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GCORP: Geographic and Cooperative Opportunistic Routing Protocol for Underwater Sensor Networks

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ABSTRACT Underwater Sensor Network (UWSN) is gaining popularity among researchers due to its peculiar features. But there are so many challenges in the design of the UWSN system, and these are quite unsustainable due to the dynamic nature of water waves. Perhaps the most tedious challenge for UWSNs is how to transfer the data at the destination with a minimal energy rate. It can be accomplished by exploiting geographic and opportunistic routing schemes to send the data efficiently to the surface sinks in cooperation with relay nodes. With this aim, we introduce a new protocol for routing, named Geographic and Cooperative Opportunistic Routing Protocol (GCORP). In GCORP, the packets are routed from the source node to the surface sinks in coordination with intermediate relay nodes. In GCORP protocol, initially, multiple sinks-based network architecture is established. Then, a relay forwarding set is being determined by the source node on the basis of depth fitness factor. Finally, the best relay is determined through the weight calculation scheme from the relay forwarding set. We conduct the simulations in NS3 to validate the proposed GCORP routing protocol concerning different network metrics. The simulations conclude that the GCORP protocol shows better performance than existing approaches.

INDEX TERMS Underwater sensor networks, multiple sinks, weighting scheme, geographic routing, cooperative routing, opportunistic routing.

I. INTRODUCTION

Our planet Earth is covered by a 3/4 ratio with water in terms of oceans, seas, rivers, lakes, streams, and canals. Plenty of unexplored and hidden resources exist underwater that needs to be explored. Underwater environments are too sophisticated for mankind to explore. Thanks to wireless technology by which this could be possible. Meanwhile, Underwater Sensor Networks (UWSNs) is gaining remarkable popularity among researchers and application developers due to possessing unique features. UWSNs have a variety of applications in both off-shore and on-shore fields, like environmental monitoring, ocean sampling networks, assisted navigation, deep-sea mining, reconnaissance, undersea explorations, and disaster prevention [2], [3]. UWSNs also, seek applications in shallow-water and underwater areas. The application hierarchy of UWSNs in potential areas is shown in Fig. 1. There are also many other areas of UWSN applications, which are not discussed here, can be found in [4].

The underwater scenario is totally odd from the terrestrial scenario due to specific characteristics of water, for example, ambient noise, signal attenuation, temperature, salinity, low acoustic-speed ($\approx$1500 m/s), and multi-path propagation [3]–[5]. These facts result in low data-rate (hardly in Kbps), high propagation delay, void communication, limited bandwidth (hardly in MHz), high deployment cost, poor

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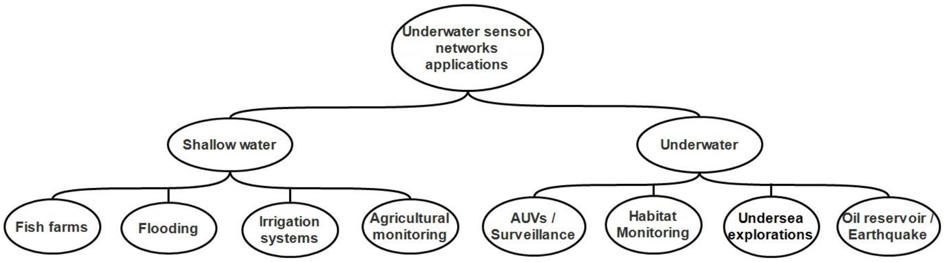


FIGURE 1. Application hierarchy of UWSNs [conceived from [2], [3]].

network connectivity, high energy tax, and so on [6]–[8]. Due to this, the data forwarding mechanism is severely affected in UWSNs. Moreover, the underwater nodes cannot be stable at their static positions to localize them for pre-configuration just because of the dynamic behavior of water tides. Even the nodes are not aware of their depth positions in underwater and it becomes difficult to estimate their depth via an embedded pressure sensor [9]. Furthermore, due to unique characteristics and a rapid diminution of water waves, the Global Positioning System (GPS) cannot be used as a localization system in underwater environments [6], [7].

Besides many other challenges of UWSNs, the routing might be the most important challenge in relaying the packets successfully at the surface sinks. Under such conditions, the geographic routing paradigm seems to be the most efficient and prominent approach in the design of UWSN routing protocols [9]–[12]. The geographical routing is simple and scalable. It can also be referred to as position-based routing. In geographical routing, the routing information is not always required to update the routing path status [13]. Alternatively, routing decisions are made locally. In each hop, only those neighbors are considered as forwarding candidates by the sources nodes that have close proximity to the surface sinks. The loop goes on until the packets finally arrive at the destination [12]. Geographic routing, along with opportunistic routing (OR), can increase the package transfer rate and curtail the energy utilization and can be termed as geo-opportunistic routing [12]. In opportunistic routing [14], [15], at first, the source node determines its relay forwarding set by broadcasting and receiving the beacon messages. Then, the source node sets the priority of the nodes from the relay forwarding set using different metrics. Finally, a node having the highest priority forwards the packet to the next-hop. Meanwhile, the remaining members of the relay forwarding set will suppress their transmissions in the favor of the highest priority node and set a hold time. In OR routing, the packet will be rebroadcasted by the second-best relay node if the best node fails to forward the packets.

Energy efficiency is perhaps the key factor in UWSN, as it consumes more power in the signal propagation than the ordinary sensor networks. The most of the existing works do not consider the energy factor in their works, such as [9]–[12] and many others [6], [16]. In this context, we must consider the energy factor in the design of the proposed routing protocol to cope with the energy consumption challenge in underwater acoustic communication. Other major drawbacks in the existing routing schemes are that they basically use flooding technique [17], [18] and fixed route each time to access the surface sink with high energy tax. We, therefore, recommend an opportunistic routing technique along with a geographic routing technique to alleviate these shortcomings.

Our proposed *Geographic and Cooperative Opportunistic Routing Protocol (GCORP)*[1] can therefore provide optimal solutions in which the packet distribution ratio and network lifetime are increased, and the end-2-end delay and energy consumption are reduced with the help of proposed weighting scheme. The key contributions of this article are discussed as follows:

- We propose a novel GCORP routing protocol to improve the network metrics. GCORP utilizes the reachability information (location information) [12], depth information [11], and current residual energy [15], [19] of the nodes and only location information of the surface sinks. All this information of the nodes is shared with neighbor nodes via periodic beaconing as in [9], [12], [14].
- In GCORP, the source node determines its relay forwarding set from the neighboring relay nodes-based on the depth fitness factor. Afterward, the weighting scheme is incorporated to select the next-hop forwarder (also referred to as the best relay node) from the relay forwarding set to route the packets from source to the destination. The weighting scheme is applied to the normalized energy, the packet delivery probability, and the normalized distance.
- To prevent unnecessary transmissions, we use a holding time model for each node of the relay forwarding set-based on the weighting scheme. By which, low priority nodes may disable their transmissions once they know that a high priority node has already sent the identical packet.

The organization for the remaining sections is described as: Section II covers the study on existing UWSN routing protocols and schemes. Section III highlights the preliminary requirements for this study in which network architecture, underwater acoustic propagation and channel model, energy model, and beacon model are discussed. In section IV, we demonstrate our proposed routing protocol (GCORP) in detail followed by different algorithms and a holding time

[1]This work is based on the preliminary work [1].

model. In section V, we discuss the simulation settings and different network metrics followed by results and discussions. Section VI describes the conclusion and works for the forthcoming article.

II. RELATED WORKS

Here, various existing UWSN geographic, opportunistic and geo-opportunistic routing protocols and their role in reliable data transfer are addressed.

A. GEOGRAPHIC ROUTING PROTOCOLS

Sine, it is clearly mentioned in the state-of-the-art of UWSN that GPS is not suitable for the aquatic environments [20]–[22]. Yet, in some studies, it is assumed that the underwater nodes can get their 3D geographic axis with the aid of localization services. But it seems a more complex and challenging task as mentioned in [11]. In geographic routing, the packets are routed from source to destination by considering the location data of the nodes. The geographic routing mostly uses the greedy forwarding path, in which the packets are greedily shared with the neighboring nodes that are in the line of surface sinks [12].

Due to the dynamic characteristics of water waves and extreme attenuation, the UWSNs are susceptible to the channel fading, and the packet loss probability is also at an extreme level. So far, it is recommended by the geographic routing to curtail the cost by minimizing the transmission frequency and energy consumption. Zeng *et al.* [23] have used the geographical transmission in their work to achieve an efficient packet delivery rate by leveraging the broadcast characteristics of the wireless medium. They suggested an Expected Packet Advancement (EPA) metric for balancing power consumption and improving the reliability of the network. Additionally, this metric gives priority to the next-hop forwarder to augment the transmission cycle. Salti *et al.* [24] have presented a novel Energy-efficient Multipath Grid-based Geographical Routing (EMGGR) scheme. In EMGGR, the routing is performed in grid-by-grid mechanism to curtail the latency by sectoring the large packet into a small part. Besides, they have used multiple gateways to optimize the reliability of the network at the cost of high energy consumption because their scheme performs complex calculations to establish the routing path. In addition, the multiple copies of the same packets are transmitted due to which more energy is consumed.

B. OPPORTUNISTIC ROUTING PROTOCOL

Two steps are involved in the key intent of the opportunistic routing. At first, a relay forwarding set determination by the source node is carried out. Then, the selection of a high priority node is performed, which transmits the packets in the direction of the destination, while low priority nodes are kept silent. The well-known solution for static networks is given by S. Biswas and R. Morris in EXOR [25]. Geographical data is not needed in these protocols. Routing is performed on the basis of link metrics and topology of the global network.

A Stateless Opportunistic Routing Protocol (SORP) is presented by Ghoreyshi *et al.* [26] with the aim of avoiding the void communication area by employing the adaptive forwarding mechanism. This mechanism is used to bypass the void communication area. Another protocol of the same author with the identical theme of resolving the void communication issue is presented in [14] and they called it Opportunistic Void Avoidance Routing (OVAR) protocol. In OVAR, the reachability information of the nodes is exchanged with neighbor nodes via a random beacon message. By which the source node can determine its relay neighboring set. Consequently, the source node determines the best node from that relay set by focusing on maximizing the packet delivery probability (PDP) in each-hop to maximize the package transfer rate. Nevertheless, the OVAR protocol did not focus on the residual energy of the nodes in the selection of the best relay node. As a result, Rahman *et al.* [15] have proposed an Energy-Efficient Cooperative Opportunistic Routing (EECOR) scheme, in which the best relay is nominated on the basis of the PDP together with the residual energy of each node by applying a fuzzy rule. In addition, they also proposed a holding time model to curtail the number of retransmissions and packet collisions during the communication between the nodes.

A Power-Efficient Routing (PER) protocol was demonstrated by Huang *et al.* [27], which comprised two phases: selection of the forwarding nodes and trimming of forwarding tree. The selection of forwarding nodes is executed on the basis of distance, angle between two neighboring nodes, and current residual energy of the nodes. Then a forwarding tree trimming mechanism is used on the number of duplicate packet being received by the forwarding nodes. In this way, the surplus energy consumption and excess packet forwarding can easily be avoided. Additionally in PER, there is no need to get the data from all neighboring nodes to pick the forwarding nodes. This practice minimizes the extra memory usage and communication overhead.

C. GEO-OPPORTUNISTIC ROUTING PROTOCOLS

Yan *et al.* [11] have proposed a Depth-Based Routing (DBR) protocol in which the packet forwarding node is selected by concerning the depth threshold parameter. The source node selects a node that is at a lower depth level than it. The network architecture of the DBR protocol is based on multiple sinks, due to which the package transfer rate is increased, and the latency is reduced because of multiple destinations. They also provided a mechanism for suppressing the redundant packets, by which energy can be saved. Mohammadi *et al.* [19] proposed a modified version of the DBR protocol and named the Fuzzy Depth-Based Routing (FDBR) protocol. They used a fuzzy mechanism for calculating the adaptive values for holding time. Their approach utilizes the hop count value, residual energy, and

TABLE 1. Comparison of various UWSN routing protocols by their features.

Protocol	Reference	OR Metric	Architecture		Node Organisation		Connectivity		Features
			Single Sink	Multi-Sink	Cluster-Based	Single-Entity	End-2-end	Hop-by-hop	
VBF	[10]	Geographic	✓	×	×	✓	✓	×	Robustness and scalable
HH-VBF	[28]	Geographic	✓	×	×	✓	×	✓	Good packet delivery ratio, robustness and scalable
AHH-VBF	[29]	Geographic	✓	×	×	✓	×	✓	Good packet deliver ratio, less energy consumption and latency
EBVBF	[30]	Geographic, energy	×	✓	×	✓	×	✓	Balanced power consumption and removing void zones
EMGGR	[24]	Geographic	✓	×	×	✓	×	✓	Multipath grid-by-grid-based geographic scheme
GEDAR	[12]	Geographic	✓	×	×	✓	×	✓	Void node detection
FBR	[31]	Geographic	×	✓	×	✓	×	✓	Energy-efficient, average latency, scalable
MPR	[32]	AUVs needed	×	✓	×	✓	×	✓	Low propagation delay, load balance
Mobicast	[33]	AUVs needed	×	✓	✓	×	×	✓	High delivery rate, low power consumption and overhead
Hydrocast	[34]	Pressure-info	×	✓	✓	×	×	✓	Minimizing co-channel interference, void node detection
VAPR	[9]	Pressure-info	×	✓	×	✓	×	✓	No void area, robustness
H2DAB	[35]	Depth-addressing	×	✓	×	✓	×	✓	High delivery ratio and cost-efficient
DBR	[11]	Depth-info	×	✓	×	✓	×	✓	Simple algorithm
FDBR	[19]	Depth-info	×	✓	×	✓	×	✓	Fuzzy-based best relay node selection
WDFAD-DBR	[36]	Depth-info and 2-hop neighbor's data	×	✓	×	✓	×	✓	Provides remedies for the shortcomings of DBR
BFSPB-WDFAD-DBR	[37]	WDFAB-DBR metrics, residual energy	×	✓	✓	×	×	✓	Reliable data transfer, energy efficient and bypass the void holes
SORP	[26]	Distance, depth	×	✓	×	✓	×	✓	Shortest path approach and void node recovery techniques
PER	[27]	Distance, angle, energy	✓	×	×	✓	×	✓	Power-efficient
OVAR	[14]	Multiple	✓	×	×	✓	×	✓	No void area, robustness and scalability
EECOR	[15]	Multiple	✓	×	×	✓	×	✓	Energy efficient, fuzzy-based best relay selection
SOFRP	[38]	—	✓	×	×	✓	×	✓	Creates physical topology to minimize the collision and less computational cost
GCORP	This work	Multiple	×	✓	×	✓	×	✓	Energy efficient, weighting-based relay node selection, low multi-path transmission

the depth differences between the nodes in order to create a fuzzy rule for controlling the holding time adaptively. Three performance metrics were used to compare the results of FDBR with DBR. The results analysis showed that FDBR is quite efficient than DBR in terms of different network metrics.

There are numerous vector and geo-opportunistic based routing protocols, for example, VBF by Xie *et al.* [10], HH-VBF by Nicolaou *et al.* [28], AHH-VBF by Yu *et al.* [29] and CVBF by Ibrahim *et al.* [39], in which only those nodes will contribute in the packet transmission that exists within the virtual pipeline, and directed towards the surface sink. No any mechanism is utilized by those protocols to balance the energy utilization of the forwarding node. In this connection, an Energy Balanced Vector-Based Forwarding Protocol (EBVBF) is introduced by Abbas *et al.* [30]. The main goal of the EBVBF protocol is to increase the network lifetime by balancing the energy utilization of the underwater nodes. Besides this, the figure of lost nodes is significantly minimum in EBVBF, which improves the packet propagation ratio and network longevity. The detailed description of various newly proposed routing schemes can be found in [6], [16], [17], [40]. In which, merits and demerits, routing mechanisms, and routing performance of the different routing protocols are discussed. A comparison of various UWSN routing protocols along with their features are summarized in Table. 1.

III. PRELIMINARY REQUIREMENTS

The preliminary requirements for this work are discussed as follows.

A. NETWORK ARCHITECTURE

The 3D UWSN network architecture for this work is shown in Fig. 2, which includes three distinct node types, i.e., surface sinks, relay nodes, and anchor nodes.

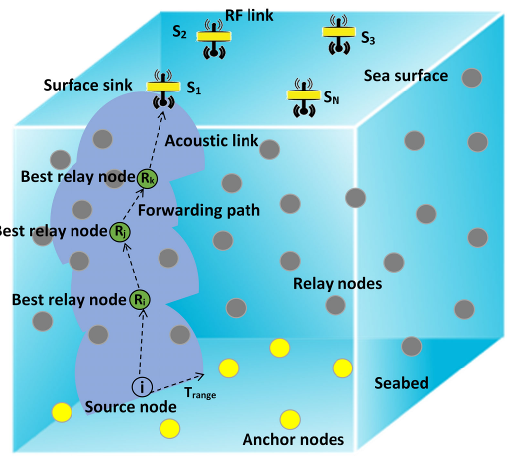


FIGURE 2. 3D UWSN network architecture.

- **Surface sinks** are randomly placed at the sea-surface level. These have two interfaces of communications; an RF (radio frequency) link is used to communicate with other surface sinks, while integration of an acoustic link is used to communicate with undersea nodes.
- **Relay nodes** are often deployed at discrete water depths with a transmission range (T_{range}). Relay nodes are liable for accumulating the packets from the source nodes and then transmit those received packets to the next-hop and continue this procedure till the packets are finally routed towards the surface sinks. Relay node has two behaviors: 1) it behaves like an ordinary sensor source) node to capture the aquatic data, and 2) it plays the role of next-hop data forwarding candidate node. Relay node communicates via an acoustic link with other nodes and surface sinks.
- **Anchor nodes** are the ordinary sensor nodes. These are placed randomly at the seabed. The location of these

nodes is also predetermined and are employed to collect the aquatic environmental data and then forward it to the next-hop. Anchor nodes also use the acoustic link for transmitting the packets to the relay forwarding nodes with identical transmission range T_{range}.

1) ASSUMPTIONS

For simplicity, we follow some assumptions:

1) The network size (X×Y×Z) is fixed.
2) Each node is aware of its 2D position information with the help of localization technique [41] as in [12].
3) Each node is aware of its present depth level with the aid of the embedded depth sensor [11].
4) The vertical movement of the nodes is insignificant. So, it can be ignored [41] as in [12], [14].
5) Nodes are considered to be homogenous by means of transmission range and energy utilization.
6) Transmission range (T_{range}) for all nodes is same.

B. UNDERWATER ACOUSTIC CHANNEL

In this section, an introductory summary on the acoustic channel model is given.

1) PROPAGATION THORP MODEL

The underwater WSN is totally different from the terrestrial WSN in terms of communication [42]. Various factors affect the underwater communication like link distance, signaling frequency, bandwidth, propagation delay, transmission, and path loss. These factors ultimately affect the network efficiency. The underwater communication can be described by the Thorp model [42]. Following is the model of acoustic channel path loss $A(D_{iR_k}, f)$ with respect to distance D_{iR_k} and frequency f of the signal:

$$A(D_{iR_k}, f) = D_{iR_k}^{g} a(f)^{D_{iR_k}} \quad (1)$$

In which, D_{iR_k} reflects the gap between source node and neighboring relay node, g determines the geometric spreading factor *(g=2 or g=1.5 or g=1* for spherical, practical and cylindrical spreading, respectively) and absorption coefficient is represented as *a(f)*. In terms of dB, Equation. 1 becomes:

$$10\log A(D_{iR_k}, f) = g \cdot 10\log D_{iR_k} + D_{iR_k} \cdot 10\log a(f) \quad (2)$$

By using above Thorp model, the *a(f)* in dB/km formulation is given below [43], likewise in [29]:

$$10\log a(f) = \begin{cases} \text{if } f \geq 0.4\, kHz \text{ then} \\ \dfrac{0.11f^2}{1+f^2} + \dfrac{44f^2}{4100+f^2} \\ \qquad +2.75 \cdot 10^{-4} f^2 + 0.003 \\ \text{if } f < 0.4\, kHz \text{ then} \\ 0.002 + \dfrac{0.11f^2}{1+f^2} + 0.011f^2 \end{cases} \quad (3)$$

2) ACOUSTIC CHANNEL NOISE

The acoustic channel is also different from the radio channel in terms of impedance [44]. The acoustic channel is severely affected by different types of noises [45]. The noise model can be formulated by Gaussian statistics as a frequency function f and given as follow [42], [46]:

$$N(f) = \sum \begin{cases} N_t(f) = \text{Turbulence noise} \\ N_s(f) = \text{Shipping noise} \\ N_w(f) = \text{Wave noise} \\ N_{th}(f) = \text{Thermal noise} \end{cases} \quad (4)$$

The above four components of noise in terms of (dB re μPa)/Hz and frequency in KHz can be modeled as [42], [45]:

$$10\log N(f) = \sum \begin{cases} 17 - 30\log_{10}(f) \\ 40 + 20(s-0.5) + 26\log_{10}(f) \\ \qquad -60\log_{10}(f+0.03) \\ 50 + 7.5\sqrt{w} + 20\log_{10}(f) - 40\log_{10}(f+0.4) \\ -15 + 20\log_{10}(f) \end{cases} \quad (5)$$

Here, $s \in [0, 1]$ and $w \in [0, 10]$ represent the shipping activity and the speed of wind (meter/sec), respectively.

3) SIGNAL TO NOISE RATIO FOR ACOUSTIC CHANNEL

If $P_{tx}(f)$ is the power required for transmitting the packets by the forwarding node with frequency f. Henceforth, Signal to Noise Ratio *(SNR)* over acoustic channel at a distance D_{iR_k} with frequency f is given as [42]:

$$SNR(D_{iR_k}, f) = \frac{P_{tx}(f)/A(D_{iR_k}, f)}{N(f)} \quad (6)$$

Now, we suppose the Gaussian distribution followed by the UWSN ambient noise and the Gaussian channel for channel capacity can be demonstrated as [15]:

$$C(D_{iR_k}, f) = \log_2(1 + SNR(D_{iR_k}, f)) \quad (7)$$

For our work, the Binary Phase Shift Keying (BPSK) is incorporated as a modulation scheme, and each symbol in BPSK carries a bit [47]. Now, the bit error probability over distance D_{iR_k} is formulated as [48]:

$$P_e(D_{iR_k}, f) = \frac{1}{2}\left(1 - \sqrt{\frac{SNR(D_{iR_k}, f)}{1 + SNR(D_{iR_k}, f)}}\right) \quad (8)$$

C. ENERGY MODEL

When a node participates in the network operation either in transmission or reception of some packets, it individually performs a scanning process to check its available energy. This available energy of that node is referred to as residual energy E_{res}. The residual energy E_{res} of a node R_k can be calculated by subtracting the consumed energy E_{cons} from the initial energy E_{init}. So, after the participation in the network operation, the total available energy of a node $E_{res}(R_k)$ can be deduced as [49]:

$$E_{res}(R_k) = E_{init}(R_k) - E_{cons}(R_k) \tag{9}$$

The nodes consume the energy after every successive transmission over a distance and reception of packets. Therefore, the consumed energy E_{cons} can be calculated as:

$$E_{cons}(R_k) = E_{tx}(b, D_{iR_k}) + E_{rx}(b) \tag{10}$$

In Equation. 10, $E_{tx}(b, D_{iR_k})$ is amount of energy used while transmitting the bits b over a distance D_{iR_k} (i.e, distance from source node to neighboring relay node) and given as [15], [50]:

$$E_{tx}(b, D_{iR_k}) = b \cdot T_0 \cdot P_{tx} \cdot A(D_{iR_k}, f) \tag{11}$$

where T_0 is the transmission period of the packets to reach the next-hop. P_{tx} is the power transmission of the nodes. Also, from Equation. 10, E_{rx}(b) is the amount of energy used by the node for collecting bits b in time T_0 and can be calculated as:

$$E_{rx}(b) = b \cdot P_{rx} \cdot T_0 \tag{12}$$

where P_{rx} reflects the reception power of the node. Etx and Erx are the transmitting and the receiving energy of a node, respectively. Therefore, the total energy utilization by the nodes k of the relay forwarding set *F(i)* to relay a packet can be obtained as:

$$E_{total}[F(i), k] = E_{tx}(b, D_{iR_k}) + k \cdot E_{rx}(b) \tag{13}$$

It is supposed that node R_k is selected as a forwarding node from the relay forwarding set *F(i)* to relay a packet. Then the total energy consumption under the proposed scheme can be determined by excluding the selected relay as follows:

$$E_{total}[F(i), R_k] = E_{tx}(b, D_{iR_k}) + k \cdot E_{rx}(b) + (k - R_k) \cdot E_{re} \tag{14}$$

where E_{re} is the energy of a relay node to overhear a packet.

D. BEACON MODEL

We consider the multiple sinks architecture as shown in Fig. 2. The surface sinks S_N are deployed at the sea surface for accumilating the data from the underwater nodes. Henceforth, the overall network architecture consists a set of multiple sinks $\mathcal{S}_N = \{S_1, S_2, S_3, \ldots, S_{|\mathcal{S}_N|}\}$, set of relay nodes $\mathcal{N}_R = \{R_1, R_2, R_3, \ldots, R_{|\mathcal{N}_R|}\}$, and set of anchor nodes $\mathcal{N}_A = \{N_1, N_2, N_3, \ldots, N_{|\mathcal{N}_A|}\}$. So, the whole network set is $\mathcal{U} = \{\mathcal{S}_N \cup \mathcal{N}_R \cup \mathcal{N}_A\}$. Let $\mathcal{V} = |\mathcal{U}|$ refers the number of nodes in set $\mathcal{U}$. All nodes in $\mathcal{U}$ are isolated from each other at the start of the beaconing process showing no connection with surface sinks. Surface sinks are the final destinations deployed at the sea surface. All nodes in $\mathcal{U}$ periodically propagate a beacon message. The beaconing model for sink node $\mathcal{S}_i$ consists of *sequence number*, *unique ID*, and *position parameters* $(\bar{x}, \bar{y})$ and for node $\mathcal{N}_i$, it includes *sequence number*, *node ID*, *current residual energy*, *depth data* and *position parameters* (x, y). Besides, the beacon message of the nodes also includes the position information of its known surface sinks as in [12]. In our work, it is supposed that sink nodes S_i are equipped with GPS module as in [9], [12]. The beaconing process is started by the sink nodes and is eventually cascaded down the whole network. Further procedures (e.g., beaconing delay) of beaconing are considered the same as followed by [9], [12], [14].

IV. GCORP

Here is an exhaustive explanation of our intimated routing protocol and entitled as GCORP.

A. PROBLEM STATEMENT

Routing is a technique by which packets are routed from one point to another point (i.e., from source to destination). UWSN is an exceptional kind of network system with several open issues and challenges. The underwater sensor nodes and acoustic devices consume more energy than that of ordinary terrestrial sensors nodes and devices [51]. Hence, efficient-energy is a prime requirement of UWSN routing protocols. Also, it is noteworthy that during data exchange, more energy is consumed in data transmission than that of during data processing [52], [53]. So, the routing protocol should be designed in a way that it can reduce and suppress all redundant and unwanted transmissions. Most of the existing protocols are widely suffered from multipath transmissions, which results in high energy consumption and low network lifetime.

Besides, the aquatic surroundings have much high ambient noises and path losses than that of terrestrial surroundings [42], which severely affects the reliable packet transmission. The traversed distance of the acoustic signal also plays a pivotal role in the packet loss [34], [54]. These factors affect the performance of the UWSN routing protocols. Well, by applying casual and informal methods, such as by using more number of nodes and maximizing the power transmission of nodes, would be energy and resources wastage in general.

B. GCORP OVERVIEW

To address the challenges discussed in the problem statement (section IV-A), such as high energy consumption, multipath transmissions, and transverse distance of the acoustic signal. We, therefore, propose a novel GCORP routing protocol that utilizes the geographic and opportunistic routing paradigm to improve the network metrics, for example, packet delivery ratio, end-2-delay, energy consumption, and network lifetime. The GCORP protocol uses the multi-sink architecture to collect the data packets from a node that generates it, in the cooperation of relay nodes as depicted in Fig. 2.

In this context, GCORP chooses the best relay for sending the packets to the surface sinks at every hop. A Global Positioning System (GPS) is equipped with every surface sink on the sea-surface for sharing their position information with the underwater nodes via periodic beaconing. It is assumed that each underwater node (i.e., anchor node and relay node) knows where it is positioned [41]. For which, they can acquire their 2D position information (x and y *coordinates*) with the help of received beacon messages sent by the surface sinks based on Time-of-Arrival (TOA) ranging method [41]. This technique of finding the position information is an energy-efficient. Because the process of receiving messages utilizes less energy than that of the process of transmitting messages [55]. Henceforth, this technique curtails extra energy consumption on finding the location data of the nodes. While the nodes can estimate their depth ($z - coordinate$) with the help of depth-pressure sensor [11]. Therefore, we consider that the nodes adopt the horizontal motion and ignore their vertical transitions [41]. Thus, position information of the neighboring nodes is shared with the aid of periodic beaconing in the same way as in [9], [12], [14]. Besides position information, the current residual energy, and depth data are also exchanged with neighbor nodes via periodic beaconing. Henceforth, surface sinks initiate the beaconing procedure and transmit beacon messages periodically to the underwater nodes. In this way, the whole network is cascaded.

In GCORP protocol, initially, a relay forwarding set is being determined by the source node from its neighboring nodes based on the depth fitness factor. Then, a weighting scheme is applied to declare the best relay node. So whenever, a packet is broadcasted by the source node for the best relay node, remaining nodes of the relay forwarding set overhear the packet and for avoiding the collision with ongoing packet transmission, they set a holding time [14], [15]. Upon acquiring the packet from the source node, the best relay must move the packet to the next-hop candidate. If the packet is overheard by other relay nodes, then that packet will be discarded. In case, if the packet cannot be broadcasted by the best relay node, then second-best relay is selected on the basis of weight value along with new holding time and will broadcast the packet to the next-hop destination. Hence, the packet forwarding procedure is continued till the packets are delivered successfully at any of the surface sinks.

1) RELAY FORWARDING SET DETERMINATION

Here, initially, a group of relay nodes is being determined by the source node that will simultaneously increase the packet advancement and packet delivery probability (PDP) in the direction of surface sinks. We have developed an algorithm based on the depth fitness factor to evaluate the packet progress towards the surface sinks, and mentioned in the Equation. 15. Algorithm. 1 describes the procedure of relay forwarding set determination by the source node, which is repetitive for each-hop till a complete route is formed in the direction of surface sinks. To calculate the priority of the neighboring relay nodes, we use a fitness variable Θ_{iR_k}, which can be calculated by taking the depth differences of the source node d_i and the neighboring nodes d_{R_k} as by [14], [15]. We have only used the depth-based fitness factor to determine the relay forwarding set to curtail the extra overhead and

Algorithm 1: Relay Set Determination

Input : j, d_i, d_{R_k} and T_{range}
Output : $F(i) \leftarrow \{R_1, R_2, R_3, \ldots R_k\}, \quad \therefore\ k = |F(i)|$
Result : Source node (i) determines its relay forwarding set $F(i)$
Initialize : $F(i) \leftarrow \emptyset$ and j $\leftarrow$ total number of neighboring relay nodes

procedure *RelayForwardingSet*($F(i)$)
  for ($k = 1;\ k = j;\ k = k+1$) **do**
    Calculate: Θ_{iR_k}
    if ($\Theta_{iR_k} > 0$) **then**
      $F(i) \leftarrow F(i) + \{R_k\}$
    else
      Discard this relay node
    end
  end
end

energy. It can be expressed in a normalized value as follows:

$$\Theta_{iR_k} = \frac{d_i - d_{R_k}}{T_{range}} \quad (-1 \leq \Theta_{iR_k} \leq 1) \tag{15}$$

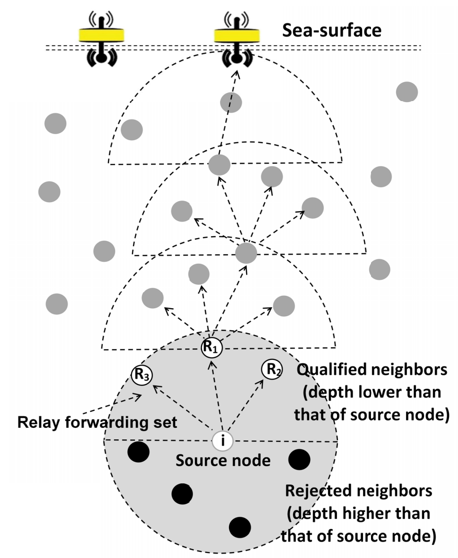


FIGURE 3. Relay forwarding set determination.

As per fitness factor, the neighboring relay nodes should be at a lower depth level than the source node, because of their close proximity to the surface sinks is feasible. If the fitness factor reflects a negative value, which indicates that the neighbor relay nodes are at a higher depth level than the source node as displayed in Fig. 3. Cooperation with these relay nodes should minimize the packet advancement towards the surface sinks. Consequently, the packet delivery probability will also be decreased and more energy will be required for relaying the packets, because of having a longer gap between the surface sinks and the neighboring relay nodes of the source node. Unlike other conventional greedy protocols, in the GCORP protocol, all such neighboring nodes that either have the same depth level as the source node or have greater depth level than the source node are excluded from the relay forwarding set.

2) BEST RELAY SELECTION

Let's assume that a source node i want to communicate with any of the surface sinks for transmitting the packets, and it has a neighboring set of relay nodes $F(i) = \{R_1, R_2, R_3, \ldots, R_k\}$ as described in Algorithm. 1. Where, $k = |F(i)|$ represents the total number of available candidate relay nodes k in the relay forwarding set $F(i)$. For example, when the neighbor relay node R_k has shared its information with the source node i via periodic beaconing. In this course, the distance between the neighboring relay node and the known surface sink is calculated. This mechanism of finding the distance is also incorporated in [12]. After this, the source node calculates the PDP of its one-hop neighboring relay node. Subsequently, the PDP for each relay node R_k of the relay forwarding set $F(i)$ will be P_{iR_k}. The source node also keeps the record of residual energy of the neighboring nodes. Normalized energy can now be expressed as follows for each neighboring relay node.

$$\alpha_0 = \frac{E_{res}(R_k)}{E_{init}(R_k)}, \quad where\ \alpha_0 \in [0\ to\ 1] \tag{16}$$

In which, these energies $E_{res}(R_k)$ and $E_{init}(R_k)$ are discussed earlier in section III-C. Now, PDP from source node i to relay nodes R_k for bits b can be represented in the following form.

$$\beta_0 = P_{iR_k} = (1 - P_e(D_{iR_k}, f))^b, \quad where\ \beta_0 \in [0\ to\ 1] \tag{17}$$

where the quantity $P_e(D_{iR_k}, f)$ is discussed in section III-B3. The main focus of a traditional routing protocol is on determining a node from the relay forwarding set $F(i)$ that optimizes the PDP only. For instance, if source node chooses a relay node R_1 and its PDP is equal to P_{iR_1}, as shown in Fig. 5. Nevertheless, if a routing protocol does not the consider the energy consumption for the best relay node selection, then ideally, the selection of the best relay node should be on the basis of increasing the PDP as max $(P_{iR_1}, P_{iR_2}, P_{iR_3}, \ldots, P_{iR_k})$ for each hop-transmission. Although, from an energy-constrained UWSNs point of view, it is not appropriate [15]. Therefore the energy of the selected node will soon be drained, because most of packets are sent by the node having the highest PDP.

After calculating the normalized energy and PDP of each neighboring node R_k of the source node i, the distance from the known surface sink to the neighbor relay nodes R_k of set $F(i)$ are also calculated as discussed earlier in this section and can be represented as $D_{S_iR_k}$. For measuring the distance, the location parameters of the surface sinks are shared via distributed beacon messages as discussed earlier. As all surface sinks are considered to be mounted on the sea surface, so their depth is thus considered as zero (0) (since $z - coordinate$ can also be referred to as depth value $\bar{d}_{S_i}$). Hence, the distance from the known surface sink to the neighboring relay nodes R_k of set $F(i)$ can be calculated as:

$$D_{S_iR_k} = \sqrt{|(\bar{x}_{S_i} - x_{R_k})|^2 + |(\bar{y}_{S_i} - y_{R_k})|^2 + |(\bar{d}_{S_i} - d_{R_k})|^2} \tag{18}$$

where $(\bar{x}_{S_i}, \bar{y}_{S_i}, \bar{d}_{S_i})$ are position-coordinates of the surface sink S_i. Similarly, $(x_{R_k}, y_{R_k}, d_{R_k})$ are the position-coordinates of the neighbor relay nodes R_k. Now the normalized distance can be calculated as:

$$\gamma_0 = \frac{D_{S_iR_k}}{\max\limits_{R_k \to k} D_{S_iR_k}} \tag{19}$$

Here in this section, we have calculated the three different quantities; the normalized energy (α_0), PDP (β_0), and the normalized distance (γ_0). By incorporating this information, we, therefore, recommend a weighting scheme in order to select the best relay node. The weighting scheme is given in the below sub-section.

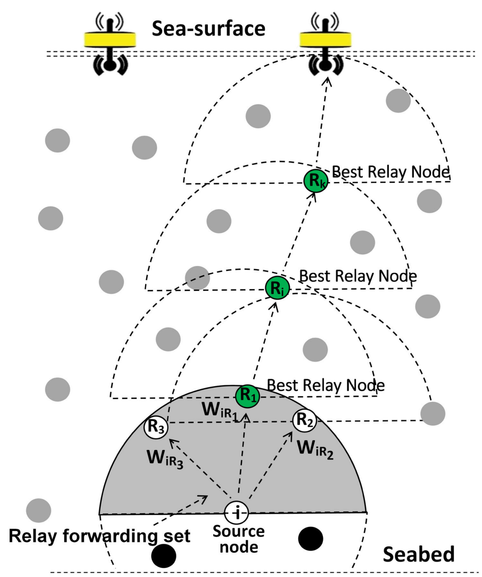


FIGURE 4. Best relay selection scheme.

3) WEIGHTING SCHEME

The weighting schemes is given as:

$$W_{R_k}(\alpha_0, \beta_0, \gamma_0) = \frac{\alpha_0 \cdot \beta_0}{\gamma_0} = \frac{(E_{res}(R_k)/E_{res}(R_k)) \cdot P_{iR_k}}{(D_{S_iR_k}/\max\limits_{R_k \to k} D_{S_iR_k})} \tag{20}$$

The neighbor relay node R_k holds the maximum weight value, will ultimately be selected as a best relay node $\mathcal{B}_{R_k}$. If we look around the Fig. 4, the relay node R_1 is selected as best relay node. Because node R_1 has greater weight value than R_2 and R_3 and their weight values are represented as W_{iR_1}, W_{iR_2} and W_{iR_3}, respectively. The Algorithm. 2 details the steps about the best relay node selection scheme.

Algorithm 2: Best Relay Selection Scheme

Input : $E_{res}(R_k),\ E_{init}(R_k),\ P_{iR_k}$ *and* $D_{S_iR_k}$
Output : $\mathcal{B}_{R_k}$
Result : Source node (i) selects its best relay $\mathcal{B}_{R_k}$ from set $F(i)$
Initialize: $\mathcal{B}_{R_k} \leftarrow \emptyset$

procedure *BestRelaySelection*($\mathcal{B}_{R_k}$)
  for ($R_k = 1$; $R_k = k$; $R_k = R_k + 1$) **do**
    Calculate: $\alpha_0 = \frac{E_{res}(R_k)}{E_{init}(R_k)}$
    Calculate: $\beta_0 = P_{iR_k}$
    Calculate: $\gamma_0 = \frac{D_{S_iR_k}}{\max_{R_k \to k} D_{S_iR_k}}$
    Calculate: $W_{R_k}(\alpha_0, \beta_0, \gamma_0)$
    if $\max_{R_k \to k} \{W_{R_k}(\alpha_0, \beta_0, \gamma_0)\}$ **then**
      $\mathcal{B}_{R_k}$ is best relay
    end
  end
end

C. HOLDING TIME MODEL

Ultimately, a relay forwarding set $F(i)$ is locally determined by the source node and accordingly, broadcasts the packet for the best relay. The GCORP is a source-based routing protocol, in which the best relay is being determined by the source node that cooperates in relaying the packets to the next-hop forwarder. In order to accept the packet, the relay node must be from the relay forwarding set else it will drop the packet. Whenever a packet is received by the selected relay then it will pass that packet to the next available forwarding node. The rest of the nodes of the relay forwarding set will schedule a holding time according to the fitness factor, and after getting the identical packets from the source node as mentioned in Equation. 15.

The holding time model is used to schedule the transmission of the packets by the relay nodes of the relay forwarding set to the next-hop as described in Equation. 21. If the selected relay forwards the packet to the next-hop forwarding node, then the rest of the nodes will overhear it and finally drop it after the confirmation of packet transmission. Otherwise, a second-best relay is chosen from the relay set to relay the packet to the next-hop forwarding node. Even for the same packet, each node of the relay forwarding set has variant fitness factor values and holding times accordingly. The GCORP protocol uses maximum energy of the neighboring nodes and packet advancement technique to select the best relay to minimize the hop count number around the routing path in the direction of surface sinks. In addition, the minimum gap between the neighboring relay nodes and the surface sinks are also considered for selecting the next-hop forwarding node. GCORP protocol also attempts to resist other neighbor relay nodes from routing the same packet multiple times by which a sufficient amount of energy can be saved. The packet forwarding procedure will be repeated until the packet arrives at any of the surface sinks. In Fig. 5, an example for the calculation of holding time for neighboring relay nodes is illustrated, in which a source node is represented by i and its one-hop neighboring relay nodes are represented by R_1, R_2, R_3 and R_4. The maximum transmission range of the source node is denoted by T_{range} and shown by a circular dotted line in Fig. 5. So, whenever source node i broadcast a packet, it will be received by each relay node that is within the transmission range. While the relay node R_4 will discard the packet because its depth is higher than that of the source node. But other nearby relay nodes R_1, R_2, and R_3 are more likely to send the packet to the next-hop, but relay node R_1 will take part in moving the packet to the next-hop destination as it ensures the maximum packet advancement in the direction of surface sinks. Therefore, relay nodes R_2 and R_3 will suppress their transmissions in the favor of adjacent relay node R_1 because of holding the maximum weight value. In case, the relay node R_1 does not transmit the packet then the second-best relay R_2 will eventually be selected according to the weight value and holding time as shown in Fig. 5. The holding time for each neighboring relay node can be determined by the equation [14], [15]:

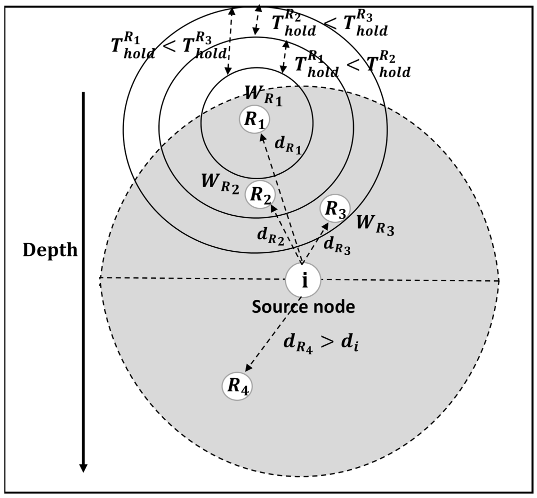


FIGURE 5. Relay selection criteria based on the weight calculation scheme and holding time calculation.

$$T^{R_k}_{hold} = (1 - \Theta_{R_k})(T_{delay}) + \frac{T_{range} - |\vec{D}_{iR_k}|}{\mathcal{V}_{sound}} \quad (21)$$

where T_{delay} and $\mathcal{V}_{sound}$ are respectively the total propagation delay and underwater sound speed. The total propagation delay must be calculated in a way that all relay nodes of the relay forwarding set can overhear the packet of the best relay before moving the packet to the next forwarding node. D_{iR_k} is the separation between the source node and the adjacent relay nodes, and it can be deduced from the information of received beacon message [12].

Equation. 21 is comprised of two parts; its first part indicates the maximum holding time of the neighboring relay nodes, which also depends on the value of the fitness factor of the neighboring nodes, which means if the value of the fitness factor is high then accordingly the shorter will the holding time as indicated by the solid circle lines in the Fig. 5. Meanwhile, the other part of the equation reveals the propagation delay between the source node and the forwarding nodes. The procedure for forwarding the data packets in the GCORP protocol is defined in Algorithm. 3.

Algorithm 3: Forwarding Data Packets

Input : Θ_{R_k}, T_{delay} *and* $\mathcal{V}_{sound}$
Output : $T_{hold}^{R_k}$
Result : *Data packets received*

procedure *ReceiveDataPacket(i, packet)*
  if $(i.ID \in header(packet) \mid i \rightarrow \mathcal{B}_{R_k})$ **then**
    Calculate $T_{hold}^{R_k}$
    $(F(i) - \mathcal{B}_{R_k})$ set $T_{hold}^{R_k}$
    if $\mathcal{B}_{R_k}\_is\_fail \leftarrow false$ **then**
      $\mathcal{B}_{R_k}(packet) \xrightarrow{forward} next\_hop$
      $(F(i) - \mathcal{B}_{R_k})$ overhear the packet and drop it
    else
      Second-best relay is selected
    end
  end
end

TABLE 2. Simulation setup.

Sr #	Parameter	Value
1	3D Network Size	500m x 500m x 1000m
2	Number of surface-sinks	4, 9, 16
3	Number of nodes	50 to 350
4	Physical Modem	LinkQuest UWM1000 [58]
5	Modulation Type	BPSK
6	Compared algorithms	DBR, FDBR, EMGGR, PER
7	Topology of the nodes	Random
8	Mobility model	2D random walk
9	Node mobility	Static, 2m/s, 4m/s
10	Transmission range of nodes	100 m
11	Acoustic speed	1500 m/s
12	Data packet size	100 bytes
13	Channel bit rate	10 kbps
14	Bandwidth	4 Khz
15	Frequency	10 Khz
16	Transmission Power	90dB re μ Pa
17	Power consumption to transmit packet	2 units
18	Power consumption to receive packet	0.75 W
19	Power consumption to overhear packet	8 mW
20	Data generation rate	1 packet/sec
21	Simulation run time	1000 sec
22	Number of simulation runs	50 times
23	Simulating tool	NS3 [56]

V. SIMULATION RESULTS

This section is bifurcated into following sub-sections.

A. SIMULATION SETTING

Meant for the implementation and performance evaluation of GCORP protocol, we choose a discrete event type network simulator (NS3) [56]. In the simulation, we use multiple sinks architecture as used by various protocols [9], [11], [12], [19], [36], [39], and deploy the nodes (relay and sensor nodes) ranging from 50 to 350 randomly in a 3D network region of dimensions 500m $\times$ 500m $\times$ 1000m. The behavior of our scheme is considered to be hybrid in terms of mobility (i.e., anchor nodes are fixed and relay nodes can move in 2D random direction concerning water waves). Relay nodes are supposed to remain inside the network region, for which we use RandomWalk 2D mobility model as used in [29], [36]. As per this model, the relay nodes can have random walk in 2D direction (X-Y plane) with a speed of 2m/sec to 4m/sec. The relay nodes are reversed back into the network region, whenever they reach the network boundary, to make sure that their mobility is always within the network region as in [39], [57].

We set other simulation parameters according to LinkQuest UWM1000 (an underwater acoustic modem) [58]: the maximum power transmission at the value of 90dB re μPa and the power consumption of the node are set as 2W, 0.75W, and 8mW for transmitting, receiving and overhearing a packet, respectively. We fix 100m as a maximum range for all nodes to communicate with each other and surface sinks. The packet generation rate and packet size are 1 packet/sec and 100 bytes, respectively. The total simulation run time for one round is 1000 sec. The results obtained from the simulations are averaged from a total of 50 runs. For easiness, we summarize the simulation parameters in Table. 2.

B. NETWORK METRICS

This section sets out the four network metrics used for the evaluation of our proposed GCORP protocol and which are: PDR, average E2E delay, average EC, and average NLT. We elaborate each network metric as below [15]:

Packet Delivery Ratio (PDR) can be elaborated as the ratio of the total number of packets received by the sink node versus the total number of packets originated by the source node. PDR can be calculated as:

$$PDR = \frac{\sum_{n=1}^{K} (\frac{D_{rn}}{D_{gn}})}{K} \tag{22}$$

where D_{rn} represents the total number of packets received by the sink node for n^{th} simulation runs, D_{gn} represents the total number of a packet generated by the source node for n^{th} simulation runs, and K represents the simulation run counts.

Average End-2-End Delay (E2E) can be described as the average time taken by the packets from generation by the source node to reception by the sink node. The whole duration of the average end-2-end delay is the set of holding time, propagation delay, transmission delay, and process delay. Average end-2-end delay can be calculated as:

$$E2EDelay_{Avg.} = \frac{\sum_{n=1}^{K} \sum_{m=1}^{D_T} \left\{ (TD_{nm} - RD_{nm}) + T_{hold}^{R_k} \right\}}{D_T K} \tag{23}$$

where D_T, TD_{nm}, RD_{nm} are the total number of successful packets being received by the surface sinks, the transmitting time of m^{th} packet in the n^{th} simulation run and the receiving time of m^{th} packet in the n^{th} simulation run, respectively. For multiple sinks architecture, the same packet might be received by multiple sinks with different end-2-end delays. So, while compiling the simulation results the smallest end-2-end delay is incorporated.

Average Energy Consumption (EC) is the total amount of energy required for transmitting, receiving, and overhearing the packets by the nodes in n^{th} simulation run and given as:

$$EC_{Avg.} = \frac{\sum_{n=1}^{K} E_{total}\{F(i), R_k\}}{K} \tag{24}$$

The proposed scheme uses the multi-sink architecture. So, the broadcast nature of the relay nodes, different sinks can receive the same packet. Henceforth, the duplicate packets are considered redundant during the calculations. Therefore, the average energy consumption is calculated for the packets that are received successfully [29], [36].

Average Network Lifetime (NLT) can be defined as the lifespan during which the network is fully functional or operational. In other words, the network lifetime is a time when the network's first node drains its energy completely. Hence NLT can be calculated from two-time differences; the first time is when simulation run time starts, and the second time is when the first node of the network drains its all energy. NLT can be formulated as:

$$NLT_{Avg.} = \frac{\sum_{n=1}^{K} (ST_n - FT_n)}{K} \tag{25}$$

where: ST_n and FT_n shows the time at which simulation starts in n^{th} simulation and the time when the first node of the network has utilized its energy completely in n^{th} simulation respectively.

C. RESULTS ANALYSIS

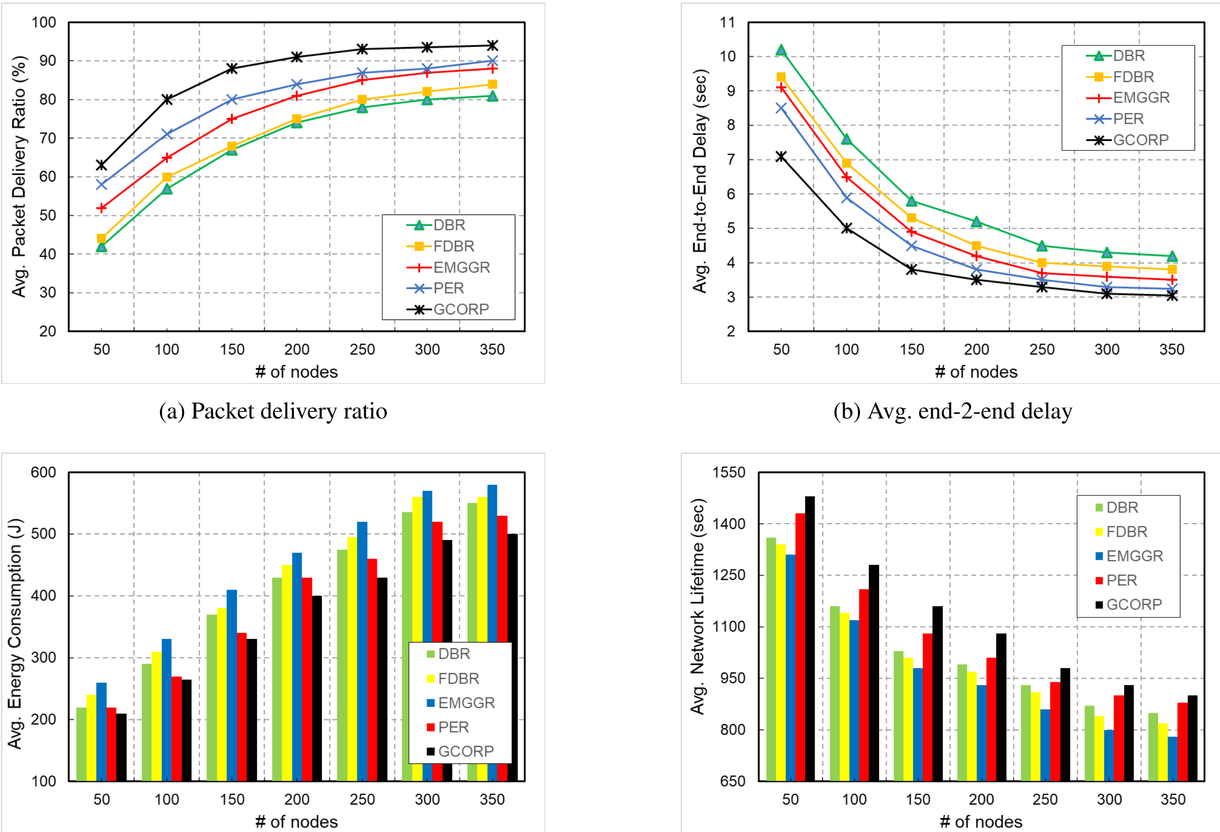
After the implementation of GCORP algorithms in NS3, now we discuss the simulation results and compare the proficiency of GCORP routing protocol with existing routing protocols (DBR, FDBR, EMGGR, and PER), with multiple sink numbers (4, 9, 16), and at random node speeds (static, 2m/s, 4m/s) in terms of said network metrics.

1) PERFORMANCE EVALUATION OF GCORP WITH EXISTING SCHEMES

Fig. 6 shows the performance evaluation of GCORP with existing protocols (DBR, FDBR, EMGGR, and PER) in terms of different network metrics. The GCORP protocol outperforms the existing protocols with respect to PDR, average E2E delay, average EC, and average NLT. Fig. 6a displays the results of PDR at different node densities. So, by increasing the node density, PDR is sufficiently improved as it covers a large area of the network. Because in a dense network, more number of forwarding nodes can be lied in the routing path and thus PDR of the routing protocol is converged to a high rate. On the other hand, most of the nodes might be unlinked from each other in a sparse network, resulting in lower PDR. In this regard, the GCORP offers a high value of PDR than other routing protocols for both sparse and dense networks. Since all of these protocols are not incorporating the PDP as a standard to select the best relay as a next-hop except the GCORP protocol. The PER has also better PDR when compared with EMGGR, FDBR, and DBR protocols. GCORP and PER protocols have negligible PDR difference in the dense network area, but the difference margin is slightly high in the sparse network area. The EMGGR protocol has better results for PDR than FDBR and DBR but less than GCORP and PER because it uses the multipath transmissions, which increases the PDR at the cost of high energy tax. The PDR difference margin is minor between the FDBR and DBR protocols. Because the FDBR protocol has used a fuzzy-based rule to select the best next-hop candidate node for routing the data towards the destination but the DBR has used only the depth information to select the next-hop candidate. Hence the success of FDBR is more than the DBR protocol.

Fig. 6b plots the average end-2-end (E2E) delay for each protocol. The average E2E delay for all protocols decreases as the node density increases. The GCORP protocol offers a low average E2E delay as compared to other benchmark protocols, such as PER, EMGGR, FDBR, and PER protocols. The hidden terminal problems do not occur in the GCORP protocol as the source node determines its relay forwarding set on the basis of the beacon message received from its one-hop neighbors. Therefore, the GCORP protocol performs efficiently than PER, EMGGR, FDBR, and DBR protocols in terms of average E2E delay, but PER protocol also showed an almost similar performance as shown by the GCORP protocol. The EMGGR protocol has used multiple short paths to reduce the delay although it consumes more energy. But the E2E delay of EMGGR is higher than GCORP and PER protocols. The FDBR protocol also performs efficiently with respect to the DBR protocol in terms of average E2E delay. Because, in DBR protocol, the hop-count value is not considered during route establishment. Whereas, the FDBR protocol considers the hop-count number while creating a routing path to reach the surface sinks.

Fig. 6c, displays the output graph of the average energy consumption (EC) versus the node density. We can observe that node density influences the average EC of the nodes.



(a) Packet delivery ratio

(b) Avg. end-2-end delay

(c) Avg. energy consumption

(d) Avg. network lifetime

FIGURE 6. **Performance evaluation of GCORP with existing schemes.**

Because more number of nodes are generating more number of packets, for which an extra amount of energy is required to transmit and receive the packets. The GCORP protocol consumes little energy to forward the packets towards the destination, as can be seen in Fig. 6c. The GCORP protocol chooses the best node to route the packet in each transmission hop. In addition, the holding time model also supports the GCORP protocol to utilize minimum energy by limiting the number of retransmissions and packet collisions. Henceforth, the GCORP protocol seems quite efficient in terms of average EC than other existing schemes. But in few cases, the proposed protocol is suffered from multipath issues as the best relay node cannot suppress the undesired transmissions of other members of the relay forwarding set if they are not within the transmission range of the best relay node. Hence, all such undesired transmissions may lead to high energy consumption. This issue can also be observed in existing works, such as PER, FDBR, EMGGR, and DBR. After the proposed protocol, PER and DBR protocols have shown better results for energy consumption than FDBR and EMGGR protocols as the both PER protocol has considered the energy metric in the route establishment and DBR protocol has used simple algorithm in the route establishment. The FDBR and EMGGR protocols are widely suffered from high energy consumption as FDBR and EMMGR protocols have used complex mechanism in the route establishment. Moreover, all benchmark protocols have not considered any technique to suppress the unwanted transmissions of the relay nodes, which results in high energy consumption. The EMGGR protocol has shown poor performance in terms of average energy consumption with respect to all other schemes. As the EMGGR protocol performs a grid-by-grid technique to design a route, which consumes a lot of energy.

Fig. 6d depicts the comparison of the average network lifetime (NLT) of GCORP against PER, FDBR, EMGGR, and DBR. It can be observed that the average NLT of PER, FDBR, DBR, and EMGGR protocols is shorter than that of GCORP protocol because the average EC of benchmarks schemes is higher than the GCORP protocol, which ultimately reduces the average NLT. Besides, the GCORP, PER, and FDBR protocols consider the remaining energy of the nodes of the relay forwarding set. However, the GCORP protocol offers a high average NLT than PER and FDBR protocols as it utilizes the holding time model to leverage the packet collisions and undesired transmission. On the other hand, the DBR protocol has utilized the depth information to select the next-hop forwarding candidate, whether the forwarding node has sufficient energy or not. The EMGGR protocol has the

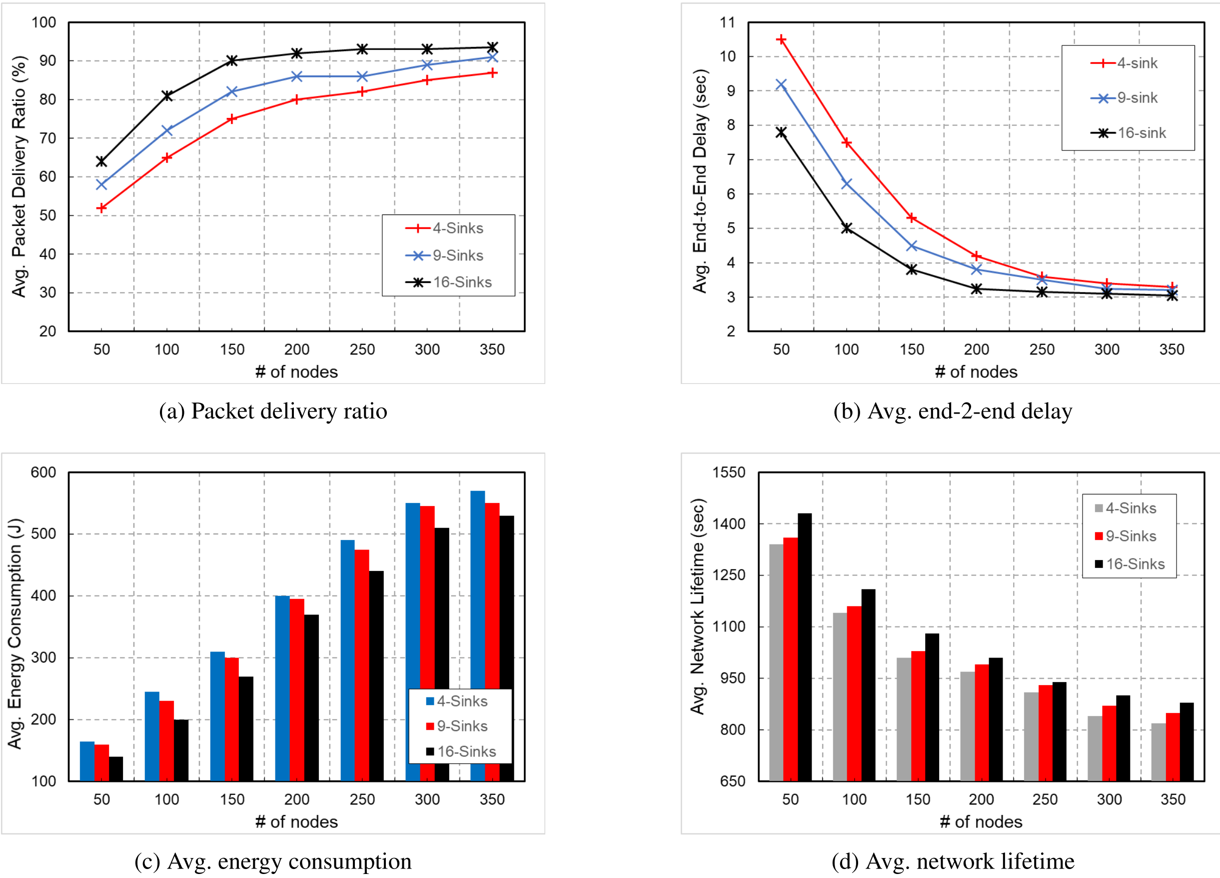


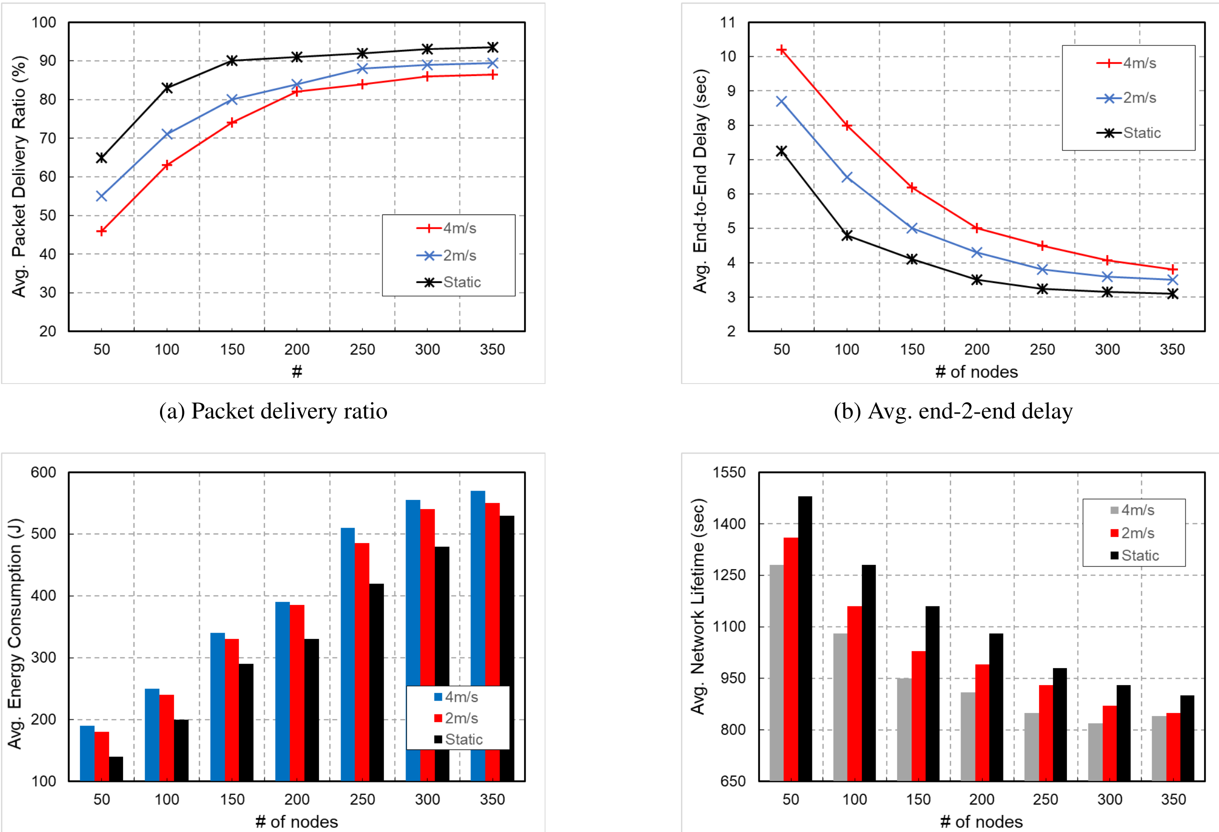
FIGURE 7. Performance evaluation of GCORP with multiple sink numbers.

lowest network lifetime than all other schemes, as it performs very complex algorithms, which affects the lifespan of the nodes.

2) PERFORMANCE EVALUATION OF GCORP WITH MULTIPLE SINK NUMBERS

To investigate the influence of multiple sink numbers over GCORP protocol, we use multiple sinks of numbers 4, 9, and 16, and the simulation results are depicted in Fig. 7. From Fig. 7a, it can be observed that the PDR of the network can be maximized by using multiple sink numbers. The PDR of GCORP protocol with 16–sinks is higher than GCORP protocol with 9–sinks and 4–sinks. Because the GCORP protocol forwards the packets at the surface sinks in greedily fashion. Thus, the increased number of surface sinks will ultimately enhance the packet delivery probability and reduce the number of packets encountered by the void holes in the last hop [36]. Also, the multiple sink numbers can increase the coverage volume of the network region. That's why multiple sinks achieve more PDR rates. But the probability of the multiple copies of the same packets received by the multiple sink numbers is also increased. This is the major flaw of using multiple sink numbers. This issue can be resolved by integrating a duplicate packet suppression technique as incorporated by WDFAD-DBR protocol [36].

The average E2E delay for multiple sink numbers is plotted in Fig. 7b. From the figure, it can be concluded that the average E2E delay is curtailed with the increase of surface sink numbers. We can achieve better results for average E2E delay with 16–sinks than with 9–sinks and 4–sinks, respectively. Because the total routing distance of the packets and holding time reduce the average E2E delay as the surface sink density increases. The Fig. 7c reflects the average energy consumption for GCORP protocol with multiple sink numbers. As per plot, the average EC is marginally affected by increasing the surface sinks density. The reason behind this situation is that the packet forwarding process is not affected by using multiple sink numbers. Consequently, the equivalent EC occurs across all distinct destination settings. The average NLT for GCORP protocol with multiple sink numbers is plotted in Fig. 7d. We can achieve more network lifespan with 16–surface sinks than with 9–surface sinks and 4–surface sinks. The network lifespan can also be increased by minimizing the probability of packet collisions and the number of retransmissions as the destination choices are increased. Therefore, the network lifespan is increased significantly under varying surface sink numbers.



(a) Packet delivery ratio

(b) Avg. end-2-end delay

(c) Avg. energy consumption

(d) Avg. network lifetime

FIGURE 8. Performance evaluation of GCORP at random node speeds.

3) PERFORMANCE EVALUATION OF GCORP AT RANDOM NODE SPEEDS

We also assessed the performance of the GCROP protocol at varying node speeds (static, 2m/sec, and 4m/sec) under the same simulation settings. The performance scenario for different network metrics with respect to multiple node speeds is given in Fig. 8. Fig. 8a depicts the PDR at varying node speeds. The PDR under the same node density condition is the lowest at 4 m/s speed and is the highest while nodes are in static condition. It can be assumed that the node movement affects the PDR rate. Which is quite un-beneficial for the reliability of the network. Well, the node mobility affects lightly in the dense network. Hence we achieve a good PDR rate in the dense network. If we look at the sparse network areas, the node mobility severely affects the PDR, and the difference margin is around 50 - 60% lower than the dense network areas.

Now we can observe the Fig. 8b, the average E2E delay is also severely affected by the random node speeds only in a sparse network but lightly affected in a dense network. The average E2E delay is primarily dependent on the number of neighbor's requests. Hence, the node mobility marginally affects the average E2E delay, if we increase the number of neighbors (i.e., node density). Then, if we see the effect of random node speeds on average EC and average NLT as shown in Fig. 8c and 8d, respectively. The random node speeds have also a serious effect on average energy usage and the average lifespan of the network. We can achieve better results in static conditions than mobility conditions. Because the topology and routing distance is affected by the node's mobility, thus more energy required to cover wide distances. Hence, it can be concluded that the static nodes give more active input than mobile nodes in terms of different network metrics.

4) PERFORMANCE TRADE-OFFS

Here, we provide a short review for the performance of the GCORP, PER, EMGGR, FDBR, and DBR protocols on the basis of simulation results as discussed in section V-C1. The summary of performance trade-offs is given in Table 3. The proposed protocol has shown good performance for different network metrics, such as PDR, end-2-delay, energy consumption, and network lifetime when compared with baseline schemes, except in solving the void node issues and multipath communication problem. Although, all baseline schemes (PER, EMGGR, FDBR, and DBR) are even suffered from void node issues and multipath communication problems. The proposed GCORP protocol has considered the

TABLE 3. Performance trade-offs.

Protocol	Reference	Features	Achievements	Trade-offs
DBR	[11]	Depth-based relay node selection is carried out	Improved PDR and low latency	High energy consumption, void occurrence and multipath problem
FDBR	[19]	Fuzzy-based relay node selection is carried out	Improved PDR and low latency than DBR	High energy consumption than DBR, void occurrence and multipath problem
EMGGR	[24]	Grid-by-grid routing technique and multiple gateways are used to collect the data packets	Enhanced packet delivery ratio and less end-to-end delay	High energy consumption, and low network lifetime due to complex routing mechanism
PER	[27]	A power-efficient routing scheme	Low end-to-end delay, balanced energy consumption	Moderate packet delivery ratio
GCORP	This works	Weight scheme is integrated to determine the relay node and holding model is used to avoid packet collisions	Improved packet delivery ratio, enhanced network lifetime, less energy consumption and low end-2-end delay	Void occurrence and multipath problem

residual energy, PDP, distance metrics in the determination of the forwarding hop to improve the PDR, network lifetime, and minimize the energy consumption and latency. The PER protocol has also considered the energy metric in their scheme to improve the performance metrics, but the PDR rate is not satisfactory as compared to the proposed protocol. Whereas the EMGGR has performed very complex calculations to achieve high PDR rate and low latency but the average energy consumption and network lifetime metrics are compromised. The FDBR protocol has shown better performance in terms of PDR and latency than the DBR protocol but lagging in terms of energy consumption and network lifetime. Hence, it has been concluded that the GCORP protocol shows better performance than the rest of the protocols in terms of different performance metrics.

VI. CONCLUSION

In this article, we have introduced a multiple sinks-based GCORP routing protocol. In this protocol, initially, the source node has determined a relay forwarding set from its neighboring relay node by calculating the fitness factor on the ground of depth data. The depth data was acquired via a distributed beacon message initiated by the multiple sinks deployed at the sea surface. Subsequently, the source node has used the weight calculation scheme to select the best relay node from the relay forwarding set. The weighting scheme is performed on the normalized energy, PDP, and the normalized distance of each relay node of the relay forwarding set. Furthermore, a holding time model is designed for each relay node with the aim of evading the packet collisions and retransmissions. We have used NS3 (Network Simulator) to get the simulation results. The simulation results have revealed that the GCORP protocol achieved better results comparatively the existing protocols (DBR, FDBR, EMGGR, and PER) in terms of different network metrics such as packet delivery ratio, average end-2-end delay, average energy consumption, and average network lifetime. Moreover, we also used the aforementioned network metrics to evaluate the efficiency of the GCORP protocol by varying the sink numbers and at different node speeds. It is concluded that the GCORP protocol also performed well in dynamic conditions.

For future recommendations, we intend to resolve the issue of void nodes by developing the void node recovery algorithms. Besides this, machine learning-based algorithms will also be designed for improving the network metrics even more than this scheme (i.e., GCORP protocol). Also, we will perform quantitative analysis to compare the performance of the newly designed algorithms.

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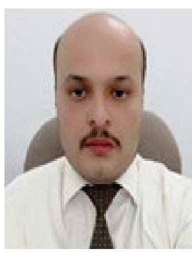

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