the node will create a beacon message and fill the fields with the corresponding information (Lines 1-4). Subsequently, the node broadcasts the beacon using the considered transmission power p_t^i and schedules the transmission of a new beacon with the subsequent transmission power level (Lines 5-8).

Algorithm 2 presents the PCR procedure performed whenever a node receives a beacon message. The overall idea behind this procedure is the obtaining of the neighboring nodes that can be reached when different transmission powers are used. Each underwater sensor node implements a neighboring table to store the information received from its neighbors. Whenever a node receives a beacon packet, it will extract the id and location information (x, y, z) of the sender, as well as transmission power the sender used to transmit the beacon (Lines 1-4). The node then estimates the link quality to the sender from the received signal strength and the modeling presented in Section 3.4 (Line 6). The distance between the two nodes is determined from the location information of

Algorithm 2 Receive Beacon Procedure

```
1: $m$: received beacon packet
2: $n.id \leftarrow m.node\_id$
3: $n.location \leftarrow m.node\_location$
4: $p_t^i \leftarrow m.p_t^i$
5: Calculates the packet delivery probability from the current node $i$ to the node $n$.
6: Calculate $p_{L_{i\to n}^{p_t^i}}$ from Eq. 5
7: neighbor_table.add ($p_t^i$, $n.id$, $p_{L_{i\to n}^{p_t^i}}$)
```

both. Finally, the obtained information is added to a neighboring table (Line 7), which will be used during the candidate set selection procedure discussed in the next section.

It is important to mention that the neighboring table of a node n_i will have multiple entries for a given neighboring node n_j. This is because n_i might receive multiple beacons transmitted from n_j, where each one was using a different transmission power. Therefore, the entries in the neighboring table will be differentiated by the transmission power level p_t and the packet delivery probability $p_{L_{i\to n}^{p_t}}$ when using this transmission power. Furthermore, since the packet delivery probability is calculated based on the distance, packet size and transmission power, the probability of a data packet transmitted from nodes n_i or n_j with a transmission power p_t will be the same if the packet is being transmitted from node n_j to n_i using the same transmission power. Therefore, the packet delivery probabilities calculated at node n_i, based on the pieces of information extracted from the beacon messages received from its neighbors, will be the same probability for a transmission from node n_i to its neighbors, when using the equivalent transmission power.

4.2. Candidate Set Selection Procedure

The candidate set selection procedure is one of the main building blocks of opportunistic routing protocols. This procedure is responsible for selecting a subset of the neighboring nodes, which will, in turn, work collaboratively to forward the received packet towards the destination.

Formally, for a sender node n_i, the candidate set selection procedure will determine the set of next-hop forward nodes $\phi_i \subset N_i$ from the neighboring nodes set N_i. To do so, it first checks which neighbors are able to continue forwarding the data packet and then selects a subset of those nodes, based on a fitness function.

The proposed PCR protocol mainly considers the energy waste to decide whether a possible candidate node will be added into the candidate set. First, it determines which neighbors make positive progress in terms of packet advancement towards the destination. After that, for each transmission power level, it determines what is the best set of candidate nodes that leads to lower energy waste. The candidate set selection procedure of the PCR is detailed discussed in the following.

Algorithm 3 presents the procedure for the candidate set selection in the proposed PCR protocol. The algorithm will provide the suitable transmission power level p_t the sender must use and the next-hop forwarder candidate set ϕ_i. To do so, for each possible transmission power level (Line 4), the following steps are performed.

First, the node will check its neighboring table and retrieve the neighboring nodes can be reached by using the transmission power level p_t (Line 5). The next step is to determine which neighbors are apt to continue forwarding the data packet towards the destination (Lines 7-12). The PCR protocol uses packet advancement as the criteria to determine if a neighbor is apt or not to do so. Hence, all neighbors that can make positive progress towards the destination are apt to continue forwarding the data packet.

Herein, we use the Euclidean distance from the current sender node to its closest sonobuoy, as well as from the neighbors to their closed sonobuoy, when determining the progress of each neighbor. We assume that all nodes know the location information of all sonobuoys. This information can be provided to the sensor nodes manually before the deployment, when the deployment locations of the sonobuoys are known beforehand, or during the network operation through a localization protocol.

From the set of apt next-hop forwarder nodes, the PCR protocol determines a subset of it, composed of the nodes that lead to the lower energy waste (Lines 16-26). It is important to mention that all the neighboring nodes in the set of apt forwarder nodes $\mathcal{A}$ are ordered according to the normalized packet advancement (Line 15), which is calculated as [23]:

$$NADV_{n_j} = P_j \times p_{L_{i\to j}^{p_t^k}}, \tag{6}$$

where P_j is the progress made by the node n_j towards a surface sonobuoy and $p_{L_{i\to j}^{p_t^k}}$, given by Eq. 5, is the packet delivery probability to the node n_j when the transmission power level p_t^k is considered.

In order to calculate the energy waste for a next-hop forwarder candidate set $\phi_i^{p_t^k}$, the following procedures are considered. First, we calculate the probability of none of the candidate nodes receive the data packet (Line 18). This probability is given as:

$$e_{\phi_i}^{p_t^k} = \prod_{\forall j \in \phi_i^{p_t^k}} 1 - p_{L_{i\to j}^{p_t^k}}, \tag{7}$$

where $\phi_i^{p_t^k}$ is the next-hop forwarding candidate set of node n_i when it is using the transmission power p_t^k. Subsequently, we estimate the number of transmissions would be necessary to successfully delivery the data packet from the node n_i to its next-hop forwarder nodes in the candidate set $\phi_i^{p_t^k}$ (Line 19). This is

Algorithm 3 Candidate set selection algorithm

```
$p_t \leftarrow 0$
$\phi_i \leftarrow \emptyset$
$\text{min\_}E_w \leftarrow \infty$
for all $p_t^k \in P$ do
  $N_i \leftarrow$ neighbor_table.get $(p_t^k)$
  $\mathcal{A}$: Set of apt neighbors
  for all $n_j \in N_i$ do
    $Adv_j \leftarrow$ packet_advancement $(n_i,\, n_j)$
    if $Adv_j > 0$ then
      $\mathcal{A} \leftarrow \mathcal{A} \cup \{n_j\}$
    end if
  end for
  $\phi_i^{p_t^k} \leftarrow \emptyset$
  $prevE_w \leftarrow \infty$
  sort($\mathcal{A}$, NADV)
  for all $n_p \in \mathcal{A}$ do
    $\phi_i^{p_t^k} \leftarrow \phi_i^{p_t^k} \cup \{n_p\}$
    $e_{\phi_i}^{p_t^k} \leftarrow \prod_{\forall j \in \phi_i^{p_t^k}} 1 - p_{L_{i \rightarrow j}^{p_t^k}}$
    $N_u \leftarrow \min \left\{ \frac{1}{1 - e_{\phi_i}^{p_t^k}} - 1, RT \right\}$
    $E_w \leftarrow N_u \left( p_t^k \frac{L}{B} + |N_i^{p_t^k}| p_r \frac{L}{B} \right)$
    if $!(E_w \leq prevE_w)$ then
      $\phi_i^{p_t^k} \leftarrow \phi_i^{p_t^k} \setminus \{n_p\}$
    else
      $prevE_w \leftarrow E_w$
    end if
  end for
  if $E_w < min\_E_w$ then
    $\text{min\_}E_w \leftarrow E_w$
    $p_t \leftarrow p_t^k$
    $\phi_i \leftarrow \phi_i^{p_t^k}$
  end if
end for
return $p_t$ and $\phi_i$
```

given by the minimum of the maximum allowed number of tries (RT) and the expected transmission count given by:

$$N_t = \frac{1}{1 - e_{\phi_i}^{p_t^k}}. \tag{8}$$

Finally, we estimate the energy waste as the energy incurred in the unsuccessful tries to deliver the data packet to the nodes in the next-hop forwarder candidate set (Line 20). The energy waste is approximated as:

$$E_w = (N_u - 1)\Big(p_t^k \frac{L}{B} + |N_i^{p_t^k}| p_r \frac{L}{B}\Big), \tag{9}$$

where B is the data rate, L is the packet size, p_t^k is transmission power level and p_r is the reception power level.

Furthermore, we determine if the inclusion of the considered neighboring node n_p in the next-hop node candidate set reduces the energy waste. Its inclusion will reduce the energy waste whenever it contributes to improving the link quality between the sender node and the candidate nodes. The considered node is removed from the set of candidate nodes if its inclusion increases the energy waste (Line 22). Finally, we keep track of the transmission power level and resulting next-hop forwarder candidate set that will lead to the lower energy waste (Lines 27-31).

4.3. Candidates' Transmission Coordination Procedure

The second main building block of opportunistic routing protocols is the procedure for coordinating the transmissions of candidate nodes. In opportunistic routing protocols, candidate nodes will forward data packets according to their transmission priorities. Ideally, only one candidate node forwards the data packet and no redundant transmission takes place. However, this may not be the case in practical scenarios because the hidden terminal problem and the characteristics of the underwater acoustic channel that may lead a candidate node to not hear the transmission of a high priority node. The redundant transmission of data packets is critical, since it increases the energy consumption and packet collisions.

The design of efficient candidates' transmission coordination procedure is an active topic in the literature [14]. In scenarios of IoUTs, the efficiency of this procedure is even more fundamental, due to the higher energy cost for data transmission and the low sound propagation speed. In the literature, timer-based and control packet-based methodologies have been used to implement procedures for the coordination of the transmissions of candidate nodes. In the former, each candidate node holds a received data packet for a small delay, before transmitting it. This delay is determined by the transmission priority of each node in the next-hop forwarder candidate set. Hence, higher is the priority of the candidate node, lower is its packet holding time. In the later, acknowledgment or other short packets are used to coordinate the transmission of the candidate nodes that successfully received the data packet. Accordingly, each candidate node that can forward the received data packet will transmit an ACK packet to inform all neighbors that it will forward the packet.

In the end, a candidate node only continues forwarding the data packet if the following two conditions hold. First, it must have successfully received the data packet. Second, all the higher priority nodes failed in forwarding the data packet. The design of the procedures that guarantees no redundant transmission of data packets is challenging due to the hidden terminal problem and characteristics of the underwater acoustic channel and IoUT scenarios.

Herein, we concentrate on the candidate set selection procedure, considering the transmission power capability of current acoustic modems. However, the PCR protocol can implement a timer-based solution for transmissions coordination, which will not incur in any overhead for the network. Accordingly, the transmission priority of the candidate nodes will be assigned based on the normalized packet advancement of each candidate node. Let's consider a sender node n_i and its candidate set $\phi_i^{p_t^k}$, where the candidate nodes are sorted according to their normalized packet advancement (NADV). A function considering the packet propagation delay can be used, where the packet holding time at each candidate node is given by the propagation delay for the reception of the packet coming from higher priority candidate nodes. Hence, the packet holding time for a given candidate node n_j with k^{th} transmission priority, can be estimated as:

$$W_{n_j} = t_d + \sum_{p=1}^{k-1} \frac{d_{p,p+1}}{s} + (k-1) \times t_{proc}, \tag{10}$$

where t_d is the propagation time of the data packet transmitted by the source node n_i, $d_{p,p+1}$ is the distance between the candidate nodes that have the p^{th} and $p + 1^{th}$ transmission priority, $s = 1500\,\text{m/s}$ is the approximates sound propagation speed, and t_{proc} is the data processing time at each candidate node. In Eq. 10, the distance between the nodes can be estimated from their locations, which can be known through beaconing for neighborhood discovery. Candidate nodes cancel scheduled transmissions for a given data packet when they hear a transmission of the same packet from a higher priority candidate node.

5. Performance Evaluation

In this section, we conduct extensive simulations for the performance evaluation of the proposed PCR protocol. We compare the proposed protocol with two classical opportunistic routing protocols designed for UWSNs: the DBR [16], Hydrocast [17] and GEDAR [26] routing protocols. We use the R[1] statistical computing software to implement the considered routing protocols. Moreover, we implement the Urick's underwater acoustic channel model [41] described in [11], the natural and human-made noise in the aquatic environment, as well as the characteristics of the underwater acoustic communication, aquatic environment, and IoUT scenarios.

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[1] https://www.r-project.org/

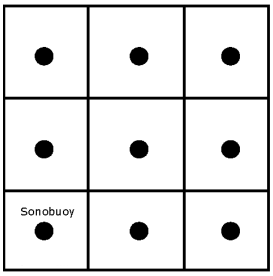


Figure 1: Planned deployment of surface sonobuoys

Table 1: Simulation parameters and topology properties.

Parameter	**Value**
Number of surface sonobuoy (sinks)	16
Number of underwater sensor nodes	100 to 340
Area of interest	3 km × 3 km × 1.5 km
A_0	5 dB
TVR	130 dBreμ Pa
Maximum communication range	{500, 1200, 2000} m
Depth threshold DBR	communication range/4
Data rate (B)	18,700 bps
Mac layer	CSMA
Packet size	150 bytes
Transmission power set - PCR	$P_t = \{8.5, 35, 55\}$ W
Power reception (P_r)	0.8 W
s (shipping)	0.5
w (wind)	4

5.1. Scenarios' setup

We consider an area of interest of 3 km × 3 km × 1.5 km. We simulate a random deployment of a varying number of underwater sensor nodes. Moreover, 16 sonobuoys are deployed in a pre-planned manner in the ocean surface, as showed in Fig. 1. The nodes' configuration values were set according to the Telesonar SM-75 SMART model [42] and common configurations used in related studies [25, 26, 17, 35]. The considered parameters and respective values are summarized in Table 1. In the candidate set determined by the considered protocols, we only include the nodes whose the probability to continue forwarding the data packet is at least of 5%. For each scenario and configuration, we plot the average result of 30 runs and confidence interval of 95 %.

5.2. Results

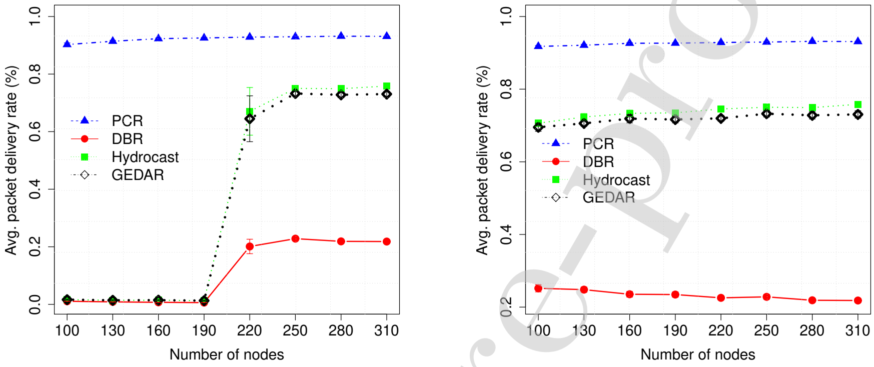
Fig. 2 depicts the average packet delivery rate when the network density increases. The packet delivery rate is defined as the average packet delivery probability from each underwater sensor node to any surface sonobuoy. It is important to mention that the DBR, Hydrocast, and GEDAR routing protocols use a fixed transmission power, while the proposed PCR routing protocol selects at each node one of the three available transmission power levels. Therefore, Fig. 2a shows the performance of the related work when the transmission power of 8.5 W is considered, although the PCR protocol can adjust the transmission power at the nodes and select one value of the discrete set $P = \{8.5\,\mathrm{W}, 35\,\mathrm{W}, 55\,\mathrm{W}\}$. The same aspect applies to the results of Figs. 2b and 2c.

As can be noticed in Fig. 2, the proposed PCR routing protocol outperforms the related work. The PCR protocol adjusts the transmission power at each hop, in order to select the suitable candidate set of neighboring nodes to continue forwarding data packets towards surface sonobuoys. Therefore, the overall packet delivery rate is improved as the power control increases network connectivity and the link quality among sender and candidate nodes. In addition, the proper transmission power control of the PCR protocol is important to reduce the number of neighbors as the number of nodes increases.

Another trend that can be observed is the improvement of the packet delivery rate of the Hydrocast and GEDAR protocols when the transmission power increases (please refer to Figs. 2a and 2b). Both protocol have an improved packet delivery ratio only in the cases of moderate to high number of nodes (Fig. 2a), due to the improvements in the network connectivity. In addition, as the transmission power increases from 8.5 W (Fig. 2a) to 35 W (Fig. 2b), the communication range of the nodes will increase as well. Hence, a given sender node will have more neighbors that can be used as next-hop forwarder nodes. The increment in the transmission power will improve the link quality among nodes. These two facts help to improve the packet delivery rate of the Hydrocast and GEDAR routing protocols. Interestingly, the same trend is not observed for the DBR routing protocol. This is due to the fact that the candidate set selection procedure of the DBR routing protocol chose at each hop, the neighbors with the highest advancement, in terms of depth, as the candidate nodes.

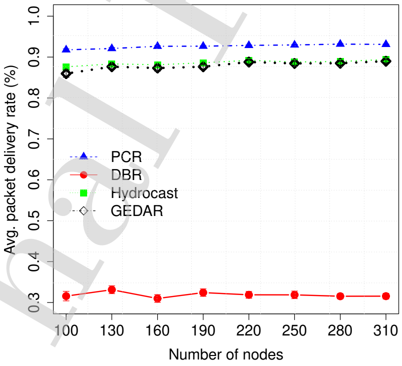
Fig. 3 illustrates the average number of candidate nodes at each hop. Again, it is important to mention that in our simulations, a candidate node is included in the candidate set of a sender only if it has at least 5% of probability to continue forwarding the packet to the destination. The results show that the PCR protocol on average relies on 2.8 candidate nodes per hop. This is achieved due to the improved link quality resulting from the selection of the suitable transmission power level at each node.

For the low-density scenario, Fig. 3a, the DBR, Hydrocast and GEDAR routing protocols have on average one next-hop node. In fact, this represents the nodes that have a direct connection with surface sonobuoys, since most of the nodes will be disconnected as corroborated by the poor performance, in term of data delivery, showed in Fig. 2a. As the used transmission power increases, the average number of nodes in the candidate sets of the DBR and Hydrocast protocols increases. This is because of the increment in the neighborhood density, which will lead to a high number of neighboring nodes apt to continue forwarding data packets.



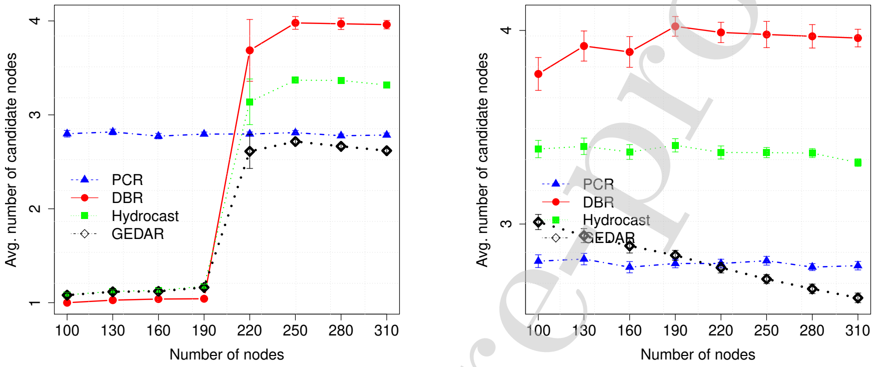
(a) $p_t = 8.5W$

(b) $p_t = 35W$



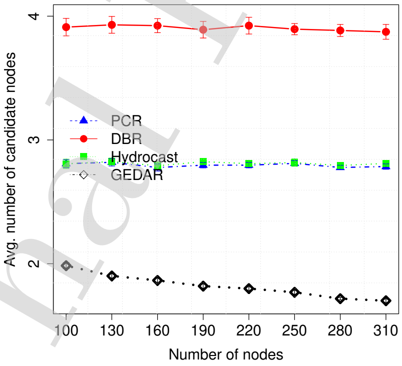
(c) $p_t = 55W$

Figure 2: Average packet delivery rate



(a) $p_t = 8.5W$

(b) $p_t = 35W$



(c) $p_t = 55W$

Figure 3: Average number of candidate nodes

When opportunistic routing protocol is employed, a data packet can take one of the multiple possible paths to reach the destination. The possible routing paths are given by the combination of the candidate nodes at each hop. However, each one of the paths will have a probability that the data packet will be delivered through it, which is determined by the link quality between the nodes and the different transmission priorities of candidate nodes.

Fig. 4 depicts the average probability of the multiple OR paths for the considered protocols. As can been seen, the PCR protocol has better performance. This is due to the better quality of the links at each hop, controlled through the selection of the most suitable transmission power, and the reduced number of candidate nodes as illustrated in Fig. 3.

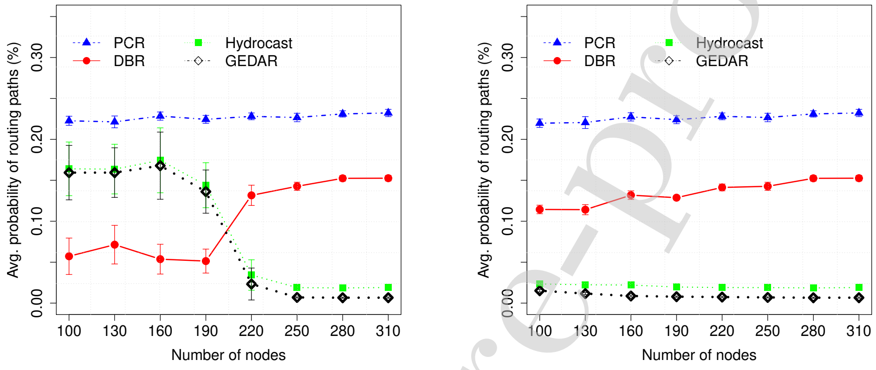
It is interesting to notice the performance of the DBR, Hydrocast and GEDAR protocols. Firstly, when the low transmission power is considered (Fig. 4a), the path probability decreases as the number of nodes increases. This happens because the introduction of more nodes in the network will create more routing paths. However, the quality of the additional routing paths, herein measured in terms of data delivery probability, not necessarily will be good enough to lead the path to have a high probability of being taken. In other words, the increment on the number of nodes might increase the number of paths that will have a low probability of being used.

The abovementioned trend is corroborated by the comparison of the performance of the Hydrocast and GEDAR routing protocols showed in Figs. 4a and 4b, which shows a reduction of 80% in the path probabilities. The increase in the transmission power from 8.5 W to 35 W and, consequently, in the communication range, in the considered scenarios led to an increased number of neighbors in each hop, but it was not enough to improve the data delivery probability at each hop. However, as shown in Fig. 4c, the average probability of routing paths increases when the transmission power is high. This is due to the improved link quality among the senders and their next-hop forwarder nodes at each hop.

5.2.1. Energy consumption

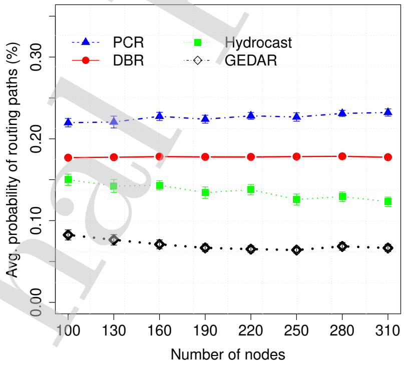
Fig. 5 shows the average energy consumption per packet transmission. As can be seen, the DBR, Hydrocast and GEDAR protocols have a lower energy cost when the transmission power is 8.5 W (Fig. 5a). This happens because only a few nodes will transmit data packets since the majority of them will not have any routing path to surface sonobuoys. The DBR protocol will have a high fraction of nodes without a routing path to surface sonobuoys due to the poor link quality of the underwater acoustic channel and the depth threshold mechanism used for selecting next-hop candidate nodes. This mechanism leads to the selection of only distant nodes, which in turn, might not be reachable because of the high packet error rate of the underwater acoustic channel. As the network density increases by increasing the transmission power, the energy cost of the DBR and Hydrocast protocol increases, as more nodes will be able to forward data packets towards the surface sonobuoys.

For the scenarios of high transmission power (please refer to Fig. 5), the PCR, Hydrocast and GEDAR routing protocol has a similar energy cost. The



(a) $p_t = 8.5W$

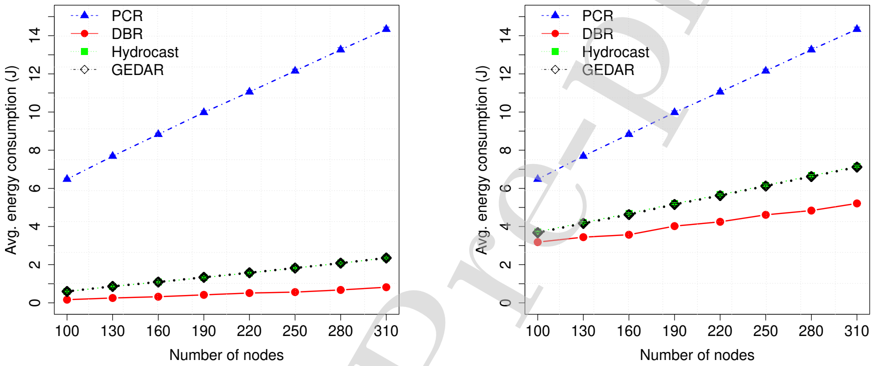
(b) $p_t = 35W$



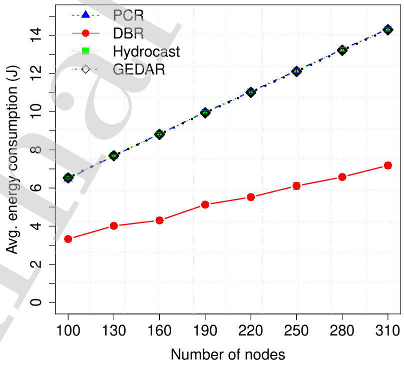
(c) $p_t = 55W$

Figure 4: Average probability of the routing paths

high energy cost in the PCR protocol is already expected as more nodes will be able to deliver collected data to a surface sonobuoy since PCR adjusts the transmission power of the nodes when needed. The performance of the PCR protocol is the same in Figs. 5a, 5b and 5c, since in all scenarios it is allowed to select one of the considered transmission power levels. However, it is important to highlight the energy-efficiency of the PCR protocol when compared to the Hydrocast. Although the energy cost is similar, the power control improves the channel quality as corroborated by the increased packet delivery rate showed in Fig. 2.



(a) $p_t = 8.5W$ (b) $p_t = 35W$



(c) $p_t = 55W$

Figure 5: Nodes' average energy consumption per round

6. Conclusion and Future Work

In this paper, we proposed the power control-based opportunistic routing protocol (PCR) for the Internet of Underwater Things. The PCR protocol was proposed to improve data delivery while keeping energy cost at acceptable levels. To do so, in addition to the normalized packet advancement towards the destination, the candidate set selection procedure of the PCR protocol explored different transmission power levels at the underwater sensor node to select the most suitable transmission power at each node, aimed to reduce the energy waste. Numerical results showed the efficiency of the PCR protocol by controlling the transmission power of the underwater sensor nodes. The PCR protocol led to improved data delivery rate, while kept the energy cost to a level similar to the related work.

As future work, we plan to consider underwater autonomous vehicles (UAV) with well-defined trajectories for data collection. Hence, the transmission power at each node would be adjusted to select the suitable level when the node will transmit towards the UAV or the surface sonobuoys. Moreover, we intend to investigate the use of duty-cycling for reducing the energy consumption at the nodes and improve the quality of candidate sets. This approach would turn-off the acoustic modem in those neighboring nodes not needed in the data forwarding process, which would reduce their energy cost.

7. Acknowledgment

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Conflict of interest

None

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