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# UDTN-RS: a New Underwater Delay Tolerant Network Routing Protocol for Facilitating Coastal Patrol and Surveillance Networks

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**Abstract:** The Coastal Patrol and Surveillance Application (CPSA) is developed and deployed to detect, track and monitor water vessel traffic using automated devices. Latest advancements of marine technologies, including the Automatic Underwater Vehicles, have allowed the development of this type of applications. To facilitate their operations, installation of a Coastal Patrol and Surveillance Network (CPSN) is mandatory. One of the primary design objectives of this network is to deliver adequate amount of data within an effective time period. This is particularly essential for reporting a detection and notifying the current status of an intruder's vessel through the adverse underwater communication channels. Additionally, intermittent connectivity of the nodes remain another important obstacle to overcome to allow smooth functioning of CPSA. Taking these objectives and obstacles into account, this work proposes a new protocol, named UDTN-RS, which is developed by ensembling forward error correction technique (namely Reed-Solomon codes or RS) in Underwater Delay Tolerant Network (UDTN) routing protocol with probabilistic spraying technique. In addition, the existing binary packet spraying technique is enhanced for supporting encoded packet exchange between the contacting nodes. A comprehensive simulation campaign is performed in identifying the effectiveness of the proposed protocol. The obtained results suggest that the proposed UDTN-RS protocol can be considered a suitable alternative of the existing protocols for sparse networks like CPSN.

**Keywords:** Coastal patrol and surveillance network; UDTN-Prob; UDTN-RS; DTN networks; DTN routing protocols; DESERT underwater simulator

## 1. Introduction

Due to the advancement of marine technologies and the contributions by several marine surveillance projects in recent years — detecting, tracking, and monitoring of water vessel traffic come to an existence using an application, called Coastal Patrol and Surveillance Application (CPSA). It is a mission-critical application based on the cutting-edge software and equipment that accumulates, analyzes, and visualizes real-time information on the activities within a coastal zone under surveillance, including harbours against sabotage or terrorism and asymmetric threat from known and unknown enemies [1,2]. For facilitating the operations of CPSA, the CPSN is mandatory to install. Again, among various CPSN topologies (e.g., static, mobile, or hybrid), in this paper, a hybrid CPSN is considered alike in [3] where the sinks remain static and a fleet of AUVs patrol an area of interest and deliver

data to the former or to the fellow contacting AUVs with a hope that the other node will deliver the data to the sink. Generally, the patrolled area of interest is large and only a few AUVs are installed for feasibility purpose. Consequently, it is impractical to discover a fixed packet relaying path from the source to the destination. The nodes experience intermittent connectivity, which can be considered as a DTN network where packets are transmitted following a Store-And-Forward (SAF) based paradigm. Every node in a DTN stores packets and forwards them opportunistically to the destination or one or multiple relaying nodes. Again, since the nodes generally remain involved in missions, they get limited opportunity to exchange data among each other due to the short inter-contact durations. To make the best out of the limited contact durations between the two contacting nodes, it is impractical to inject packets in a chaotic fashion. Instead, the UDTN-Prob protocol divides the estimated contact duration fairly between the contacting nodes for exchanging data, which is one of the influencing factor of selecting it as the parent protocol in this work.

As mentioned earlier, to support intermittent connectivity between the contacting nodes in DTN, the SAF paradigm is utilized. Now, most of the protocols under this paradigm can be classified into two groups, namely forwarding-based and replication-based [4]. In the former category, a node stores packets locally and opportunistically forwards them to selective nodes without replicating. This replication-free strategy tends to offer a higher efficiency in terms of overhead, energy dissipation, and others; but also yields a lower packet delivery ratio [5,6]. Therefore, they are not suitable for many time-critical applications, including CPSN, where reporting of an intruder vessel to the control center within the effective time is more important than achieving other efficiency indices. Alternatively, replication-based protocols allow multiple copies of a packet to inject into the network. These protocols impose a higher replication overhead in the network along with the incremental dissipation of bandwidth and energy. Conversely, they maximize the chances of successful delivery. Again, due to circulating multiple replicas of a packet in the network, there is a higher likelihood that at least one replica will reach to the destination within a delineated time frame. Therefore, they are more suitable for mission-critical applications, and hence, chosen in this paper.

However, instead of casual replication — which is the most common strategy adopted by this class of protocols — for increasing packet delivery ratio and/or decreasing end-to-end delay, it can be admixed with an appropriate FEC technique for tackling several underwater channel related issues. For instance, transmissions through underwater channels are largely prone to errors, and it aggravates when operated over shallow-water acoustic channels [7]. To deal with this issue, many protocols employ retransmission-based error correction techniques, where generally missing of an ACKnowledgement (ACK) packet is assumed be the triggering instance for retransmission. However, since the propagation speed of acoustic signal is only 1500m/s and typical communication range of an underwater modem is from a few hundred meters to a few kilometers [8–10], a Stop-&-Wait (S&W) based Automatic Repeat Query (ARQ) approach — the most common approach of error correction in lower layers in terrestrial networks as well as in underwater networks — imposes a larger inter-packet transmission delay. In order to tackle this issue, several juggling based retransmission approaches are proposed [11–13]. Although, these approaches reduce inter-packet transmission interval, but unable to resolve various other issues, including additional overhead due to ACKs, time synchronization complexity, time wastage for the guard duration (for avoiding collision between DATA packet transmission and ACK reception), and energy dissipation due to ACK packets. However, a rational admix of FEC with cautious replication can resolve these issues with manifold advantages, including error correction without retransmission, no ACK transmission, no time synchronization, and many others. Hence, in this paper, a new protocol is proposed by ensembling RS in UDTN-Prob protocol to attain those advantages, and called UDTN-RS. The contributions of this paper can be summarized as follows:

- developing a new protocol by ensembling RS in UDTN-Prob for facilitating the target application (i.e., CPSA) by delivering adequate amount of data within the effective time period.
- enhancing the existing binary packet spraying technique for supporting encoded packets.

- performing a comprehensive simulation campaign to identify the effectiveness of the proposed technique.

The rest of the paper has been organized as follows. In Section 2, we discuss the relevant DTN protocols with their error correction techniques. Section 3 elaborates the target application and its network architecture that is taken into account in this paper. Afterwards, Section 4 explains the UDTN-Prob protocol, which is the base protocol, and the proposed enhancements of UDTN-RS. Simulation scenarios and the acquired results are presented and analyzed in Section 5 and 6, respectively. This paper ends with concluding remarks in Section 7.

## 2. Related Works

Till date, many routing protocols for underwater DTNs are proposed in the literature. One of the typical ways of classifying these protocols is whether or not packets are replicated. Among them, routing protocols that replicate packets are called replication-based routing protocols [15], as opposed to forwarding-based protocols, which never replicate packets [16]. As a general observation, replication-based protocols achieve better packet delivery ratios over forwarding-based protocols, at the price of the greater overhead by injecting multiple replicas into the network. Again, the former also ensures the minimum end-to-end delay by increasing the chances of transmitting at least one packet among many replicas through the shortest path. Consequently, between both these classes, replication-based protocols are more suitable for CPSN due to the constraint of receiving adequate number of packets within the effective time period. Hence, it is taken into account in this paper. Most prominent protocols in this class are investigated below.

Epidemic routing protocol [17] is one such replication-based protocol, which performs massive replication by replicating a packet to each newly discovered contact that does not already own a copy of that packet. Therefore, similar to the flooding technique, epidemic routing is likely to achieve the best packet delivery ratio among all the replication-based approaches, albeit at the price of a very large replication overhead. Conversely, other routing protocols of this class endeavor to limit the replication overhead by generating and delivering replicas to only a handful of contacting nodes. For instance, Max Prop [18] prioritizes the packets to be transmitted or dropped upon contact with a peer based on a number of parameters, including packet generation time and lists of previous encounters. Even though, it incorporates a controlled strategy; however, it still experiences a considerable amount of overhead due to its flooding-based nature.

On the other hand, in Spray-And-Wait (SAW) protocol [19], the replication of each packet is restricted to a fixed number of copies. In the vanilla version of SAW, only the source is allowed to replicate, whereas the binary version allows intermediate relays also to replicate packets. However, in the latter version, the maximum number of replicas allowed is evenly split between the current and the next relay except the last replica, which it tries to deliver to the destination by itself. Another variant of it [20] considers overdue contacts as one of the criteria of selecting relays. The assumption that is considered here is that the nodes that did not encounter the destination for a long time are more likely to encounter it soon and hence, become the preferred relays.

PROPHET [21] is another replication-based routing protocol which limits the packet replication by forwarding a packet only to those neighbours that exhibit higher probabilities of delivering the packet to the destination within a short period of time. Another analogous protocol, named Resource Allocation Protocol for Intentional DTN (RAPID) [15] also limits the replication by computing the utility of the packets employing a list of global routing metrics, including the average delay or the number of missed deadlines and then, replicating packets with the highest utility only. Alternatively, single replication is advocated in the Prediction Assisted Single-copy Routing (PASR) protocol [23], which outperforms multi-copy routing in some resource-constrained underwater network scenarios.

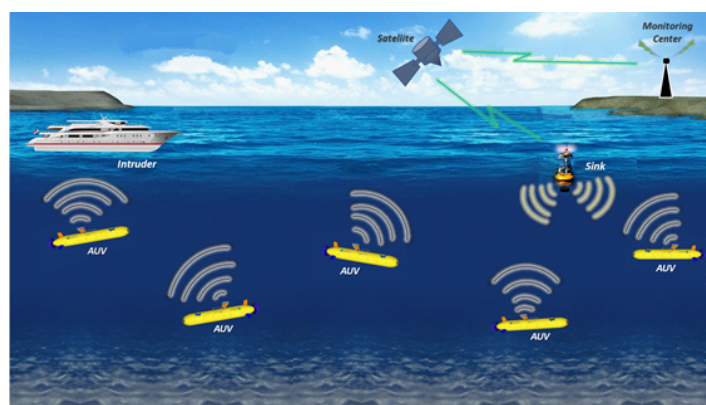
In [22], a new DTN protocol is proposed, named UDTN-Prob protocol, which exploits the contact duration between the nodes and their contact knowledge to increase the packet delivery ratio and decrease the end-to-end delay. In the UDTN-Prob protocol, the probabilities of the contacts between

intermediate nodes and sinks are estimated based on the relevant information exchanged. Afterwards, this knowledge is utilized in selecting the list of the packets to be exchanged with a prescribed probability. The statistics of future meeting times are inferred initially from synthetic mobility models, which well approximate the behavior of actual nodes and are updated as the network runs. This allows making the best use of the infrequent contacts among the nodes. Through the knowledge of the statistics of inter-contact intervals with the sink, the nodes can transmit only those packets that have a sufficiently high chance of being delivered to the sink before their lifetime expires.

In case of error correction, most of the aforementioned protocols employ a retransmission-based (aka ACK-based) error correction technique. However, due to the long inter-packet transmission delay for the long round trip time (RTT), this approach offers limited performance. For overcoming this issue, UDTN-Prob and a few other protocols employ a juggling-based packet retransmission approach where multiple packets are transmitted within a single RTT [11]. However, the juggling-based approaches impose higher implementation complexity, time synchronization problem, overhead for injecting ACK packets, and wasting time in the form of guard time to accommodate ACK packets. Therefore, this paper proposed a new protocol by ensembling RS [24] in UDTN-Prob protocol and incorporating a new packet spraying technique. This protocol is simple in terms of implementation, does not require time synchronization, no ACK required, no guard time required, and can overcome most of the aforementioned limitations.

### 3. Network Scenario

In recent times, coastal authorities are encouraged in employing automatic devices in marine activities, including CPSA (which is the focus of this paper) due to the advancements in the design of AUVs and other relevant devices over the last decade. In this paper, for imitating a realistic CPSN, a fleet of AUVs are considered patrolling autonomously an area of interest, inspecting surface ships or underwater assets, and delivering collected data to sinks, which are further connected with a control center as demonstrated in Fig. 1. Since the area of CPSNs are considerably large and generally, only a few AUVs are deployed to cover the area, they remain out of the contact of the control center and their fellow AUVs most of the time. Therefore, the inter-contact interval between the AUVs are generally high, and hence, discovering a fixed route from a source to a destination is impractical. In other words, AUVs experience intermittent connectivity; and therefore, they need cooperation from the other fellow nodes to deliver their packets to the destination. Again, since the connection between the nodes are



**Figure 1.** A hybrid coastal patrol and surveillance network where AUVs are patrolling an area of interest and collecting respective data. Since nodes are not within the communication range of each other and experience intermittent connectivity, and thus, form a DTN network. Hence, for data exchange, they utilize store-and-forward based routing protocols where the data are exchanged opportunistically with an objective of delivering them to the sink, which is further connected with the control center.

intermittent, they have to perform the task in a SAF-based manner by employing a DTN routing protocol.

In the CPSA, when a vessel enters into a surveillance area, one or more AUVs start following it [14]. Here, the responsibility of the follower(s) is to acquire desired data of the target (e.g., timestamped trajectory data) and report to the shore-based control center via sinks. For this, whenever an AUV detects a contact with a fellow AUV, they opportunistically exchange data with each other with a hope that the other node will deliver the data to the destination. Since this kind of application is mission-critical, timely delivery of adequate amount of data is immensely important for realizing the motive of the target.

#### 4. Proposed Protocol: UDTN-RS

This section includes the details of the existing UDTN-Prob protocol [22], the technique of ensembling RS in the UDTN-Prob, and the enhanced packet spraying technique.

##### 4.1. UDTN-Prob protocol

As mentioned earlier, the UDTN-Prob is a replication-based routing protocol with a list of distinguishing features that are highlighted previously and will be explained briefly in this section. Unlike other plain replication-based protocols, it employs statistical knowledge for restricting replication. In details, it leverages the knowledge of inter-contact intervals of the nodes to calculate their chances of meeting the destination in the future. Once the estimation of probable sink meeting time is performed, it is exploited in identifying the packets that have the greatest chance of being delivered before the expiry. Accordingly, those packets or a subset of those packets are exchanged between the contacting nodes. In addition, UDTN-Prob also calculates the probable contact duration between the nodes and fairly divides this duration between the contacting nodes.

For enabling these strategies, the UDTN-Prob introduces a new messaging scheme, which is comprised of three phases: 1) contact discovery via BEACON packets, *ii*) analysis of contacts via INFO packets, and *iii*) contact establishment via RESPONSE packets. In the first phase, every node periodically broadcasts BEACON packets for discovering other contacting nodes. Generally, in DTNs, deployed nodes generally experience intermittent connectivity due to infrequent contacts, and may also experience prolonged periods of isolation and hence, this phase is important. After transmitting a BEACON packet, a node, denoted as *A*, starts a timer and keeps waiting for receiving corresponding INFO packets from its neighbors, if any.

On the other hand, if another node, denoted as *B*, receives a BEACON packet, it replies with a corresponding INFO packet, as demonstrated in Fig. 2. This packet contains a number of information, including its current position and velocity (necessary for estimating the contact duration), a subsampled version of the distribution function of the inter-contact time between itself and the destination and other relevant information. After transmitting the INFO packet, it starts waiting for the corresponding RESPONSE packet for a fixed waiting time. If no RESPONSE packet is received before expiring the waiting time, *B* moves to the idle state.

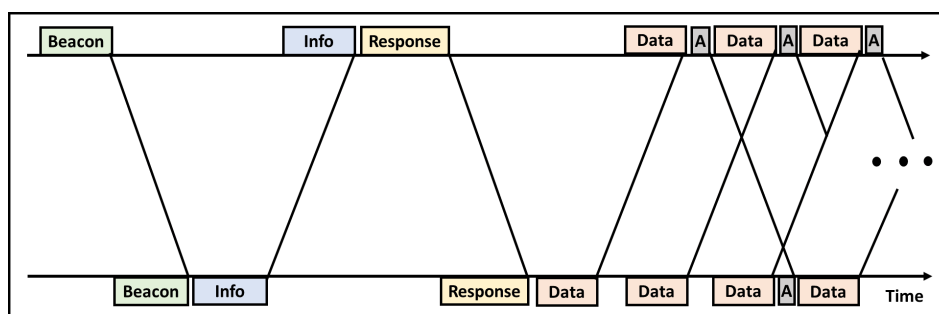


Figure 2. Example of packet exchange of UDTN-Prob protocol.

In case of  $A$ , it keeps collecting all the INFO packets from the neighbors and stores them in a buffer until the relevant waiting time is over. This way, it gets an opportunity to select the best from the available options. Once the timer expired, it fetches all the INFO packets from the buffer and calculates the approximate inter-contact durations employing the position and velocity information that are shared in the INFO packet using the following equation [22]:

$$\tau_{AB}^c = \frac{-(\alpha_{AB}^{(r)} \cdot \beta_{AB}^{(r)})}{\|\beta_{AB}^{(r)}\|^2} + \frac{\sqrt{(\alpha_{AB}^{(r)} \cdot \beta_{AB}^{(2)})^2 - \|\beta_{AB}^{(r)}\|^2(\|\alpha_{AB}^{(r)}\|^2 - \delta_{TX}^2)}}{\|\beta_{AB}^{(r)}\|^2} \quad (1)$$

Here,

$\alpha_{AB}^{(r)}$  is the relative position and could be found as:

$$\alpha_{AB}^{(r)} = \alpha_A - \alpha_B + \zeta_\alpha \quad (2)$$

$\beta_{AB}^{(r)}$  is the relative velocity and could be found as:

$$\beta_{AB}^{(r)} = \beta_A - \beta_B + \zeta_\beta \quad (3)$$

$\delta_{TX}$  is the transmission range of a transducer and could be calculated as [22]:

$$\delta_{TX} = \frac{b}{\log a(f)} W \left( \frac{\log a(f)}{b} \left( \frac{\gamma_{tgt} L}{\rho_{TX}} \right)^{-\frac{1}{b}} \right) \quad (4)$$

where,

$\alpha_A \Rightarrow$  position of node  $A$

$\alpha_B \Rightarrow$  position of node  $B$

$\zeta_\alpha \Rightarrow$  estimations errors for the relative position

$\beta_A \Rightarrow$  velocity of node  $A$

$\beta_B \Rightarrow$  velocity of node  $B$

$\zeta_\beta \Rightarrow$  estimations errors for the relative velocity

$b \rightarrow$  spreading factor — geometry of the propagation [26]

$a(f) \Rightarrow$  thorp absorption coefficient for  $f$  in kHz [25]

$W(x) \Rightarrow$  principal branch of the Lambert function [22]

$\gamma_{tgt} \Rightarrow$  target Signal-to-Noise Ratio (SNR) [25]

$L \Rightarrow$  data packet length

$\rho_{TX} \Rightarrow$  transmit source level [22].

Once the inter-contact durations for all the INFO transmitted nodes are calculated,  $A$  selects the node that exhibits the longest probable contact duration, which must also satisfy the minimum threshold condition, i.e.,  $\tau_{AB}^c > \tau_{min}^c$ . Here,  $\tau_{min}^c = 2T_D + 2T_A + 2\Delta$ , where  $T_D$ ,  $T_A$ , and  $\Delta$  are the transmission times of a DATA packet, an ACK packet, a fixed guard time (equivalent to a short propagation delay among the nodes), respectively. Let us assume that,  $B$  satisfies all the above conditions and gets selected. Consequently,  $A$  transmits a RESPONSE packet to  $B$ , which includes the share of its own contact duration, simply computed as  $\tau_A = \eta \tau_{AB}^c$ . Here, the factor  $\eta$  could be employed for implementing priority policies. If there is no accountable priority policy, the estimate contact duration can be equally divided among the contacting nodes by setting,  $\eta = 0.5$  (for AUV) and  $\eta = 1$  (for SINK, since it has no packet to transmit for the application considered in this work), and

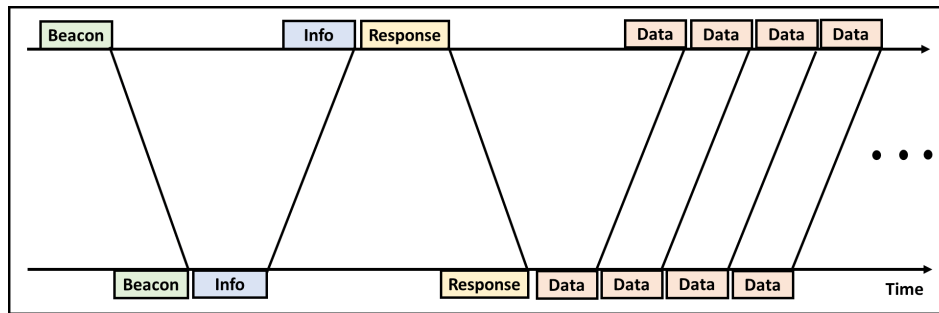


Figure 3. Example of packets exchange of UDTN-RS protocol.

incorporate this information in the RESPONSE packet. After sending this packet, based on the mode of INFO transmitting node (i.e., AUV or SINK),  $A$  moves to either WaitDataRx state (if AUV) or moves to DataTx state (if SINK). The other INFO transmitted nodes move back to the Idle state after expiring the timer.

When  $B$  receives the corresponding RESPONSE packet, it calculates its portion of the data transmission duration employing a simple equation,  $\tau_B = \tau_{AB}^c(1 - \eta)$ . Here,  $\eta = 1$  for a SINK, since it has no packet to transmit as mentioned earlier; and hence, moves to WaitDataRx state. Otherwise, it moves to DataTx state and starts transmitting packet for its own assigned portion of the duration. In DataTx state, the sender first employs a packet selection technique that commences with the estimation of number of packets,  $\nu$  that can be delivered within  $\tau_B$  epoch. Afterwards, from the buffer, only those packets are selected whose lifetimes are more than one-hop sink  $\theta$ -meeting time prediction (see [22]). Note

it imposes a large computational complexity with a very limited performance gain and hence, not selected in this paper. Again, if this condition selects more than  $\nu$  packets, only top- $\nu$  packets are selected based on the packet lifetime.

After finishing the packet transmission of its own stake, the sender switches its role and move to WaitDataRx state or Idle state based on the mode of the INFO transmitting node. Unlike UDTN-Prob protocol, thanks to the FEC technique, a node does not have to wait for the ACK packets as demonstrated in Fig. 3. Again, when  $A$  is in WaitDataRx state, it keeps receiving packet until its time for data transmission starts. This way, estimated contact duration is fairly utilized by both parties.

Fig. 4 shows the state transition diagram of UDTN-RS protocol where a complete list of states and the events that triggers state changes (i.e., transitions) are provided.

#### 4.2. Ensembling RS in UDTN-Prob

This section discusses the ensembling technique of RS in UDTN-Prob and the mechanism of recovering erroneous packets using the RS( $n, k, t$ ) code where  $k$  is the unencoded packets,  $n$  is the encoded packets and  $n > k$ , and  $t$  is the number of packets that can be recovered if contain errors.

Now, when a UDTN-RS enable node receives a packet from the upper layer, it stores the packet in a buffer until there are  $k$  unencoded packets for the identical destination and application pair. Again, this approach may lead to the starvation problem that may occur due to the lack of adequate number of packets for indefinite time. For resolving this problem, a timer is introduced that forces a sender to transmit packets without any encoding after expiration. Conversely, once the count of unencoded packets for an identical destination and application pair reaches to  $k$ , they are fetched from the buffer and encoded to  $n$  packets. To incorporate these changes, two new fields are introduced in the routing header, namely ground\_id (GID) and packet\_id (PID), where  $GID \in \mathbb{Z}^+$  and any negative GID value indicates unencoded packet, and  $0 \leq PID < n$ .

Note that during the transmission, encoded and unencoded packets receive an identical attention. Thereby, this approach incorporates the RS FEC technique at a cost of a low buffering delay at the transmitting side. In addition, it is noteworthy to mention that encoding only occurs at the source node



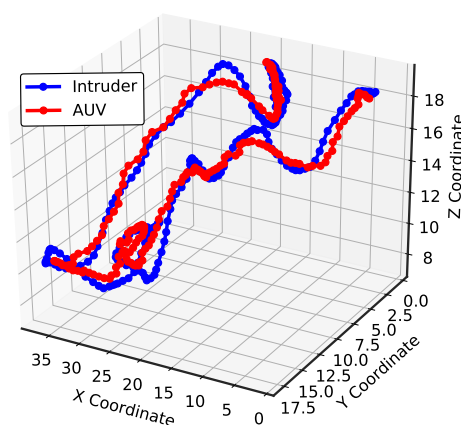
When this spraying technique is enhanced for the proposed protocol, the demand of the application (i.e., CPSA) is taken into account, i.e., delivering adequate number of packets within the effective time period. For satisfying these constraints, it is necessary to maintain the tradeoff between packet delivery ratio and end-to-end delay. For that, instead of transmitting all  $n$  encoded packets of a group, UDTN-RS sprays only  $k$  of them. The rationales of such selection are as follows. Firstly, the contact durations between the nodes are considerably short with respect to inter-contact intervals, and hence, when a node comes to a contact with another node, generally it carries many packets to transmit. Consequently, transmitting  $k$  encoded packets allows a node to spray considerably more groups of packets to the other contacting nodes and thus, it makes an effort in reducing end-to-end delay. In addition, limiting spraying to  $k$  packets also increases chances of spraying a single group of packets to more number of intermediate nodes; and thus, increases the chances of delivering adequate number of packets to the destination. Again, to choose  $k$  encoded packets from  $n$  encoded packets, a round robin technique [27] is employed in UDTN-RS since all packets have equal priority.

## 5. Simulation Scenarios

The effectiveness of the proposed protocol is evaluated using a comprehensive simulation campaign. For that, DESERT underwater simulator [28] has been utilized, which is a package of ns-miracle [29] and ns2 [30]. This open-source simulator is available online, and offers a complete set of underwater networking features, which are necessary for imitating real underwater environment. It also includes the World Ocean Simulation System (WOSS) package [31], which is a framework aimed at improving underwater network simulations through a more realistic account of acoustic propagation.

For our simulation campaign, our CPSN is installed at the coordinates  $39.97^{\circ}N$  and  $11.82^{\circ}E$ , and spread thereafter. This network is comprised of one fixed sink, which is placed at one side of the network, and either 5 or 10 mobile AUVs are deployed. At the beginning of every simulation, all AUVs are deployed randomly over a selected area. Once the simulation begins, they start moving freely within the area. Their trajectories are simulated as random realizations of a Gauss-Markov process with fixed self-correlation parameter  $\alpha = 0.8$  [32]. This leads to random yet smooth trajectories that reproduces the actual trajectories sufficiently well that autonomous underwater vehicles may follow during patrol, reconnaissance or survey missions (see Fig. 5). Again, an analogous model is also assumed for the intruders. Upon detection of an intruder, a follower (i.e., an AUV) will start following it maintaining an offset distance for being stealth and avoid any unwanted collision.

All the nodes communicate via a Binary Phase Shift Keying (BPSK) modulation technique at a bit rate of 4800 bps using a central frequency of 25 kHz and a bandwidth of 9 kHz. By setting a



**Figure 5.** Trajectories of an intruder and a follower (i.e., an AUV). Once the follower recognized the intruder, the follower starts following the intruder if not already engaged in another campaign. The follower maintains a distance from the intruder to avoid any unnecessary collision.

source level of  $PTX = 150$  dB re  $\mu$  Pa relative to a distance of 1m from the source, this leads to an estimated nominal transmission range  $d_{TX} = 2000$ m. The size of the BEACON packet is 10 Bytes, the INFO, RESPONSE, and DATA packets are 125 Bytes. All the results are presented in this paper after averaging over 25 runs.

In case of UDTN-Prob, packets are sprayed using the binary spraying technique and the replication frequency of a packet is restricted to 5. On the other hand, alike [24],  $n$  and  $k$  are selected as 3 and 2, respectively for UDTN-RS and the replication frequency of a group is restricted to 3. Three metrics are considered in evaluating the performance of the compared protocols, namely Normalized Packet Delivery Ratio (PDR), End-to-End Delay, and Normalized Throughput. Here, PDR is the ratio between the number of packets received and the number of packets transmitted; whereas, End-to-end delay is calculated based on the difference between the packet reception time and the packet generation time. And, normalized throughput of a node is the ratio of payload reception time against the simulation time.

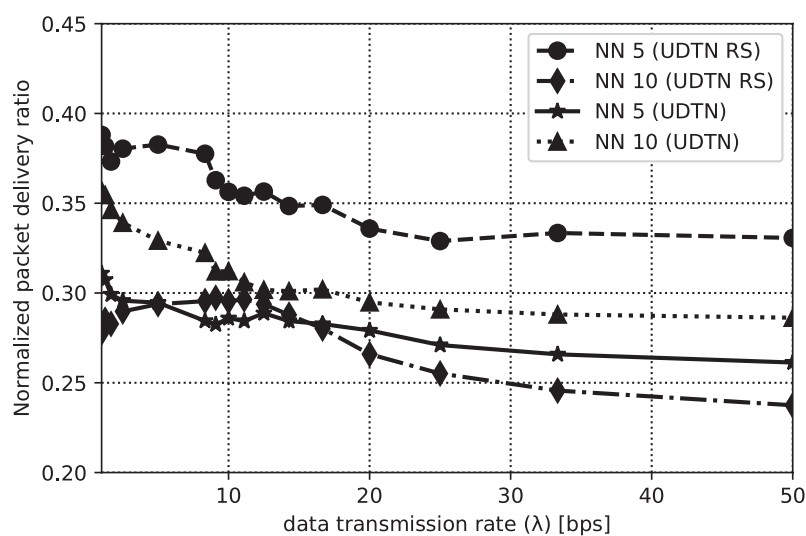
## 6. Results Discussions

This section presents and discusses the results that are acquired from our comprehensive simulation campaign. The results are grouped together based on their scenarios, and discussed accordingly.

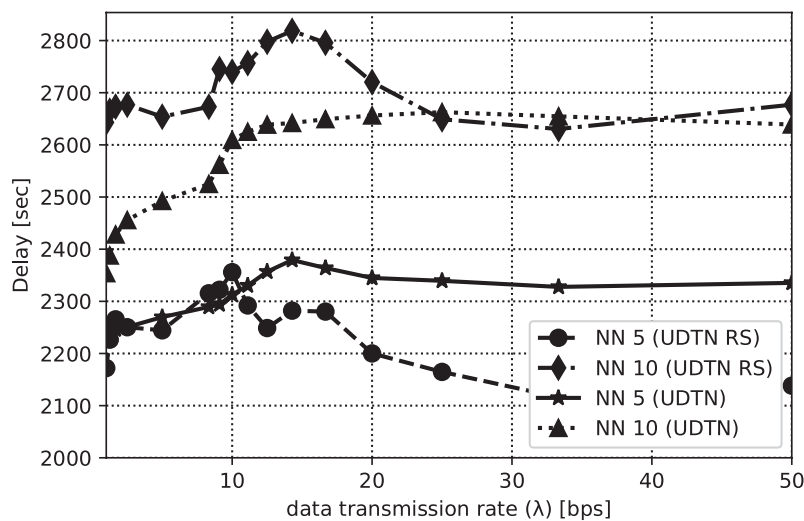
### 6.1. Scenario 1: varying data transmission rate

In this scenario, data transmission rate,  $\lambda$  was varied from 1 bps to 50 bps to observe the performance of the proposed protocol for various packet loads in the network. The acquired results are plotted in Figs. 6, 7 and 8 for node 5 and node 10 and compared with that of its ancestor, UDTN-Prob protocol. One of the core reasons of selecting 5 and 10 nodes is that when the area is fixed, increased number of nodes increases inter-contact frequencies in the network. Thereby, the simulation with 5 nodes exhibits sparse scenario and 10 nodes exhibits dense scenario with the likelihood of twice as many contacts as the former.

The acquired results of this scenario explores several preeminent facts. As could be observed from Fig. 6 is that the PDR declines with increasing  $\lambda$ . This observation is true for any protocols and any number of nodes. Again, in case of sparse network where there are a small number nodes, our proposed technique performs comparatively better than the UDTN-Prob in terms of the PDR (see Fig. 6). Thanks to the ensembling RS in UDTN-Prob and the enhanced packet spraying technique that



**Figure 6.** Packet delivery ratio for various data transmission rate and two sets of nodes.



**Figure 7.** Delay for various data transmission rate and two sets of nodes.

replicated and forwards packets conscientiously. Conversely, the retransmission-based error correction technique of UDTN-Prob imposes delays in packet transmission for accommodating ACK packets, and hence, the contacting nodes can exchange relatively lower number of packets from a pile of packets. The highest normalized PDR, 0.38 is received by the proposed protocols for 5 nodes.

However, when the inter-contact intervals are relatively low (in dense network), it can be observed that UDTN-Prob exhibits better performance at the expenses of higher overhead (see Section 6.3). In other words, albeit, UDTN-RS injects relatively lower overhead in the network than UDTN-Prob, it shows comparable performance in many cases. For instance, when a UDTN-Prob node generates 10 packets and the highest forwarding rate is restricted at 5, it injects  $10 \times 5 = 50$  packets in the network. Conversely, UDTN-RS transmits  $\frac{10}{2} \times 3 \times 3 = 45$  packets in the network.

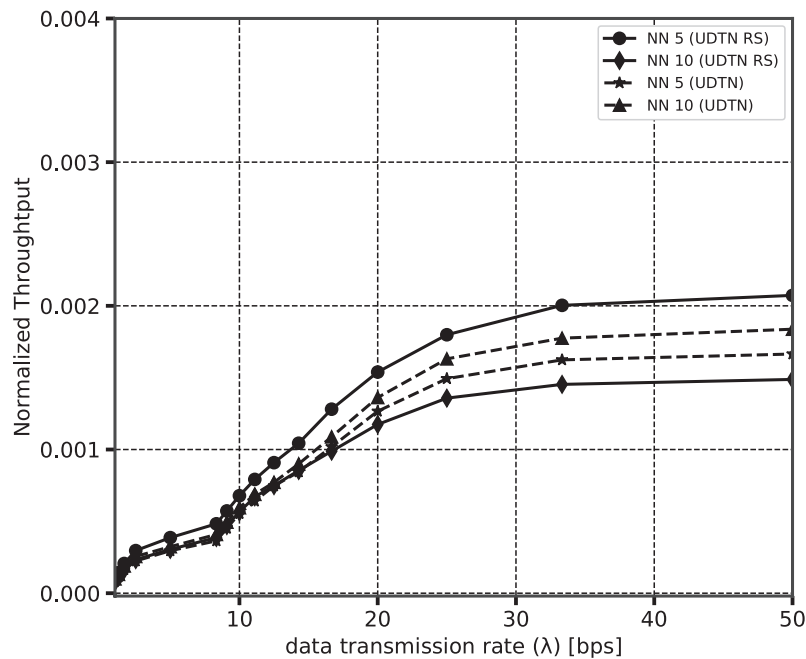
In case of end-to-end delay (see Fig. 7), for any  $\lambda$  values, UDTN-RS demonstrates the lowest delay for the sparse network. Thanks to the enhanced packet spraying technique, which ensures packet delivery within the relatively shortest period of time even when there are minimum number of nodes in the network. It even beats the end-to-end delay of UDTN-Prob with 10 nodes whose expected inter-contact frequencies are twice higher, let alone 5 nodes. Hence, UDTN-RS can be considered as a suitable alternative for CPSA in terms of delay.

As oppose to the PDR, normalized throughput (see Fig. 8) increases rapidly for any compared protocols until moderate loads or mid  $\lambda$  in the network and stagnate at the higher  $\lambda$  values. All the compared protocols reach to the threshold at around  $\lambda = 40$ . Again, for any network topology, UDTN-RS with 5 nodes outperforms the rest. Even it is higher than that of 10 nodes of UDTN-Prob. The highest normalized throughput received in this network is 0.0021 by the proposed protocol for sparse network scenario.

## 6.2. Scenario 2: varying area size

As could be observed from the previous scenario is that the performance of the compared protocols varies for sparse and dense network topologies. To explore more about this, another set of simulation campaign was conducted by varying the network area from  $4 \times 4$  to  $10 \times 10$  km<sup>2</sup>. The acquired results for normalized PDR, End-to-End delay, and normalized throughput are presented on Figs. 9, 10 and 11, respectively.

Analogous to the observation of scenario 1 for the normalized PDR (see Fig. 9), it declines with increasing  $\lambda$  for any compared protocols. Likewise, the normalized throughput (see Fig. 10) also declines with increasing  $\lambda$  value, as oppose to scenario 1. It is because, with increasing network area,

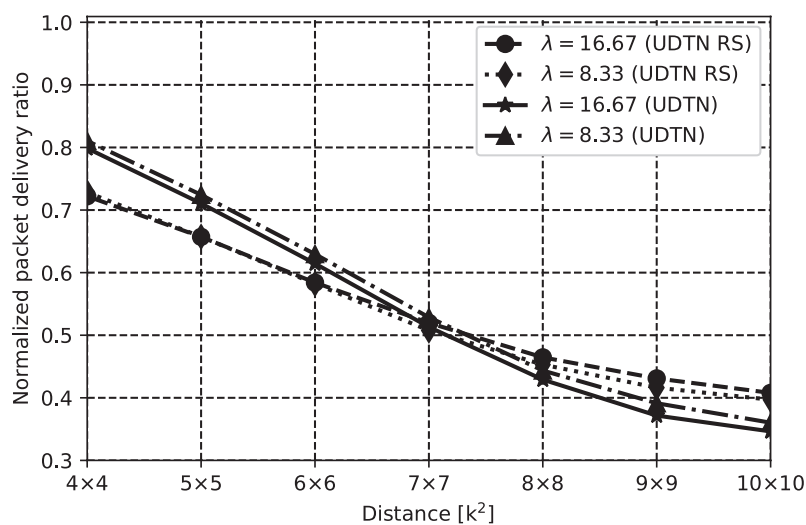


**Figure 8.** Normalized throughput for various data transmission rate and two sets of nodes.

inter-contact interval also increases, and hence, considerably lower number of packets are delivered to the destination.

The results of normalized PDR and normalized throughput explore the fact that when the area is short, UDTN-Prob performs considerably better than the proposed technique at the price of higher overhead (see Section 6.3). However, with the increasing area, the performance of UDTN-Prob declines. In continuation of that, after a certain area size, the performance falls below the proposed technique; and the latter continues to dominate afterwards. Thanks to the ensembling of RS in UDTN-Prob and to the enhanced packet spraying technique that assist the proposed technique in dealing with increasing area size. The area after which UDTN-RS overpowers UDTN-Prob is  $7 \times 7 \text{ km}^2$ .

Again, when the area size is comparatively small, all the compared protocols exhibit lower end-to-end delay. However, it increases sharply upto a mid area size and afterwards, it observes



**Figure 9.** Packet delivery ratio for various area size.

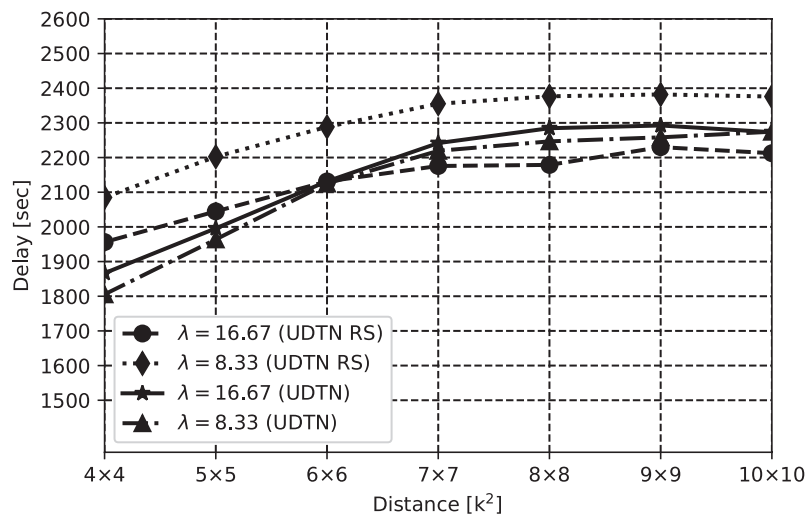


Figure 10. Delay for various area size.

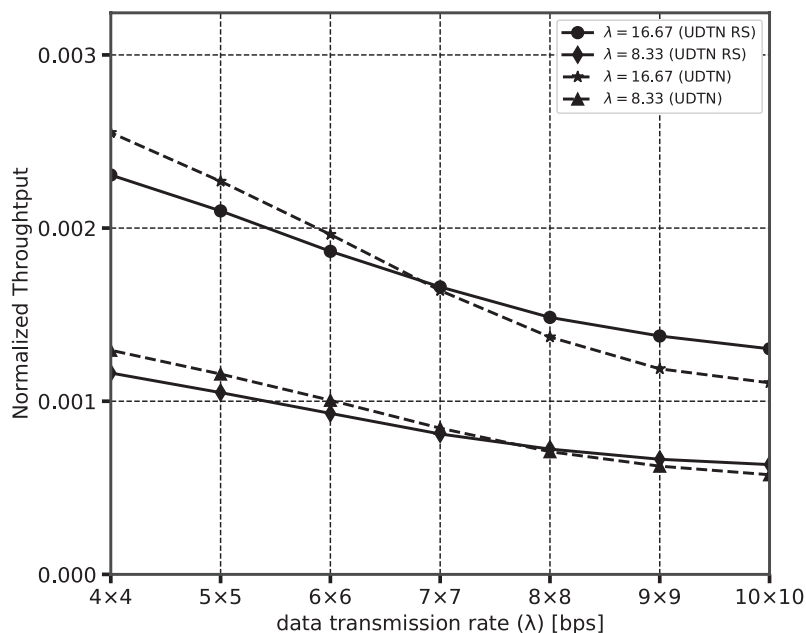


Figure 11. Normalized throughput for various data transmission rate and two sets of nodes.

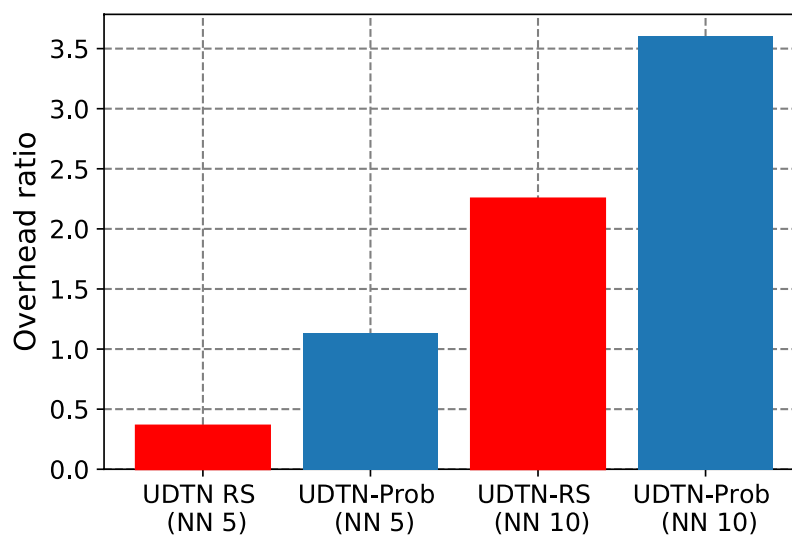
slow growth for the large area size. Among all the compared protocols and two  $\lambda$  values, UDTN-RS outperforms the rest in higher area size for  $\lambda = 16.67$ . However, when  $\lambda = 8.33$ , the proposed protocol suffers due to not having adequate number of packets for encoding. By calibrating the timer for independent packet transmission, this problem can be resolved. On the other hand, UDTN-Prob achieves the lowest end-to-end delay for the compact scenarios.

### 6.3. Scenario 3: overhead ratio

One of the design goals of UDTN-RS is to reduce overhead and increase packet transmission rate per contact. For that, the RS FEC technique is chosen, which reduces overhead in the following manner: *i*) in this proposed technique, no ACK packet is injected in the network, and thus, reduce overhead in the network; and *ii*) by injecting a lower number of copies of a single packet in the network as explained in Section 5. In addition, the proposed technique also takes advantage of replication to increase PDR. However, from our experiment, it has been discovered that even with lower replication copies, the



**Figure 12.** A contour graph of overhead ratio varying number of copies and number of nodes for UDTN-RS.



**Figure 13.** Comparison of overhead ratios for various number of nodes.

proposed technique receives comparable or higher performance as demonstrated in previously. The relationship between the number of copies with respect to the number of nodes for UDTN-RS is depicted in Figure 12 using a contour graph. Again, in Fig 13, the comparison of overhead ratios is shown for the compared protocols for sparse and dense networks. As could be observed from the figures is that UDTN-RS introduces lower overhead in the network with respect to its counterpart. A tradeoff between the encoding and replication must be maintained to achieve performance goals, which can be performed by calibration these parameters.

## 7. Conclusion

This paper proposed the UDTN-RS protocol for facilitating coastal patrol and surveillance application — a time critical application that demands delivery of adequate number of packets for realizing the activities of the coastal area. In the proposed protocol, the RS is ensembled in UDTN-Prob for compensating the inherent erroneous nature of the underwater channels. In addition, an enhanced packet spraying technique is incorporated in the protocol for facilitating delivering adequate number

of packets within the effective time period. The effectiveness of the proposed protocol is evaluated by performing a comprehensive simulation campaign. Results of the simulations are acquired and compared with that of its ancestor, UDTN-Prob protocol, where the proposed protocol outperforms its ancestor in sparse networks. Hence, it can be concluded that the UDTN-RS is a better alternative to UDTN-Prob protocol for coastal patrol and surveillance networks.

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## References

1. M. Chitre, S. Shahabudeen, and M. Stojanovic, "Underwater acoustic communications and networking: Recent advances and future challenges," *Marine Technol*, vol. 42, no. 1, pp. 103–116, 2008.
2. I. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," *Ad Hoc Net*, vol. 3, pp. 257–279, May 2005.
3. S. Azad, P. Casari, and M. Zorzi, "Coastal patrol and surveillance networks using AUVs and delay-tolerant networking," *IEEE Oceans*, May 2012.
4. A. Khasawneh, M.S.B.A. Latiff, O. Kaiwartya, and H. Chizari, "Next Forwarding Node Selection in Underwater Wireless Sensor Networks (UWSNs): Techniques and Challenges," *Information* vol. 8, no. 3, 2017.
5. R. S. Rathore, S. Sangwan, S. Mazumdar, O. Kaiwartya, K. Adhikari, R. Kharel, and H. Song, "W-GUN: Whale Optimization for Energy and Delay-Centric Green Underwater Networks," *Sensors*, vol. 20, 2020.
6. A. M. Khasawneh, O. Kaiwartya, A. Khalifeh, L. M. Abualigah, and J. Lloret, "Green Computing in Underwater Wireless Sensor Networks Pressure Centric Energy Modeling," *IEEE Systems Journal*, 2020.
7. S. Azad, P. Casari, C. Petrioli, R. Petroccia, and M. Zorzi, "On the impact of the environment on MAC and routing in shallow water scenarios," *Proc. of IEEE/OES OCEANS*, July 2011.
8. L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI Micro-Modem: An Acoustic Communications and Navigation System for Multiple Platforms," *Available: <http://www.whoiedu>*, 2020.
9. B. Benson, G. Chang, D. Manov, B. Graham, and R. Charles, "Design of a low-cost acoustic modem for moored oceanographic applications," *Proc. of ACM WUWNet*, September 2006.
10. G. Toso, R. Masiero, P. Casari, O. Kebkal, M. Komar, and M. Zorzi, "Field Experiments for Dynamic Source Routing: S2C EvoLogics modems run the SUN protocol using the DESERT Underwater libraries," *Proc. of MTS/IEEE OCEANS*, October 2012.
11. S. Azad, P. Casari, F. Guerra, and M. Zorzi, "On ARQ Strategies over Random Access Protocols in Underwater Acoustic Networks," *Proc. of IEEE/OES OCEANS*, June 2011.
12. S. Azad, P. Casari, and M. Zorzi, "The Underwater Selective Repeat Error Control Protocol for Multiuser Acoustic Networks: Design and Parameter Optimization," *IEEE\_J\_WCOM*, vol. 12, no. 12, pp. 4866–4877, 2013.
13. M. Chitre and W. S. Soh, "Reliable Point-to-Point Underwater Acoustic Data Transfer: To Juggle or Not to Juggle?," *IEEE\_J\_OE*, vol. 40, no. 1, pp. 93–103, January 2015.
14. S. Tripp, "Autonomous underwater vehicles (AUVs): a look at Coast Guard needs to close performance gaps and enhance current mission performance," *Coast Guard Research and Development Center Groton CT*, 2006.
15. A. Balasubramanian, B. N. Levine, and A. Venkataramani, "DTN routing as a resource allocation problem," *ACM SIGCOMM Computer Communication Review*, vol. 37, No. 4, pp. 373–384, August 2007.
16. S. Jain, K. Fall, and R. Patra, "Routing in a delay-tolerant network," *ACM SIGCOMM*, vol. 34, No. 4, pp. 145–158, 2004.
17. A. Vahdat and D. Becker, "Epidemic routing for partially connected ad hoc networks," *Department of Computer Science, Duke University, Tech. Rep*, no. CS-2000-06, April 2000.
18. J. Burgess, B. Gallagher, D. Jensen, and B. N. Levine, "MaxProp: Routing for vehicle-based disruption-tolerant networks," *IEEE INFOCOM Vol. 6*, pp. 1–11, April 2006.

19. T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Spray and wait: An efficient routing scheme for intermittently connected mobile networks," *ACM WDTN*, pp. 252–259, August 2005.
20. D. Pan, M. Lin, L. Chen, and J. Sun, "An improved spray and wait with probability choice routing for opportunistic networks," *Journal of networks*, vol. 7, no. 9, pp. 1486–1492, September 2012.
21. A. Lindgren, A. Doria, and O. Scheln, "Probabilistic routing in intermittently connected networks," *ACM MobiHoc*, pp. 239–254, July 2003.
22. P. Casari, S. Azad, M. Zanforlin, and M. Zorzi, "Underwater Delay-Tolerant Routing via Probabilistic Spraying," *IEEE Access*, vol. 6, no. 1, pp. 77767–77784, December 2018.
23. Z. Guo, B. Wang, and J.-H. Cui, "Generic prediction assisted single-copy routing in underwater delay tolerant sensor networks," *Ad Hoc Netw*, vol. 11, no. 3, pp. 1136–1149, May 2013.
24. E. Cherkaoui, S. Azad, P. Casari, L. Toni, N. Agoulmine, and M. Zorzi, "Packet error recovery via multipath routing and reed-solomon codes in underwater networks," *IEEE Oceans*, pp. 1–6, 2012.
25. M. Zorzi, P. Casari, N. Baldo, and A. F. Harris, "Energy-efficient routing schemes for underwater acoustic networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1754–1766, December 2008.
26. M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," *ACM SIGMOBILE Mobile Comput. Commun. Rev.*, vol. 11, no. 4, pp. 34–43, 2007.
27. W. Stallings, "Operating Systems: Internals and Design Principles," *Pearson*, 2015.
28. P. Casari, C. Tapparello, F. Guerra, F. Favaro, I. Calabrese, G. Toso, S. Azad, and M. Zorzi, "Open source suites for underwater networking: WOSS and DESERT underwater," *IEEE Network*, vol. 28, no. 5, pp. 38–46, 2014.
29. N. Baldo, M. Miozzo, F. Guerra, M. Rossi, and M. Zorzi, "Miracle: The multi-interface cross-layer extension of ns2," *Wireless Commun. Netw*, pp. 761–792, March 2010.
30. T. Issariyakul and E. Hossain, "Introduction to network simulator 2 (NS2)," *Introduction to network simulator NS2*, pp. 1–18, 2009.
31. F. Guerra, P. Casari, and M. Zorzi, "World Ocean Simulation System (WOSS): a simulation tool for underwater networks with realistic propagation modeling," *ACM WUWNet*, pp. 1–8, November 2009.
32. B. Liang and Z. J. Haas, "Predictive distance-based mobility management for PCS networks," *IEEE INFOCOM*, pp. 1377–1384, 1999.