IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 9 October 2023, accepted 26 October 2023, date of publication 20 November 2023,
date of current version 21 December 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3334638

RESEARCH ARTICLE

UDTN-RS: A New Underwater Delay Tolerant Network Routing Protocol for Coastal Patrol and Surveillance

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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. The latest advancements of marine technologies, including Automatic Underwater Vehicles, have encouraged 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 an adequate amount of data within an effective time frame. This is particularly essential for the detection of an intruder's vessel and its notification through the adverse underwater communication channels. Additionally, intermittent connectivity of the nodes remains another important obstacle to overcome to allow the smooth functioning of CPSA. Taking these objectives and obstacles into account, this work proposes a new protocol by ensembling forward error correction technique (namely Reed-Solomon codes or RS) in Underwater Delay Tolerant Network with probabilistic spraying technique (UDTN-Prob) routing protocol, named Underwater Delay Tolerant Protocol with RS (UDTN-RS). In addition, the existing binary packet spraying technique in UDTN-Prob is enhanced for supporting encoded packet exchange between the contacting nodes. A comprehensive simulation has been performed employing DEsign, Simulate, Emulate and Realize Test-beds (DESERT) underwater simulator along with World Ocean Simulation System (WOSS) package to receive a more realistic account of acoustic propagation for identifying the effectiveness of the proposed protocol. Three scenarios are considered during the simulation campaign, namely varying data transmission rate, varying area size, and a scenario focusing on estimating the overhead ratio. Conversely, for the first two scenarios, three metrics are taken into account: normalised packet delivery ratio, delay, and normalised throughput. The acquired results for these scenarios and metrics are compared to its ancestor, i.e., UDTN-Prob. The results suggest that the proposed UDTN-RS protocol can be considered as a suitable alternative to the existing protocols like UDTN-Prob, Epidemic, and others for sparse networks like CPSN.

INDEX TERMS Coastal patrol and surveillance network, DESERT underwater simulator, DTN networks, DTN routing protocols, UDTN-Prob, UDTN-RS.

The associate editor coordinating the review of this manuscript and approving it for publication was Christian Esposito.

I. 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 comes 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]. As a typical application, we can assume an area of interest of a sea segment that is patrolled by AUVs to inspect any asset (boat, ship, or other water vehicles) and monitored by a shore-based control centre. When an asset enters into the surveilled area, one or more nearby AUVs will identify and will start following it. While following the asset, one of the primary responsibility of the follower AUVs is to detect the trajectory of the asset alongside some other desired data. These acquired data are timestamped and need to be reported to the control centre whenever opportunity comes. Generally, the patrolled area is large, and hence, the AUVs may remain out of the range of the shore centre or other AUVs most of the time. Consequently, this is impractical to assume that a fixed packet relaying path would be found from the source to the destination. Hence, the AUVs need to take assistance from the other nodes to relay their data to the control centre opportunistically and store-and-forward based manner, i.e., by employing Delay-Tolerant Network (DTN) protocols.

As could be observed from the earlier discussion, for facilitating the operations of the CPSA, the Coastal Patrol and Surveillance Network (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(s) 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 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 factors of selecting it as the parent protocol in this work.

Most of the protocols under SAF 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 centre within an acceptable 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 on the network along with the incremental dissipation of bandwidth and energy. Conversely, they maximise 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 Forward Error Correction (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 to be the triggering an 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], [9], [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], [12], [13]. Although, these approaches reduce inter-packet transmission interval, they are 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 below:

- Development of a new protocol by ensembling RS in UDTN-Prob.
- Design of an enhanced binary packet spraying technique for supporting encoded packets.
- Thorough comparative analysis of the proposed protocol with the existing state-of-the-art protocols.

These contributions facilitate the target application (i.e., CPSA) for functioning efficiently by delivering an adequate amount of data within the effective time frame.

The rest of the paper has been organized as follows. In Section II, we discuss the relevant DTN protocols with their error correction techniques. Section III elaborates the target application and its network architecture that are taken into account in this paper. Afterwards, Section IV 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 V and VI, respectively. This paper ends with concluding remarks in Section VII.

II. RELATED WORKS

Till date, many routing protocols for underwater DTNs are proposed in the literature. Based on the replication characteristics of these protocols, they can be broadly classified as replication-based or forwarding-based. Here, the protocols in the former class replicate packets [18], [19], and as oppose to that, they in the later class only forward packets without any replication [20]. Even though, the forwarding-based protocols offer a higher efficiency in terms of overhead, energy dissipation, and others, they suffer from lower packet delivery ratio and higher end-to-end delay. Consequently, they are not preferable for many time-critical applications, including CPSA, where reporting of an intruder vessel to the control centre within the effective time frame is more important than achieving other efficiency indices, as mentioned previously in Section I. Conversely, by injecting multiple replicas in the network, the replication-based protocols maximise the chances of successful delivery and minimise end-to-end delay since there is a higher likelihood that at least one replica will reach to the destination within a delineated time frame. Hence, a protocol in this class is selected for ensembling RS, and the most prominent protocols in this class are investigated below.

One of the state-of-the-art protocols in this class is Epidemic routing protocol [21], which performs massive replication by replicating a packet to each newly discovered contact that does not already own a copy of that packet. Due to the flooding nature, this protocol is likely to achieve the highest packet delivery ratio in this class, albeit at the price of a very high replication overhead. Later, several other routing protocols are proposed that endeavour to achieve similar packet delivery ratios like the epidemic routing protocol but with a lower replication overhead. For that, most of them replicate packets to only a handful of contacting nodes.

Max Prop [22] is one such protocol that prioritizes a sender for delivering its packets to the other contacting nodes based on a number of parameters, including lists of previous encounters and packet generation time. Even though, it incorporates a number of strategies for controlling the overhead; however, such elementary strategies are unable to lower the number of replicas and thus, experience a high replication overhead. On the other hand, Spray-And-Wait (SAW) protocol [23] lowers the number of replicas by restricting it to a fixed number of copies. Herein, among its two variants, in the vanilla version, the source is the sole replicating node of a packet; whereas, in the binary version, even the intermediate nodes can replicate. However, the latter variant splits the number of allowable replicas evenly between the current and the next relay with an exception for the last packet, which it tries to deliver to the destination by itself. In another variant of SAW in [24], it selects the next relay based on several criteria where overdue contacts are also considered as one of the main criteria. The main assumption 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. Instead of this naive assumption, an efficient relay node selection technique could be integrated in this protocol to enhance the performance in terms of packet delivery ratio, end-to-end delay and others, which is performed in the proposed protocol by replicating the packets based on the statistics of the future contacts between the relay and the sink.

Among the other protocols, PROPHET [26] limits the packet replication to only those contacting nodes whose delivery probabilities to the destination are higher within a short period of time. One of the limitations of this protocol is that it assumes that the trajectories of the nodes are periodical and fully known a prior; which is impractical. Rather, for CPSA, a random mobility model is preferable and that would be typical of AUVs while they carry out their missions and react to events, which is taken out into consideration in this paper.

Another analogous protocol, named Resource Allocation Protocol for Intentional DTN (RAPID) [18] only replicates those packets that have higher utilities, which are computed employing a list of global routing metrics, including the number of missed deadlines and average delay. Alternatively, Prediction Assisted Single-copy Routing (PASR) protocol [28] advocates single replication in some resource-constrained underwater network scenarios and demonstrate its superiority over multi-copy routing. As mentioned earlier, single copy transmission minimizes the chances of packet delivery and end-to-end delay, which are crucial for the applications like CPSA.

In [16], a hybrid coding-aware routing protocol (HCAR) is proposed that introduces the interflow network coding for designing a new routing framework that supports reactive routing with opportunistic routing. However, these type of routing protocols introduces additional complexity to the network nodes as well as the routing decision-making

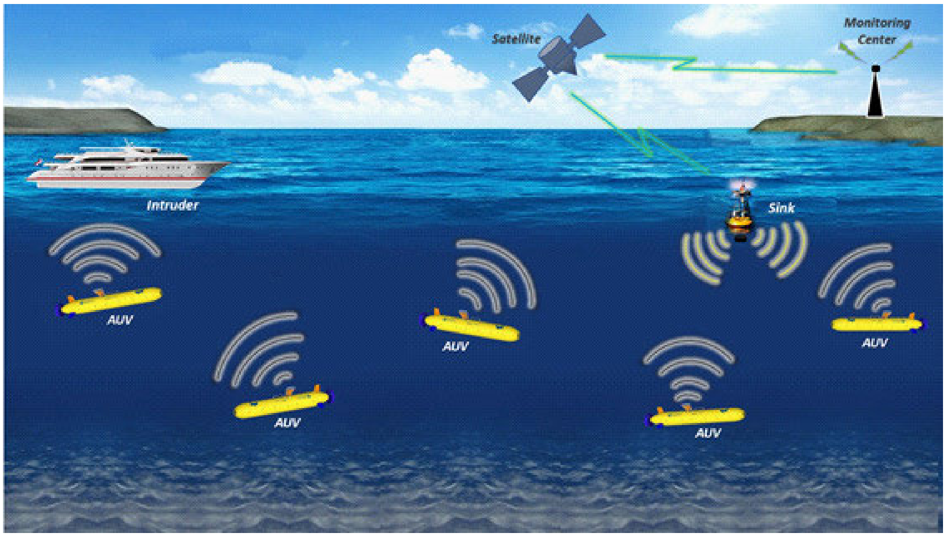

FIGURE 1. A hybrid coastal patrol and surveillance network where AUVs are patrolling an area of interest and collecting respective data. Since nodes are not within the communication range of each other and experience intermittent connectivity, and thus, form a DTN network. Hence, for data exchange, they utilise 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 centre.

process and can result in increased processing overhead, memory requirements, and energy consumption, particularly in resource-constrained underwater sensor nodes. In addition, due to the high dependency on exchanging codes packets among the contacting nodes, it demands a high degree of synchronisation among the nodes for encoding and decoding, which is challenging to attain in dynamic underwater environments, where nodes may have intermittent connectivity and varying communication conditions.

An adaptive cooperation-based geographic segmented opportunistic routing protocol (ACGSOR) is proposed for UASNs in [17] that restricts the number of relay nodes for limiting number of packet injection in the network. However, since ACGSOR employs intricate mechanisms for segmenting the geographic area fo facilitating cooperation decisions and adapting conditional changes, this make implementation, testing, and maintenance more challenges over other traditional protocols. Again, as the network size grows, the complexity of this protocols may increase exponentially, and hence, may experience scalability problem.

In [27], 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 utilised 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 and not preferable for mission-critical applications like CPSA. For overcoming this issue, UDTN-Prob and a few other protocols employ a juggling-based packet transmission/retransmission approach where multiple packets are transmitted within a single RTT [11]. However, the juggling-based approaches impose higher implementation complexity along with time synchronization problem, high overhead problem (for injecting ACK packets), and they also waste a considerable amount of time in the form of guard time to accommodate ACK packets. Therefore, this paper proposed a new protocol that does not require time synchronization, ACK packets, guard time, and can overcome most of the aforementioned limitations. Moreover, it is simple in terms of implementation with respect to those juggling-based approaches, including the parent protocol, UDTN-Prob. The proposed protocol ensembles RS [29] in this modified UDTN-Prob protocol and incorporates a new packet spraying technique to make it compatible with mission-critical applications like CPSA, which is discussed elaborately in Section IV.

III. NETWORK SCENARIO

In recent times, coastal authorities are encouraged in employing of automatic devices in marine activities, including CPSA (which is the focus of this paper) due to the advancements in

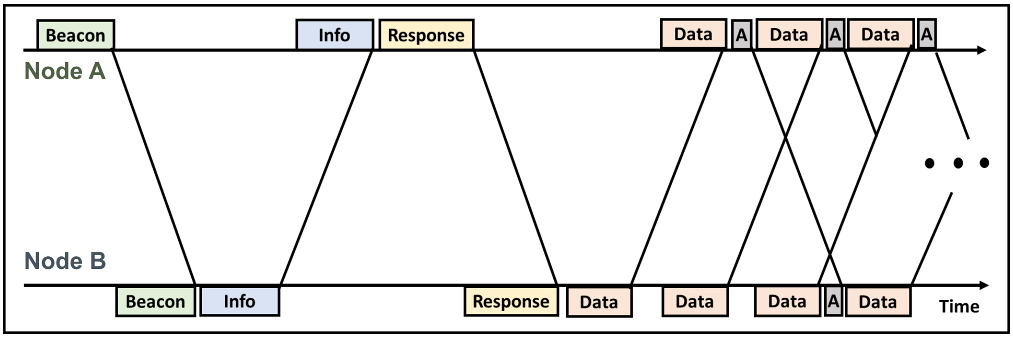

FIGURE 2. Example of packet exchange of UDTN-Prob protocol.

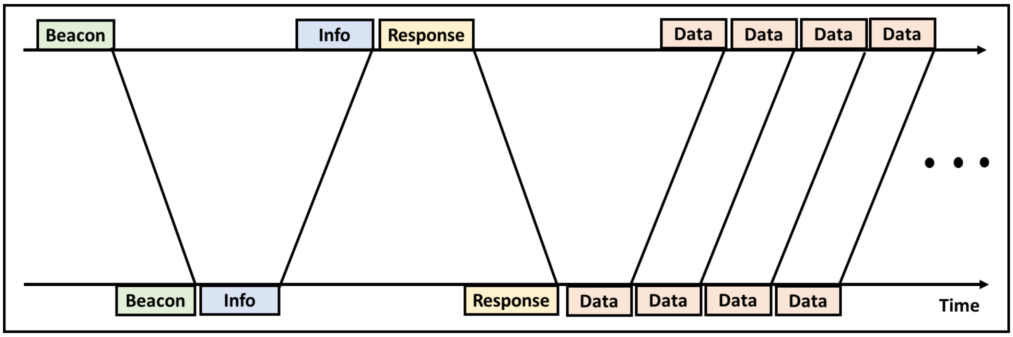

FIGURE 3. Example of packet exchange of UDTN-RS protocol.

the design of AUVs and other relevant devices over the last decade. In this paper, for imitating a realistic CPSN, a fleet of AUVs is considered to patrol autonomously an area of interest, inspecting surface ships or underwater assets, and delivering collected data to sinks, which are further connected with a control centre as demonstrated in Fig. 1. Since the areas of CPSNs are considerably large and generally, only a few AUVs are deployed to cover the area, they remain out of contact with the control centre and their fellow AUVs most of the time. Therefore, the inter-contact interval between the AUVs is 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 is 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 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 centre via sinks. For this, whenever two AUVs detect contact, they employ DTN protocols to opportunistically exchange data with each other with the hope that the other node will deliver the data to the sink. Since this kind of application is mission-critical, timely delivery of an adequate amount of data is immensely important for realising the motive of the target. Consequently, satellite based communication links are generally preferred by the sinks to deliver the data to the shore-based control centre for further processing.

IV. PROPOSED PROTOCOL: UDTN-RS

This section includes the details of the existing UDTN-Prob protocol [27], the technique of ensembling RS in the UDTN-Prob, and the enhanced packet spraying technique.

A. 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 detail, 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 is 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:

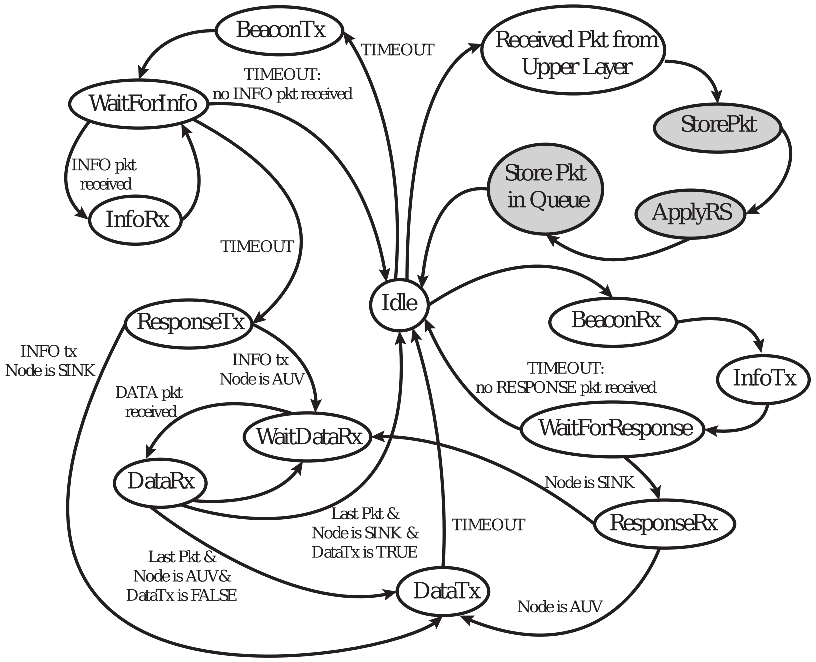

FIGURE 4. State transition diagram of UDTN-RS, where the states related to ensembling RS to the UDTN-Prob protocol are shown using *grey* colour. The diagram also shows the information flow among the states and can alternatively be considered as information flow diagram.

TABLE 1. Summary of the state names that are utilised in describing packet transmission of UDTN-RS in Fig. 4.

State Name	Description
Idle	AUVs are in idle state
BeaconTx	AUVs transmit BEACON packets periodically
BeaconRx	Other AUVs or SINKs receive BEACON packets
WaitForInfo	After transmitting BEACON, AUVs wait for receiving INFO packets
InfoTx	Transmit of INFO packets by AUVs or SINKs
InfoRx	AUVs received INFO packets
WaitForResponse	Wait for receiving RESPONSE packets
ResponseTx	AUVs transmit RESPONSE packets to its peer
ResponseRx	RESPONSE packet receive by AUVs or SINKs
WaitDataRx	Wait for receiving DATA packets
DataRx	DATA packets received
DataTx	Transmit DATA packets
Apply RS	Apply Reed-Solomon technique

1) contact discovery via BEACON packets, 2) analysis of contacts via INFO packets, and 3) 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 experience intermittent connectivity, and may also experience prolonged periods of isolation, hence, this phase is important. After transmitting a BEACON packet, a node, denoted as A, starts a random timer and keeps waiting for receiving corresponding INFO packets from its neighbours, if any. Note that all the timers utilised in UDTN-RS are similar to its ancestor UDTN-Prob protocol until otherwise mentioned explicitly. Furthermore, the transmission range of the AUV's can be increased by employing recent techniques like in [15].

On the other hand, if another node, denoted as B, receives a BEACON packet, it replies with a corresponding INFO packet, as demonstrated in Figs. 2 and 3. 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. Note that the state transition diagram (or flow diagram) of UDTN-RS is given in Fig. 4 and the descriptions of various state names are mentioned in Table 1.

In the case of A, it keeps collecting all the INFO packets from the neighbours 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 duration employing the position and velocity information that is shared in the INFO packet using the following equation [27]:

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

TABLE 2. Summary of the notations that are utilised in this paper.

Symbol	Description
α_A	position of node A
α_B	position of node B
ζ_α	estimations errors for the relative position
β_A	velocity of node A
β_B	velocity of node B
ζ_β	estimations errors for the relative velocity
b	spreading factor — geometry of the propagation
$a(f)$	thorp absorption coefficient for f in kHz
$W(x)$	principal branch of the Lambert function [27]
γ_{tgt}	target Signal-to-Noise Ratio (SNR) [30]
L	data packet length
ρ_{TX}	transmit source level [27].

Here, $\alpha^{(r)}_{AB}$ is the relative position and could be found as:

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

where α_A is the relative position of node A, α_B is the relative position of node B, and ζ_α is the estimation error for the relative positions, which absorb the possible discrepancies in estimation. ζ_α is a random term that can be determined by a simple trial-and-error basis. This assumption is rational since the handshake period is relatively a small time with respect to data transmission and/or data reception and the trajectories of the nodes hardly change (distinctly) within this short time. On the other hand, $\beta^{(r)}_{AB}$ is the relative velocity and could be found as:

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

where β_A is the relative velocity of node A, β_B is the relative velocity of node B, and ζ_β is the estimation error for the relative velocities, which is similar to ζ_α and possess the same rationale. It is noteworthy to mention that for calculating τ^c_{AB}, a conservative approach is embraced where it is assumed that two nodes are moving towards each other, which makes the protocol robust to mobility.

Assuming f is the carrier frequency of the acoustic signals, ρ_{TX} is the transmit source level, b is the spreading factor that describes the geometry of propagation [31], $a(f)$ is the Thorp absorption co-efficient in linear-scale for f in kHz [30], L is the data packet length, the transmission range, δ_{TX}, of a transducer can be calculated as [27]:

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

where, $W(\chi)$ is the principal branch of the Lambert function, $\chi \geq -e^{-1}$, defined as the unique solution of the equation $\psi e^{\psi} = \chi, \psi \geq -1$ [32]. γ_{tgt} is the corresponding target Signal-to-Noise Ratio (SNR) at the receiver for an underwater acoustic transmission. and can be calculated using the existing link-budget equations in [31].

Once the inter-contact duration, τ^c_{AB} 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., $\tau^c_{AB} > \tau^c_{min}$. Here, $\tau^c_{min} = 2T_D + 2T_A + 2\Delta$, where T_D, T_A, and Δ 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 $\tau_A = \eta\tau^c_{AB}$. Here, the factor η could be employed for implementing priority policies. If there is no accountable priority policy, the estimated 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 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) as illustrated in Algo. 1. 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, $\tau_B = \tau^c_{AB}(1 - \eta)$. Here, $\eta = 1$ for a SINK, since it has no packet to transmit as mentioned earlier; and hence, moves to the WaitDataRx state. Otherwise, it moves to the DataTx state and starts transmitting packets for its own assigned portion of the duration. In the DataTx state, the sender first employs a packet selection technique that commences with the estimation of the number of packets, ν that can be delivered within the τ_B epoch. Afterwards, from the buffer, only those packets are selected whose lifetimes are more than one-hop sink θ-meeting time prediction (see [27]). Note that, the UDTN-Prob protocol also supports two-hop sink θ-meeting time prediction. However, it imposes a large computational complexity with a very limited performance gain and hence, is not selected in this paper. Again, if this condition selects more than ν packets, only top-ν packets are selected based on the packet lifetime.

After finishing the packet transmission of its own stake, the sender switches its role and moves to the WaitDataRx state or Idle state based on the mode of the INFO transmitting node. Unlike the UDTN-Prob protocol, thanks to the FEC technique, a node does not have to wait for the ACK packets as illustrated in Algo. 2. Again, when A is in the WaitDataRx state, it keeps receiving packets until its time for data transmission starts. This way, the estimated contact duration is fairly utilised by both parties.

B. 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

Algorithm 1 Behavior of Connection Initiating Node

```
Input: Current Node A, Present State, pState
switch pState do
    case Idle do
        if A rx pkt and has k pkt (including new pkt) for the same destination in the buffer then
            Fetch all k pkt
            Encode to n pkt
        else if A !SINK and has pkt to tx then
            Set BEACON tx timer
            if Timer Expires then
                Send BEACON pkt
                pState ← WaitForInfo
    end
    case WaitForInfo do
        Set INFO pkt collection timer
        while Timer not expired do
            Collect INFO pkt
        end
        pState ← ResponseTx
    end
    case ResponseTx do
        Select a node based on max $\tau^{c}_{AB}$
        Send RESPONSE pkt to selected node
        if INFO tx node is AUV then
            pState ← WaitDataRx
        else if INFO tx node is SINK then
            pState ← DataTx
    end
    case DataTx do
        Set tx timer
        while Timer not expired do
            Send k DATA pkt from each group
        end
        pState ← Idle
    end
    case WaitDataRx do
        Set rx timer
        while Timer not expired or last packet !tx do
            Collect DATA pkt
        end
        if last packet received and node is AUV and data tx is FALSE then
            pState ← Idle
        else if last packet received and node is SINK and data tx is TRUE then
            pState ← Idle
    end
end
```

Algorithm 2 Behavior of Connection Accepting Node

```
Input: Current Node B, Present State, pState
switch pState do
    case Idle do
        if B rx BEACON pkt then
            Update inter-contact time distribution
            pState ← InfoTx
    end
    case InfoTx do
        Estimate position and velocity information
        Send INFO pkt to A
        pState ← WaitForResponse
    end
    case WaitForResponse do
        Set response rx timer
        if RESPONSE rx before timeout then
            pState ← ResponseRx
    end
    case ResponseRx do
        if Node is AUV then
            pState ← DataTx
        else if Node is SINK then
            pState ← WaitDataRx
    end
    case WaitDataRx do
        Set rx timer
        while Timer not expired or last packet !tx do
            Collect DATA pkt
        end
        if last packet received and node is AUV and data tx is FALSE then
            pState ← Idle
        else if last packet received and node is SINK and data tx is TRUE then
            pState ← Idle
    end
    case DataTx do
        Set tx timer
        while Timer not expired do
            Send DATA pkt
        end
        pState ← Idle
    end
end
```

and application pair. Again, this approach may lead to the starvation problem that may occur due to the lack of an adequate number of packets for an 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 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 an unencoded packet, and $0 \leq \text{PID} < n$.

Note that during the transmission, encoded and unencoded packets receive 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 and decoding at the destination node and the intermediate nodes only forward the packets. When an unencoded packet is received at the destination, it immediately transmits this to the upper layer. Conversely, the destination waits to receive at least k correct packets from n encoded packets of a group before decoding and sending to the upper layer.

C. ENHANCED PACKET SPRAYING TECHNIQUE

For UDTN-RS, an enhanced packet spraying technique is designed to incorporate encoded packets; whereas unencoded packets are already taken care of in the UDTN-Prob protocol, which is also adopted in this new protocol. When two nodes come to an agreement on packet transmission after exchanging control packets, this enhanced packet spraying technique decides: how many encoded packets of a group to transmit and which members to select in case of this fragmentary transmission.

It is noteworthy to mention that UDTN-Prob employs a packet spraying technique similar to the one in [31]. More specifically, the binary technique of SAW is employed where a node transmits half of the copies of a packet and keeps half; except the last packet, which it tries to deliver by itself. For instance, if a node carries L copies of a packet, in each encounter, only $\lfloor L/2 \rfloor$ copies will be delivered to the contacting node until the last copy.

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 an 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 duration between the nodes is considerably short with respect to inter-contact intervals, and hence, when a node comes into 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 the chances of spraying a single group of packets to more intermediate nodes; and thus, increases the chances of delivering the adequate number of packets to the destination. Again, to choose k encoded packets from n encoded packets, a round robin technique [33] is employed in UDTN-RS since all packets have equal priority.

V. SIMULATION SCENARIOS

For evaluating the performance of our proposed protocol, we have conducted a comprehensive simulation campaign employing DESERT underwater simulator [34], which is a package of ns2 [36] and ns-miracle [35]. Note that this is an open-source simulator with a comprehensive list of underwater communication features for imitating real underwater scenarios. Moreover, the World Ocean Simulation System (WOSS) package [37] can be incorporated with it to receive a more realistic account of acoustic propagation for improved underwater network simulations.

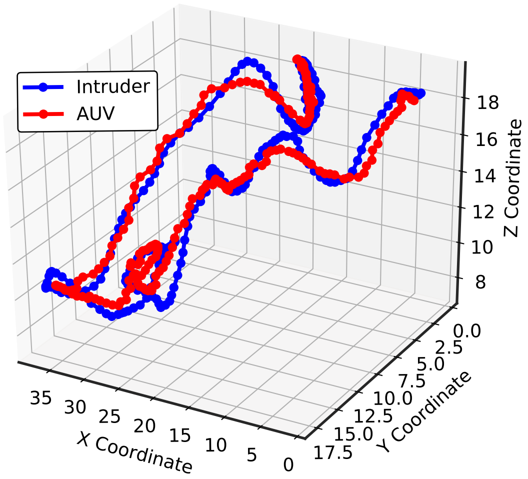

FIGURE 5. Trajectories of an intruder and a follower (i.e., an AUV). Once the follower recognised the intruder, the follower starts following the intruder if not already engaged in another campaign. The follower maintains a distance from the intruder to avoid any unnecessary collision.

For our simulation campaign, our CPSN is installed at the coordinates $39.97°N$ and $11.82°E$, and spread thereafter. This network is comprised of one fixed sink, which is installed nearest side of the shore area and 5 or 10 mobile AUVs, which are deployed within an area of 4×4 to 10×10 km^2. At the starting of every simulation, these nodes are placed arbitrarily within the selected area and afterwards, they start moving freely within the area following Gauss-Markov (GM) mobility model [38]. In GM, trajectories of a node are generated as fixed realisations following a fixed correlation parameter, α. In this simulation campaign, the value of a is set to 0.8 for generating random yet smooth trajectories imitating the actual trajectories during patrolling, reconnaissance, or survey missions (see Fig. 5). 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 of ω meters for being stealth and avoiding any unwanted collision.

Alike in [27], as a modulation technique, Binary Phase Shift Keying (BPSK) is selected at a bit rate of 4.8 kbps with a bandwidth of 9 kHz and a central frequency of 25 kHz. The source level, P_{TX} is set to 150 dB re μ Pa relative to a distance of 1m from the source. This selection leads to an estimated nominal transmission range of d_{TX} to around 2 km. The BEACON packet is fixed to a size of 10 Bytes and the rest of the packets, namely INFO, RESPONSE, and DATA packets are fixed to 125 Bytes. All the results are presented in this paper after averaging over 25 runs.

In the 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 [29], 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 Normalised Packet Delivery Ratio (PDR), End-to-End Delay, and Normalised 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, the normalised throughput of a node is the ratio of payload reception time against the simulation time.

VI. RESULTS AND 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.

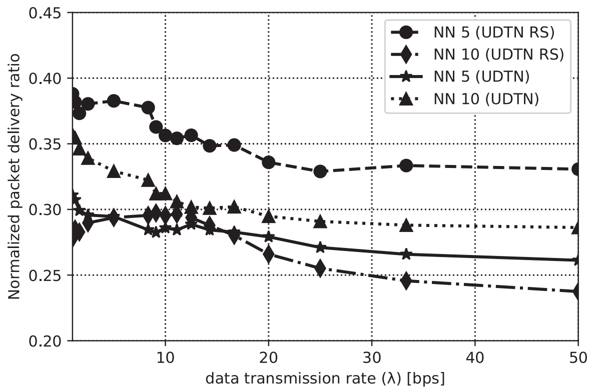

FIGURE 6. **Packet delivery ratio for various data transmission rates and two sets of nodes.**

A. SCENARIO 1: VARYING DATA TRANSMISSION RATE

In this scenario, the data transmission rate, λ 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 for selecting 5 and 10 nodes is that when the area is fixed, an increased number of nodes increases inter-contact frequencies in the network. Thereby, the simulation with 5 nodes exhibits a sparse scenario, and 10 nodes exhibit a dense scenario with the likelihood of twice as many contacts as the former.

The acquired results of this scenario explore several preeminent facts. As could be observed from Fig. 6 is that the PDR declines with increasing λ. This observation is true for any protocols and any number of nodes. In the case of a sparse network where there are a small number of nodes, our proposed technique performs 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 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 a relatively low number of packets from a pile of packets. The highest normalised PDR, 0.38 is received by the proposed protocols for 5 nodes in sparse networks.

However, when the inter-contact intervals are relatively short (in the dense network), it can be observed that UDTN-Prob exhibits better performance at the expense of higher overhead (see Section VI-C). In other words, albeit, UDTN-RS causes 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.

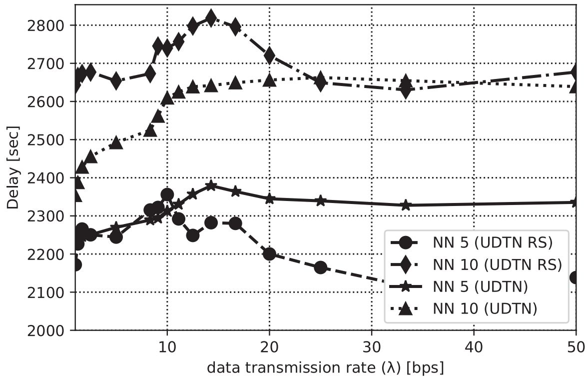

FIGURE 7. **Delay for various data transmission rates and two sets of nodes.**

In the case of end-to-end delay (see Fig. 7), for any λ values, UDTN-RS demonstrates the lowest delay for the sparse network. Due to the enhanced packet spraying technique, it ensures packet delivery within a relatively short period of time even when there is a minimum number of nodes in the network. At a higher data rate, UDTN-RS performs comparably with UDTN with 10 nodes in the dense network whose expected inter-contact frequency is double that in the sparse network in our simulation. Hence, UDTN-RS can be considered a suitable alternative for CPSA in terms of delay.

As opposed to the PDR, normalised throughput (see Fig. 8) increases rapidly for any compared protocols until moderate loads or mid λ in the network and plateaus at the higher λ values. All the compared protocols reach the threshold at around $\lambda = 40$. Again, for any network topology, UDTN-RS with 5 nodes outperforms the rest by a significant margin, especially when the data rate is higher. One interesting observation is that UDTN-RS with a lower

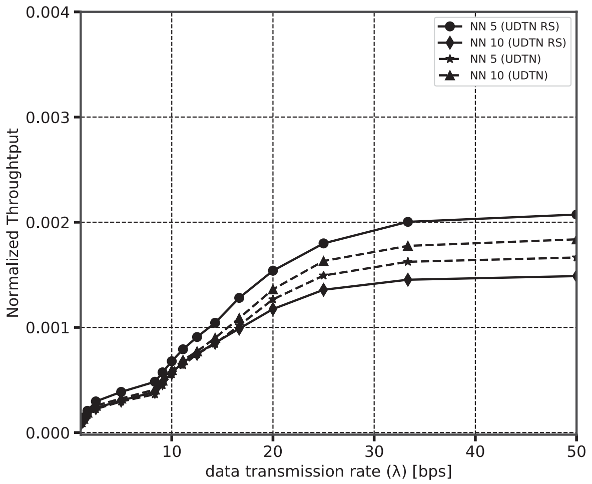

FIGURE 8. Normalised throughput for various data transmission rates and two sets of nodes.

number of nodes (5 nodes) achieves higher throughput than UDTN-Prob with higher nodes (10 nodes). The highest normalised throughput received in this network is 0.0021 by the proposed protocol for sparse network scenario. From the observations of Figs. 6 to 8, it is evident that with fewer nodes, UDTN-RS consistently outperforms UDTN-Prob in the PDR, delay and throughput.

B. 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 simulations was conducted by varying the network area from 4 × 4 to 10 × 10 km^2. The acquired results for normalised PDR, end-to-end delay, and normalised throughput are presented on Figs. 9, 10 and 11, respectively.

Analogous to the observation of scenario 1 for the normalised PDR (see Fig. 9), it declines with increasing λ for any compared protocols. Likewise, the normalised throughput (see Fig. 11) also declines with increasing λ value, as opposed to scenario 1. It is because, with increasing network area, inter-contact interval also increases, and hence, a considerably lower number of packets are delivered to the destination.

The results of normalised PDR and normalised throughput explore the fact that when the area is smaller, UDTN-Prob performs considerably better than the proposed technique at the price of higher overhead (see Section VI-C). 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 assists the proposed technique in dealing with increasing area size. The area beyond which UDTN-RS outperforms UDTN-Prob is 7 × 7 km^2.

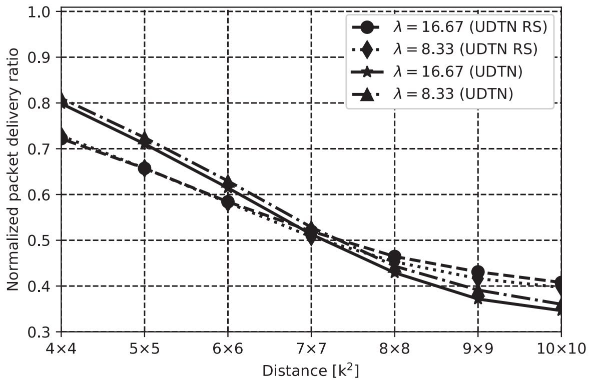

FIGURE 9. Packet delivery ratio for various area sizes.

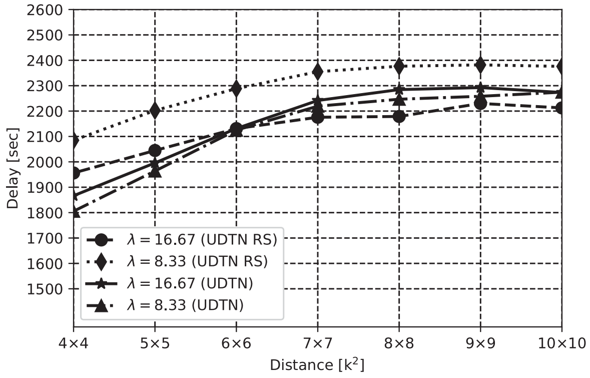

FIGURE 10. Delay for various area sizes.

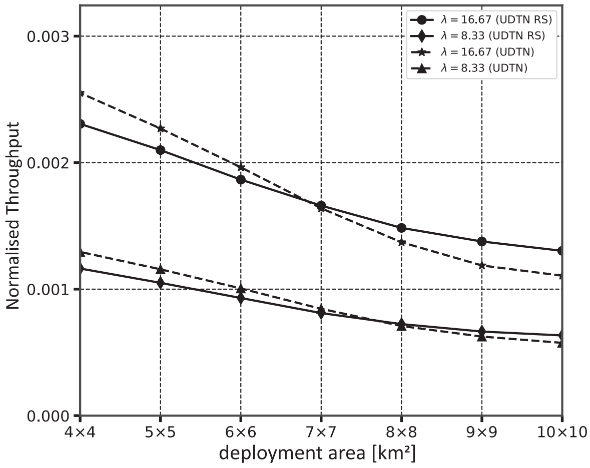

FIGURE 11. Normalised throughput for various data transmission rates with varying deployment areas.

Again, when the area size is comparatively small, all the compared protocols exhibit lower end-to-end delay. However, it increases sharply up to a mid-area size and afterwards, it observes slow growth for the large area size. Among all the compared protocols and two λ 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 an 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 compact scenarios. From these above scenarios (namely varying data transmission rate and varying area size), it could be concluded that the proposed protocol outperforms other compared protocol in terms of compared metrics (namely normalised packet delivery ratio, end-to-end delay, and normalised throughput) when the network is sparsely populated (like CPSA).

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

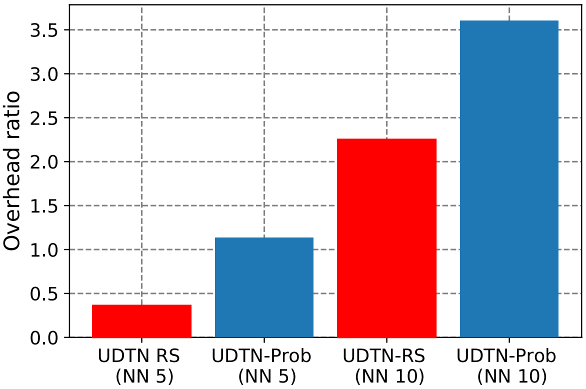

FIGURE 13. Comparison of overhead ratios for a various number of nodes.

C. 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 into the network, thus, reducing overhead in the network; and *ii*) by injecting a lower number of copies of a single packet in the network as explained in Section V. 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 proposed technique receives comparable or higher performance as demonstrated 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 trade-off between the encoding and replication must be maintained to achieve performance goals, which can be performed by calibration of these parameters.

VII. CONCLUSION

This paper proposed the UDTN-RS protocol for facilitating coastal patrol and surveillance application — a time-critical application that demands delivery of an adequate number of packets for realising 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 binary packet spraying technique is designed for supporting encoded packets and incorporated into the UDTN-RS protocol for facilitating an adequate number of packet delivery within the effective time period. The effectiveness of the proposed protocol is evaluated by performing a comprehensive simulation in three different scenarios employing DESERT underwater simulator along with WOSS package to receive a more realistic account of acoustic propagation. Comparing the acquired results of the proposed protocol with the widely used UDTN-Prob protocol substantiate its superior performance in sparse underwater networks. Hence, it can be concluded that the UDTN-RS is a better alternative to the UDTN-Prob protocol for coastal patrol and surveillance networks.

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