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FFRP: Dynamic Firefly Mating Optimization Inspired Energy Efficient Routing Protocol for Internet of Underwater Wireless Sensor Networks

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ABSTRACT Energy-efficient and reliable data gathering using highly stable links in underwater wireless sensor networks (UWSNs) is challenging because of time and location-dependent communication characteristics of the acoustic channel. In this paper, we propose a novel dynamic firefly mating optimization inspired routing scheme called FFRP for the internet of UWSNs-based events monitoring applications. The proposed FFRP scheme during the events data gathering employs a self-learning based dynamic firefly mating optimization intelligence to find the highly stable and reliable routing paths to route packets around connectivity voids and shadow zones in UWSNs. The proposed scheme during conveying information minimizes the high energy consumption and latency issues by balancing the data traffic load evenly in a large-scale network. In additions, the data transmission over highly stable links between acoustic nodes increases the overall packets delivery ratio and network throughput in UWSNs. Several simulation experiments are carried out to verify the effectiveness of the proposed scheme against the existing schemes through NS2 and AquaSim 2.0 in UWSNs. The experimental outcomes show the better performance of the developed protocol in terms of high packets delivery ratio (PDR) and network throughput (NT) with low latency and energy consumption (EC) compared to existing routing protocols in UWSNs.

INDEX TERMS Internet of Underwater Things, bio-inspired routing, firefly mating optimization, underwater wireless sensor network, routing protocol.

I. INTRODUCTION

The oceans contain about 96.5% of all earth water is extremely important for the survivability of human life since it provides nourishment, natural resources, ways of transportation, greater defense margin and several other benefits. However, a vast portion of the oceans around 95% is still unexplored due to the lack of appropriate acoustic communication technologies. Recently, significant advancements in the Internet of underwater things (IoUT) technology have facilitated the exploration process of the oceans by connecting various ubiquitous sensor devices to provide reliable and efficient data collection in UWSNs [1], [2]. The acoustic sensor nodes (ASNs) in underwater acoustic sensor networks (UASNs) have the potentials to monitor real-time underwater events with failure detection and self-organizing capabilities. Therefore, UASNs have received significant attention in a variety of ocean monitoring applications, such as navigation assistance, tactical surveillance, mine recognition, underwater pollution analysis and

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monitoring the natural disaster. However, the communication between acoustic sensors is challenging due to the low signal propagation speed of the signals in the underwater environments (UWEs) [3]–[5]. The low bandwidth, path loss, noise, Doppler spreads, multi-path effects and high power consumption are other important issues that affect the transmission of the data packets between ASNs in UWSNs [6], [7] compared to the ground-based wireless sensor networks (WSNs) [8]. Therefore, UASNs are facing the issues of high bit error rate (BER), large propagation latency, low data transmission capacity and highly dynamic topology structure in UWEs. Thus, an efficient and reliable data collection due to aforesaid factors is challenging in UWSNs. Although, the radio waves and optical communication are other alternatives for data transmission in UWSNs. However, the radio signals are suffering from absorption and high signal attenuation while optical communication is facing severe scattering issues in UWEs [9]–[11]. In fact, these communication solutions are intolerant to faults, not scalable and expensive, and thus not suitable for low-cost time-critical events monitoring purposes in UWEs. In this respect, the acoustic signals compared to radio waves and optical communication seem to be the best solution for providing an efficient and reliable data collection for real-time events monitoring applications [12]. Recently, several routing schemes have been designed in the literature (see Section 2 for detail) with the aim to provide efficient and reliable data gathering by mitigating the harmful interference impacts of the UWEs. However, each of them is facing severe issues, such as low packet delivery ratio, high latency, excessive route failures, control message overhead, energy consumption, and low network throughput, which severely limited the performance of UWSNs.

A. RESEARCH CONTRIBUTIONS

We propose a novel dynamic firefly mating optimization inspired routing protocol called FFRP for the internet of UWSNs-based events monitoring applications. The routing problem is modelled using the traditional and mixed-integer linear programming (MILP) in UWANs. The key research contributions of the developed scheme are listed as: First, we modify the existing firefly mating optimization algorithm as a dynamic firefly mating optimization algorithm to avoid local optimum problems. The new features added to the existing firefly algorithm, including the memory intelligence with priority, dynamic flying speed during mating, mating with the restricted mates, and hybrid genetic operators with different probabilities to avoid local optimum in the given problem search space. Then, based on the dynamic firefly mating optimization algorithm, a novel data gathering protocol is proposed for efficient and reliable data delivery to the remote user. The proposed mechanism during conveying information selects the highly stable and quality-aware elite data paths between source and destination in the network. The proposed scheme extremely reduces the impact of data path loops, latency and high energy consumption by efficiently balancing data traffic burden equally in UWSNs. Besides, transmission of the packet over highly stable links between acoustic nodes increases overall packet delivery ratio and network throughput in UWSNs. Finally, extensive simulations are conducted through NS2 and AquaSim 2.0 to validate the performance of the FFRP scheme against existing schemes in UWEs.

B. PAPER ORGANIZATION

In the remaining part of the paper, Section II reviews the literature and Section III provides the detail of the proposed routing scheme. Section IV explains the energy consumption and channel models, while the comparative performance of the FFRP scheme against other schemes in UWEs is presented in Section V. Finally, the research is concluded with a highlight on future works in Section VI.

II. LITERATURE REVIEW AND CHALLENGES IN UWSNS

Optimizing the energy consumption performance for efficient and reliable data delivery is crucial for UWSNs. In the last several years, many different ways have been attempted by researchers to solve routing problems with different degrees of success. For example, in [13] and [14] authors tried to solve the issues of high energy consumption and latency for reliable packets transmission in void regions in UASNs. These depths-based routing schemes successfully reduced the latency and EC, however, they face the issues of low network throughput (NT) and high packet error rate in UASNs. In addition, the authors in [15] and [16] also proposed data packets forwarding mechanisms, which employ depth variance characteristics of the relay nodes to minimize packet error rate and energy consumption in UASNs. However, both of them face poor synchronization, data redundancy, and control message overhead issues during forwarding packets in void regions in UASNs. A vector-based opportunistic routing in [17] solves a few issues faced by depth-based routing protocols in UASNs. The proposed scheme by employing the key idea of packets forwarding over smallest hop counts minimizes the latency and overall energy consumption issues for marine monitoring applications. The work in [18] considers dynamic transmitting power levels of the down-stream relay nodes to prolong the network lifetime of the UWSNs. However, the scheme faces the issues of low data delivery ratio and severe delay in UWSNs.

To solve the issues of low PDR and NT, the research in [19] discusses a novel tree-based packet relaying technique for underwater monitoring applications. In the suggested scheme, the authors divide the entire working procedure into tree constructions and information collection phases. In the first phase, various dynamic shortest-path trees are constructed where multiple gateway nodes are defined to restrict the association count of neighbouring nodes and then data is collected from these gateway nodes using autonomous underwater vehicles in the data collection phase. The performance of the proposed protocol is observed better in terms of achieving high data rates and network throughput, however, it is at the expense of excessive control message overheads in UWSNs.

TABLE 1. Comparison of routing schemes in UWSNs.

Sr.No.	Routing scheme	Static channel	Architecture	PDR	Delay	Energy consumption	Throughput	Congestion	Reliability	Robustness	Convergence
1	MCUW [18]	✓	Flat	✓		✓					
2	DSDBR [13]	✓	Flat	✓	✓	✓					
3	AEDG [19]	✓	Tree	✓	✓		✓				
4	CARP [20]	✓	Flat	✓	✓		✓				
5	EGRCs [21]	✓	Clustering	✓	✓	✓					
6	GEDAR [14]	✓	Flat	✓	✓	✓					
8	LRP [22]	✓	Clustering	✓	✓	✓	✓				
9	ENMR [23]	✓	Flat	✓	✓	✓					
10	AREP [24]	✓	Flat	✓	✓	✓					
11	E-CBCCP [25]	✓	Clustering	✓		✓					
12	EDOVE [15]	✓	Flat	✓	✓	✓					
13	QERP [26]	✓	Clustering	✓	✓	✓					
14	RE-PBR [16]	✓	Flat	✓	✓	✓					
15	SDCS [27]	✓	Hybrid	✓	✓	✓					
16	CACR [28]	✓	Flat	✓	✓	✓					
17	DVOR [17]	✓	Flat	✓	✓						
18	DQELR [29]	✓	Flat	✓	✓	✓	✓				
19	RACAA [30]	✓	Flat	✓	✓	✓					
20	MERP [31]	✓	Clustering	✓	✓	✓		✓			
21	Proposed scheme	✓	Flat	✓	✓	✓	✓		✓	✓	✓

Cross-layer routing mechanisms presented in [20] and [28] mainly focus on the link quality between ASNs during information gathering in UASNs. The performance of both schemes is found remarkable in achieving terms of low latency, EC, and PDR in UASNs. However, the first routing protocol is facing the issues of congestion and data path loops, while the second scheme suffers from high control message overhead issues compared to the first scheme in UASNs. To tackle these issues, the study in [29] discusses a deep Q-network based routing protocol, which takes into account both unicast and broadcast communication mechanisms for energy-efficient and loop-free packet transmission in UASNs. On the contrary, the work in [21] proposed a novel clustering solution for reliable data transmission in UASNs. In the proposed scheme, the entire acoustic sensor network is divided into several small size cubes called clusters. To maintain the data transmission reliability, a cluster leader in each cluster is selected by considering its remaining energy, location, and association with the neighbouring nodes. Likewise, the studies in [22], [25], [26] and [31] also exploited the link quality to route packets over a set of shortest path cluster leaders towards the sink. The simulation results indicate that these routing protocols perform the best in achieving low EC and latency. However, they face some common issues, such as cluster heads scheduling, network stability, corrupted data packets, and high routing table management cost in a highly sparse and dense UWSNs. The research in [27] divides the entire acoustic sensors into the upper layer and lower layer to achieve low EC and packet error rate in UASNs. The work in [23] proposed a color space-based disjoint multipath routing mechanism to greedily forward data packets towards the sea surface sink. The authors in [24] and [30] try to overcome the issues of poor link quality in void regions for reducing the latency and EC of sensors in UASNs. The directional beamwidth based packets forwarding in both routing schemes significantly minimizes the packet error rate, latency, and EC with the expense of packets collision and communication overheads in UASNs. A cross-layer packets forwarding mechanism is proposed in [32] for efficient and reliable data delivery in UWASNs. However, the proposed scheme faces the issues of high energy consumption due to excessive control message overheads in the network. In Table 1, we compare different routing schemes with their unique data forwarding characteristics in UWEs.

All aforesaid routing schemes have been developed with the key aims of providing energy-efficient and reliable packet delivery at low cost in the highly dynamic UWEs. However, most of them face the poor link quality issues and control message overheads during finding or repairing the broken links, which leads to high nodes energy consumption and latency in UASNs. In addition, excessive rerouting due to frequent route failure caused by adaptive shortest paths also brings interference, latency, and increases the chance of packet collision in UASNs. Moreover, the packets forwarding over excessive hop counts by considering the shortest paths also increases the chance of invalid data packets due to path loops in UASNs. Furthermore, it also leads to high congestion and routing table management cost due to quickly draining the batteries of the ASNs in UASNs. Besides, most of them fail to find alternative routes when a link failure occurs and thus losing a significant amount of packets, which contributes to low network throughput in UASNs. All these facts motivate researchers to develop such an optimized routing protocol

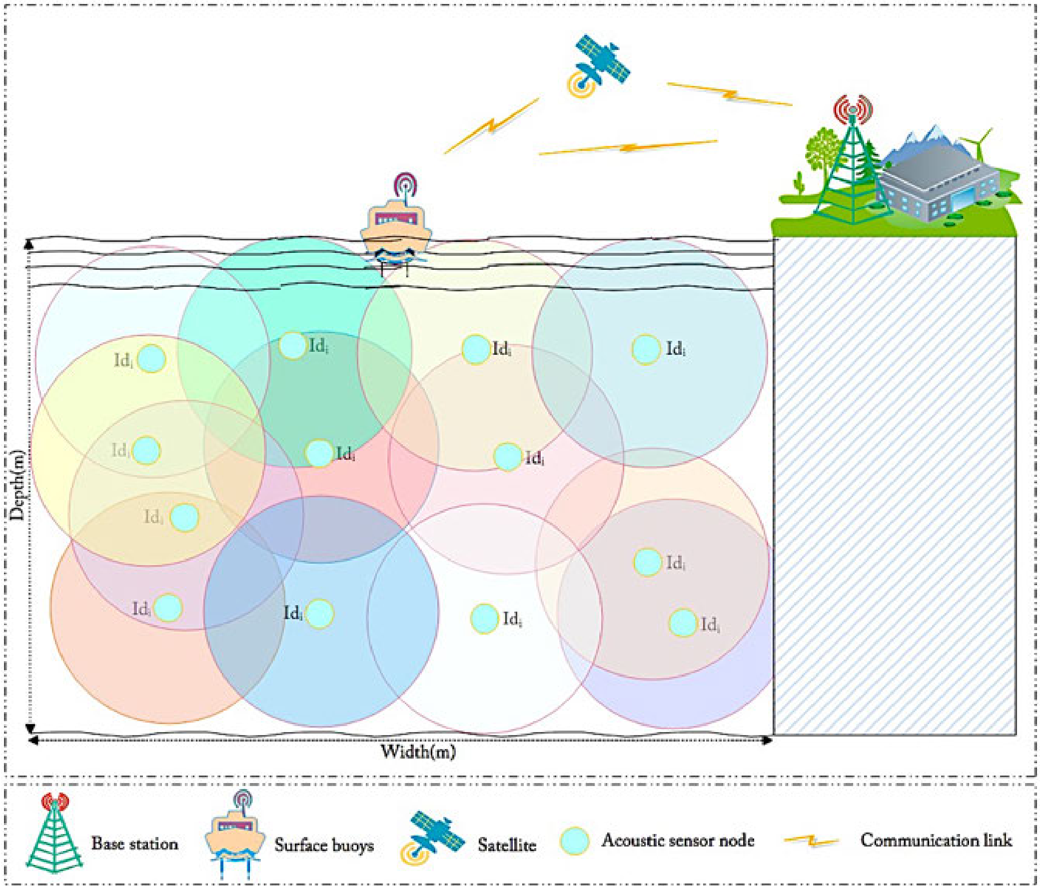

FIGURE 1. Network model in FFRP protocol.

that should based on dynamic firefly mating optimization concept for UWSNs.

III. PROPOSED FFRP PROTOCOL IN UWSNS

The details of the proposed routing scheme are given below.

A. NETWORK MODEL

Figure1 illustrates the network model of the proposed FFRP scheme. The proposed model consists of a set of randomly deployed ASNs embedded with key functions, such as sensing, sampling, and transmitters, a sea surface buoys (sink) and the base station (BS). The acoustic nodes deployed over the ocean bottom in a geographic area of interest are aware of their location, which can be computed using the localization scheme discussed in [33] in UASNs. In addition, the ASNs are equipped with acoustic transceivers and have limited residual energy, asymmetric communication links, and short communication range, and therefore follow a multi-hop packets transmission pattern. Consequently, the routing paths with different lengths have diverse propagation latency in UASNs. In UWEs, each acoustic node has a unique identifying number and this number increases from the bottom towards the sink as shown in Figure 2. Moreover, the ASNs in

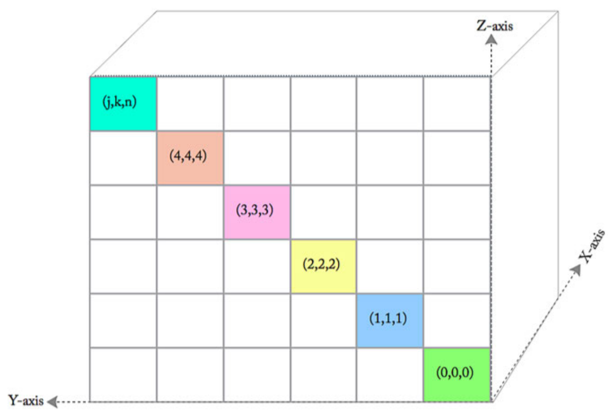

FIGURE 2. Unique identity assignment to ASNs in FFRP protocol.

UASNs have different information angles of departure (AoD) and angle of arrival (AoA), and move in both horizontal and vertical directions with speed around 0 to 1.1 m/min and 0 to 0.7 m/min, respectively. In both directions, this slow movement of ASNs is assumed negligible. We also assume that the sink float on the sea surface and is embedded with a global positioning system (GPS), radio modem and acoustic transceiver in UASNs. The sink by disseminating periodic beaconing periodically updates the base station about its current location in UWSNs. The key aim of the sink is to collect information from the acoustic nodes using acoustic signals and send this information to the offshore base station through radio signals for monitoring and control purposes. The BS acts as an interface between the sink and the user located at a remote location. Consequently, a remote user by using highly stable communication technology (e.g., cellular or satellite) can monitor, configure and control the ASNs in UASNs. Finally, we consider a Carrier Sense Multiple Access (CSMA) mechanism to avoid packet collision in UASNs.

B. BIO-INSPIRED COMPUTING

In the optimization procedure, the best feasible solution of a given problem of interest is constructed which is called a feasible set. Generally, combinatorial and continuous optimization problems are the two main categories of optimization problems. These two optimization methods generally consider a set of discrete variables and continuous variables, respectively. In addition, stochastic and deterministic algorithms are two basic optimization schemes to provide better efficiency for certain problems. The stochastic mechanism explores new regions on a global scale by employing the randomness in its strategies and thus avoid the algorithm being trapped in local optima compared to the deterministic strategy [34]. The final results of this algorithm within a given criterion may be slightly different but often converge to the same optimal results with an additional number of iterations. The stochastic algorithms are modelled based on the biological processes in nature and therefore mostly called meta-heuristic algorithms. The heuristic means lower-level search to discover the fittest solution for survival by trial and error within a search space while the meta-heuristic is a high-level search in which an algorithm is subjective to the particular trade-off between randomization and local search. The randomization procedure helps the solution to avoid being trapped into local optima while the local search continuously progresses until an advanced solution is identified in the problem search space. The exploration and exploitation are two major components in each meta-heuristic algorithm search process. In recent years, several nature-inspired biological algorithms such as genetic algorithm (GA) [35], cuckoo search (CS) [36], firefly algorithm (FA) [37] have been proposed to solve optimization problems. The main advantages of these algorithms include the low probability of entrapment into local modes and faster convergence due to appropriate information-sharing during optimization. The FA algorithm is a class of stochastic nature stimulated meta-heuristic methods that use a type of randomization to search a set of solutions. GA is a popular optimization technique that starts with an initial population, which contains several arbitrarily generated chromosomes by using basic three genetic operators, namely selection, crossover, and mutation. The key aim of the selection operator is to stochastically choose chromosomes with higher fitness values in the mating pool while the crossover operator selects and combines some genes from the chromosomes into the offspring. In the last, some genes of the offspring are changed randomly by employing the mutation operator in the evolution process. This entire evolution procedure is repetitively executed till one of the ending conditions is encountered such as the elite solution is not found for a defined number of iterations, the maximum iteration number is reached or the chromosomes percentage is the same in the population.

C. DYNAMIC FIREFLY MATING OPTIMIZATION

In nature, the fireflies are social animals, mostly discovered in the tropical regions. The fireflies live on the branches of the trees and lay eggs on the ground around the trees. The very appealing feature of the fireflies is their light blaze emitting at regular intervals from their abdomens through chemical reactions called bioluminescence in their bodies. This light flash signal has many purposes, such as attract mating partners, warn potential predators, luring preys, and communication with the neighboring fireflies. The female fireflies in the breeding season discharge pheromones into the air, which are carried away in the direction controlled by the wind. These pheromones are the signals to male fireflies their readiness to mate. The male fireflies approach the females by following the pheromone trail in the downwind direction. The female releases more pheromones have more opportunity to attract males to mate. Then, the males fly around and flash courtship signals to the females' perch on the trees. The females are attracted to males who release brighter flashing signals. The flashing light signals follow physical rules and therefore the light intensity decreases as the distance between fireflies increases. Thus, the brighter male receives mating responses from the females by observing the flashing of their lights. The mating rounds take place until the female spermatheca capacity is achieved or the males run out of semen in their semen reservoir. The fittest male sperms are most probably to be picked to inseminate a female's eggs. However, this entire mating process cannot be implemented directly since it does not provide guaranteed information exchange between neighboring acoustic sensor nodes in the harsh nature UWEs. There are several issues, first, it is highly possible that the female mates several times with a single male until her spermathecal is full, which does not provide a set of alternative solutions. Second, it is also possible that a female mate with several males with the poor or incomplete exchange of sperms, which is leading to high diversity in the solutions. Third, due to lack of memory intelligence, the fireflies fail to optimize solution in a robust manner. Fourth, the traditional single point genetic operators cannot provide the best solution due to poor exchange of genome in the mating process. In addition, the flying speed and previous mating history of the fireflies, and blocking of sperms of a male with poor fitness values further increase the robustness and reliability of mating optimizing to search optimal solutions in the given problem search space. Therefore, it is highly required to modify the existing fireflies mating optimizing algorithm by embedding these features in the mating model before employing for data collection in UWSNs. This will avoid algorithm falling into local optimum and thus obtains high precision results during data gathering in UWSNs. Consequently, the existing fireflies mating optimizing algorithm [38] has been modified by considering aforesaid factors to provide reliable optimal routing solutions in UWSNs. Considering the properties of the fireflies, the key objective function of our proposed scheme numerically can be indicated as

$$\phi_{FFR} = max \sum_{i=1}^{|n|} \left(P_{dr} + T_p + R_b + S_b\right)^i + min \sum_{i=1}^{|n|} \left(D_e + E_c\right)^i \quad (1)$$

In the proposed scheme, the dynamic firefly mating optimization algorithm based on the characteristics and flashing patterns of the real fireflies can be summarized based on the following rules as

- In the beginning, the algorithm is initialized using a random number $r \in [0, 1]$. Then, the entire firefly population $P(F) = \left(M(F_i) + F(F_j)\right)$ is is divided into two subgroups, namely male fireflies $M\left(F_i\right) = \left(M(F_1), M(F_1), \ldots, M\left(F_n\right)\right)$ and female fireflies $F\left(F_j\right) = \left(F(F_1), F(F_2), \ldots, F\left(F_n\right)\right)$. In the n dimensional N_{dim} search search space each firefly within the lower bound L_b and upper bound L_u can be be randomly initialized using the formula is as follows

$$F_j = \int_{L_b}^{L_u} \left[L_b + rand\left(L_u - L_b\right)\right] \quad (2)$$

  In this bounded search space, the separation $\left(S_{ep(i)}\right)$ and cohesion $\left(C_{oh(i)}\right)$ of individual firefly to the neighbors in each iteration can be numerically written as

$$S_{ep(i)} = -\sum_{j-1}^{nb} P_i\left(F_i\right) - P_j\left(F_j\right) \quad (3)$$

$$C_{oh(i)} = \left(\sum_{j-1}^{nb} \frac{P_j\left(F_j\right)}{nb}\right) - P_i\left(F_i\right) \quad (4)$$

  in which nb is the sum of neighboring fireflies in the vicinity. It's worth noting that the F_i is a neighbor of F_j only if the distance between F_i and F_j is less than the defined maximum distance and vice versa.
- Second, all fireflies attract other fireflies regardless of gender differences since they are unisex. Thus, a male firefly $M\left(F_j\right)$ senses and chooses a female firefly $F\left(F_i\right)$ based on her released pheromone $\varkappa$ belongs to 0 and 1 which changes with the wind speed $\left(W_s\right)$ and direction $\left(W_d\right)$, which can be numerically indicated as

$$M\left(F_i\right) = F(F_j)_{\varkappa} + W_s + W_d\left(5\right) \quad (5)$$

- Third, the light intensity of firefly is affected when it passes through the medium and can be determined by the objective function. Only the dimmer firefly moves to the firefly that is brighter and attractiveness is proportional to their brightness which decreases as their distance increases. However, the firefly will move randomly if there is no brighter firefly than a given firefly. Consequently, the intensity of light $\left(L_I\right)$ changes over distance $\left(d\right)$ exponentially and monotonically can be numerically indicated as

$$L_I = L_{I(0)} e^{-\sigma d^2} \quad (6)$$

  The attractive coefficient $\left(L_a\right)$ due to the firefly's light intensity at a given distance $d = 0$ can be computed as

$$L_a = L_{a(0)} e^{-\sigma d^2} \quad (7)$$

  The distance between two fireflies F_i and F_j located at position P_i and P_j is measured in Eq.8, as shown at the bottom of the next page. Consequently, the position updates formula of the firefly F_i fly towards the firefly F_j based on the emitted light can be written in Eq.9, as shown at the bottom of the next page. In which σ, N_{dim}, and S_f show the light absorption parameter, the number of dimensions and the fixed step size factor belongs to $r \in [0, 1]$, respectively. After the transition from positions P_i to P_j, the male firefly's speed (S) and energy (E) at time (t) can be numerically indicated as

$$S\left(t+1\right) = \partial + S\left(t\right) \quad (10)$$
$$S\left(t+1\right) = E\left(t\right) - E_r\left(t\right) \quad (11)$$

  in which ∂ is a factor belongs to $[0, 1]$ and indicates reduction in energy after each transition from the total remaining energy at time t.
- Fourth, each firefly is using its dual-sensing antennas senses the existing of a predator in the vicinity. The disruption outwards an enemy of firefly individual represented by $\left(D_o\right)$ as

$$D_o = P_i\left(\xi_i\right) + P_j\left(F_j\right) \quad (12)$$

  In which ξ_i is the potential enemy located at a position P_i to the firefly F_j positioned at P_j.
- Fifth, the mating process repeatedly occurs until the female spermathecal is full during mating at least once and most twice with each brighter male to produce efficient offspring for the next generation in the habitat. During the mating process, the male firefly updates its position guided by the best female firefly $\left(F\left(F_j\right)_{best}\right)$

can be numerically indicated as

$$M\left(F_i\right)^{t+1} = M\left(F_i\right)^{t} + L_a \times r\left(F\left(F_j\right)_{best}^{t} - M\left(F_i\right)^{t}\right) \tag{13}$$

By adding the distance f function parameters for the intensity of light for both male and female butterflies moving towards each other eq.13 can be numerically indicated as

$$M\left(F_i\right)^{t+1} = M\left(F_i\right)^{t} + d_1\left(L_I\right)\left(F\left(F_j\right)_{best}^{t} - M\left(F_i\right)^{t}\right) \tag{14}$$

$$F\left(F_i\right)^{t+1} = F\left(F_i\right)^{t} + d_2\left(L_I\right)\left(M\left(F_j\right)_{best}^{t} - F\left(F_i\right)^{t}\right) \tag{15}$$

where

$$d_1\left(L_I\right) = \begin{cases} 1, & f\left(d_{\left(F_j\right)_{best}^{t}}\right) < f\left(d_{M\left(F_i\right)_{best}^{t}}\right) \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

$$d_2\left(L_I\right) = \begin{cases} 1, & f\left(d_{M\left(F_i\right)^{t}}\right) < f\left(d_{F\left(F_j\right)_{best}^{t}}\right) \\ 0, & \text{otherwise} \end{cases} \tag{17}$$

Thus, the number of best selected female fireflies by the male fireflies in the given search space can be numerically indicated as

$$F\left(F_j\right)_{best} = \left[F\left(F_j\right)_{best}^{1} + F\left(F_j\right)_{best}^{2}, \ldots, F\left(F_j\right)_{best}^{n}\right] \tag{18a}$$

he male fireflies with fittest sperms are allowed to mate with the interested female at most twice compared to the males with lower fitness values. The key aim is to reduce the mating time, computation complexity and energy consumption by avoiding males with lower fitness values in the search space. During the mating process, each female keeps the sperms of mating males which can be numerically indicated as

$$F\left(F_i\right)S_{c\left(i\right)} = \begin{bmatrix} S_{c(1)} \\ S_{c(2)} \\ \vdots \\ S_{c(n)} \end{bmatrix} \tag{18b}$$

$$S_{c(j)} = \left[S_j^1, S_j^2 \ldots, S_j^n\right] \quad j = 1, 2, \ldots, N_{sperm} \tag{18c}$$

in which N_{sperm} is the total number of sperms in the spermatheca and $E_{enr}\left(F_i\right)$ is the energy used in finding an appropriate female firefly for mating in the system. Unlike existing schemes, we use random arithmetic crossovers (CO) with probability 0.97 and 0.98 between two parents (P^1, P^2) and three parents (P^1, P^2, P^3) to increase the diversity in the population as

Two parents:

$$P^1 = \left(P_1^1, P_1^2, \ldots, P_k^1\right) \text{ and } P^2 = \left(P_1^1, P_1^2, \ldots, P_k^1\right) \tag{18d}$$

Two offspring:

$$OS^1 = \left(OS_1^1, OS_2^1, \ldots, OS_k^1\right) \text{ and } \quad OS^2 = \left(OS_1^2, OS_2^2, \ldots, OS_k^2\right) \tag{18e}$$

such that

$$OS_i^1 = \lambda P_i^1\left(1 - \lambda\right)P_i^2 \tag{18f}$$

$$OS_i^2 = \lambda P_i^2\left(1 - \lambda\right)P_i^1 \tag{18g}$$

and three parents

$$P^1 = \left(P_1^1, P_2^1, \ldots P_k^1\right), \quad P^2 = \left(P_1^2, P_2^2, \ldots P_k^2\right), \quad P^3 = \left(P_1^3, P_2^3, \ldots P_k^3\right) \tag{18h}$$

Three offspring:

$$OS^1 = \left(OS_1^1, OS_2^1, \ldots, OS_k^1\right), \quad OS^2 = \left(OS_1^2, OS_2^2, \ldots, OS_k^2\right) \text{ and } \quad OS^3 = \left(OS_1^3, OS_2^3, \ldots, OS_k^3\right. \tag{18i}$$

$$CO_i^1 = OS_i^1 + \lambda \times \left(OS_i^2 - OS_i^3\right) \tag{18j}$$

$$CO_i^2 = OS_i^2 + \lambda \times \left(OS_i^3 - OS_i^1\right) \tag{18k}$$

$$CO_i^3 = OS_i^3 + \lambda \times \left(OS_i^1 - OS_i^2\right) \tag{18l}$$

For $\lambda \in [0, 1]$. The crossover method by altering genes between different parents at distinctive locations generates a new chromosome better than the parents. Then, the mutation operator is applied at multi-points with the probability between 0.01 and 0.05 in order to keep the diversity in the solution, which helps the scheme to avoid local optimum problems in the search space. The mutation method (MO) swaps the genes at different points between chromosomes, randomly. The can be numerically indicated as

$$MO^1 = OS_i^1 + \lambda \times \left(\overset{\cdots}{OS_1^3}, \widehat{OS_2^2}, \ldots, OS_4^1, \ldots, OS_k^1\right) \tag{18m}$$

$$d_{(F_i,F_j)} = ||P_i\left(F_i\right) - Pj\left(F_j\right)||^2 = \sqrt{\sum_{k=1}^{N_{dim}}\left(P\left(F_i\right)_k - P\left(F_j\right)_k\right)^2} \tag{8}$$

$$P\left(F_i\right)^{t+1} = P\left(c\right)^{t} + L_a\left(\left(F_j\right)^{t} - \left(F_i\right)^{t}\right) + S_f\left(r - 0.5\right) \tag{9}$$

$$MO^2 = OS_i^2 + \lambda \times \left(OS_1^2, \widehat{OS_2^1}, \ldots, \overline{OS_4^3}, \ldots, OS_k^2\right) \tag{18n}$$

$$MO^3 = OS_i^3 + \lambda \times \left(\overset{\cdots}{OS_1^1}, OS_2^3, \ldots, \overline{OS_4^2}, \ldots, OS_k^3\right) \tag{18o}$$

Consequently, the fitness of each firefly is measured as

$$fit_j^t = \frac{fit_i^t}{\sum_{j=1}^{n} fit_j^t} \tag{18p}$$

Then, the fittest firefly for the next generation $(g+1)$ is elected from the existing solution (g) to reduce the search problems, is indicated as

$$\left(F_i\right)^{g+1} = \begin{cases} F_i^{g+1}, if \left(F_i\right)^g < fit\left(F_i\right)^{g+1} \\ F_i^g, \text{otherwise} \end{cases} \tag{18q}$$

After sorting, the mating history of the female firefly with various firefly males from the best to the worst in decreasing manner is shown as

$$worst^t = \min_{j \in \left[k=j=1,2,\ldots,N_{sperm}\right]} fit_j^t \tag{18r}$$

$$best^t = \max_{j \in \left[k=j=1,2,\ldots,N_{sperm}\right]} fit_j^t \tag{18s}$$

Thus, each female firefly mates with the brighter and dimmer males keep history for a particular time, which is used in the next round of the mating process.

D. TERMS AND CONCEPTS USED IN INTERFACING AND IMPLEMENTATIONS

In this section, the working principle of the proposed dynamic firefly mating optimization scheme is mapped with the acoustic sensors in the UWEs. In the proposed scheme, the habitat or tropical zone indicates the undersea area where the acoustic sensor nodes are randomly deployed for monitoring events in UWSNs. The fireflies are social animals means that the acoustic sensor nodes are equipped with the communication, processing and autonomous decisions making capabilities in the UWEs. The fireflies are the acoustic nodes, which are divided into two types, namely male fireflies and female fireflies. The male firefly is an acoustic node that requires some sorts of information to reach the destination in UWSNs. On the contrary, the female firefly is an acoustic node, which keeps the required information and may act as a forwarding node towards the destination in UWSNs. The flashlight indicates the strength of the transmitted acoustic signals between acoustic nodes in the UWEs. The strength of the signals decreases as the distance between the source and destination increases in the network. During the initialization, the information of the neighboring acoustic sensors is stored in the memory table of each acoustic node in the network. In the mating process, the male's flash light-emitting illustrates that an acoustic node that requires information sends a request message to the associated acoustic node. On the other hand, the female's flash light-emitting shows that the acoustic node may have the required information and replies to the sender node by sending a reply message in the network. The female spermatheca capacity is the memory size of a female to stored received information while the male's sperm indicates the amount of information is sent by an acoustic node to the associated sensor node during the coupling process. The size of memory is set to constant for all acoustic nodes in UWSNs. The resources of the firefly consumed during following an interested firefly indicate that a significant sum of energy is spent during the sensing, sending and receiving information. The forwarding sensor node energy consumption depends on the transmission distance between sender and receiver in the network.

Generally, the transmission energy consumption of a packet is high as compared to the energy consumed during receiving a packet in the acoustic sensor networks. The effect of the wind direction on a firefly means that the movement of the seawater, which may affect the transmission between acoustic nodes in the UWEs. In the entire evolutionary process, the received information of the requested sensor is computed by applying genetic operators at the receiver node to find the best next-hop towards the destination in the network. Then, the resultant information is broadcasted to the neighboring nodes so that each node receives this information saved it in its memory table with decreasing priority. The information stored with high priority indicates the flashlight brightness is used during the communication process in the network. The requested acoustic node based on this information communicates with the desired acoustic node that acts as a brighter firefly with the most accurate information compared to others in the network. In the mating process, a female firefly is avoided to mate several times with a single male means that a relay node is restricted to communicate multiple times with the distinct single node in order to avoid node's buffer overflow problems. Only, the requested nodes with appropriate information are allowed to mate with the particular sender nodes at least once and at most twice in the network. Thus, the information sharing between the best acoustic nodes multiple times provides a set of alternative solutions to the destination. On the other hand, this mechanism avoids algorithm to fall into local optima since the nodes with poor information are prohibited to mate multiple times, which in turn leads to obtain high precision results during data gathering in UWSNs. Besides, this mechanism further increases the robustness and reliability of the information sharing process for finding optimal solutions in the given problem search space. The entire aforesaid mechanism helps proposed scheme to avoid falling into local optimum and therefore it obtains high precision data gathering results in UWSNs. The following sections explain the entire data collection mechanism in UWSNs.

E. PACKETS FORWARDING IN FFRP

In the FFRP scheme, the network initialization process is similar as discussed in [26]. In the network initialization process, each ASN constructs an information table of the

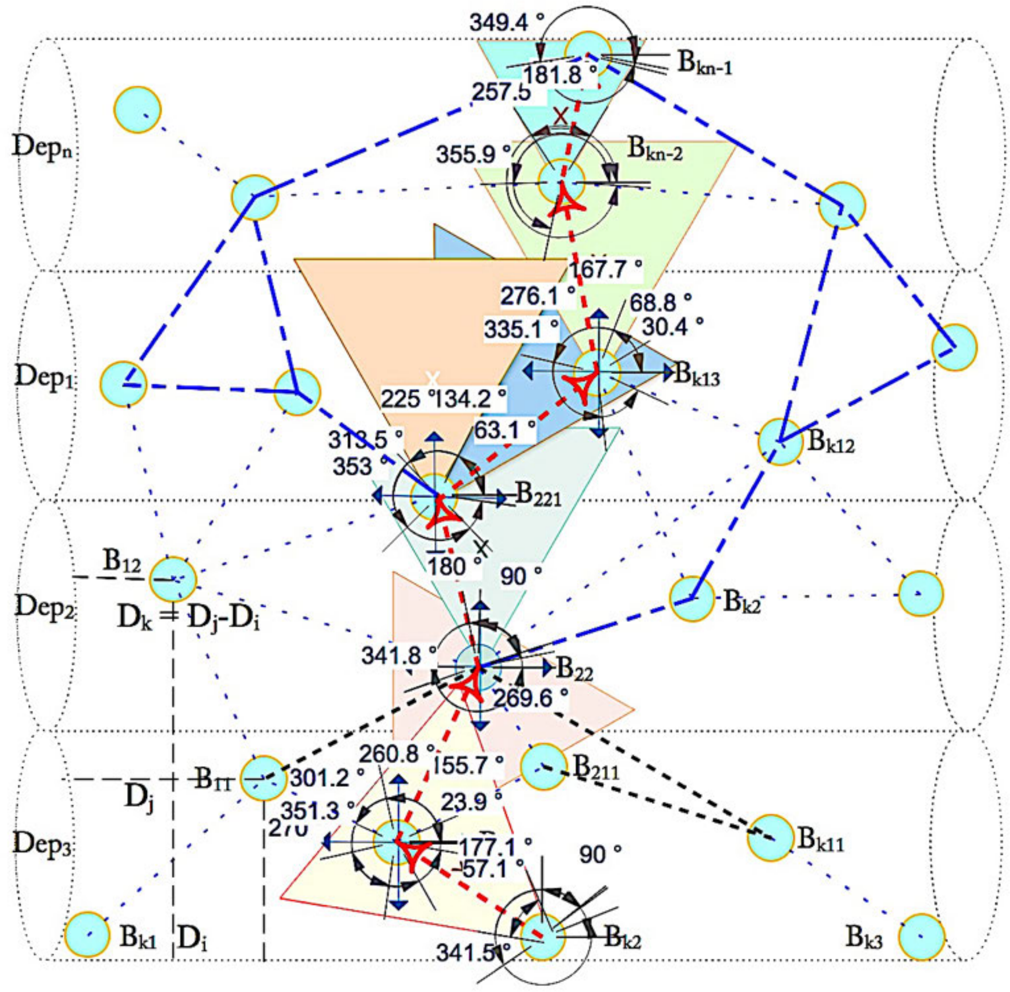

FIGURE 3. Routing in FFRP protocol.

neighbouring ASNs in UASNs. In the route discovery process, a source node has packets to convey, initiates the route construction process by sending a route discovery message (rd_{msg}) to neighbouring ASNs in UWSNs. The (rd_{msg}) message contains information like sender ASN level number, identity, remaining energy (RE), AoA and AoD and distance to the sea surface sink. This level information depends upon the distance between the ASN and the sink. The sensor node level is marked n only if it directly receives the packets from the sink. The value of this level number is decreasing periodically for the ASNs located in the downward direction like $n-1$, $n-2$, etc., and approaches to 0 as depicted in Figure 3. After successfully receiving the rd_{msg} request message, each receiver acoustic sensor updates its local records of the sender in the routing table. Then, it replies to the sender by sending a $(reply_{msg})$ message containing the information, such as its level number identity, remaining energy, AoA and AoD and distance to the sea surface sink. The receiver ASN after receiving the $(reply_{msg})$ message successfully updates the sender information and assigns a unique priority in decreasing order in its local routing table. The value of the sender node level is set to 0 only if it is located at the same or lower level of the receiver node, otherwise is 1, which indicates that the sender is closer to the sink. The acoustic sensors located at the same level to the source node are called guide nodes or helper nodes and usually have a lower priority in the routing table. Generally, an acoustic node with high-level value, RE, lower AoD and distance to the neighbouring nodes and the sink has high priority in the routing table. Consequently, each ASN updates its routing table with the recent information and sets the priority value of the neighbouring ASNs in both downwards and upwards direction in UASNs. Then, each source node selects the best next-hop relay node based on its high priority to convey data towards the sink. After selecting the best forwarder, it sends a $(readydata_{msg})$ message to the potential forwarder towards the sink. The key aim of this message is to inform the relay node about the arrival of the sender's data in UASNs. Subsequently, this entire process repeats at each relay node until the entire data of the source node is forwarded to the sink. In a case, if a suitable relay node is not found with the highest priority in the transmission range, then the source ASN selects a forwarder with lower priority in the routing table.

During the data forwarding process, it is possible that an acoustic sensor due to conveying a huge amount of events data may suffer from packet overflow problems along a particular routing path in UASNs. Therefore, we also add a new parameter after a predefined iteration, namely buffer overflow time of each relay node in the priority list to avoid congestion in UASNs. Consequently, each relay node periodically monitors its buffer occupancy level to prevent the congestion occurrence in UASNs. The congestion avoidance process starts if the buffer occupancy exceeds a defined threshold level. The key aim of the congestion avoidance process is to inform the sender node by sending a congestion occurrence $(cong_{msg})$ message to divert the data traffic to other neighbouring relay nodes as indicated by blue lines in Figure 3. The entire procedure extremely minimizes the overall packet loss rate and thus contributes to the high PDR and throughput in UASNs. Finally, the sink after successfully receiving the data sends a $ackn_{msg}$ message to the sender, which must be delivered to the source node in UASNs. After receiving $ackn_{msg}$ message, the receiving node looks into the routing table and marks itself as a reverse relay node candidate only if it was the packets forwarder along a distinct routing path towards the sink. In this way, the reverse route construction information is propagated at each downstream forwarders located on the lower levels until the $ackn_{msg}$ message is delivered to the source node in UASNs. This procedure finds guaranteed reverse routing path from the sink towards the source node in the network. Thus, each relay node in the proposed scheme is responsible to manage two tables in an upwards and in a downwards direction containing the best forwarding nodes with high priority. At this stage, each ASN knows its forwarding neighbors and the routing path length in an upwards and in a downwards direction in UASNs. In addition, in this entire process if an acoustic node receives similar messages more than once from the same sender acoustic node then it replies once and rejects the others. The mathematical modeling of our proposed scheme by following the objectives discussed in above Eq.1 can be explained as

$$\forall R \wedge K \in link\left(L\right) = \left[1, 2, \ldots, n\right] \tag{19}$$

$$\sum_{k \in K} X_{DP_i\left(ij\right)} = 1, \quad \forall j \in N, \ \forall j \in R \tag{20a}$$

$$\sum_{k \in K} X_{DP_i\left(jk\right)} = 1, \quad \forall i \in N, \ \forall j \in R \tag{20b}$$

$$\sum_{k \in R} X_{DP_i\left(jk\right)} = \sum_{j \in R} X_{DP_i\left(jk\right)}, \forall i \in N, \forall j \in R \tag{20c}$$

$$\sum_{k \in P} P_k W_{jk} \leq Y, \quad \forall i \in N, \ \forall j \in R \tag{20d}$$

$$\sum_{k \in D} d_k W_{jk} \leq Y, \quad \forall i \in N, \ \forall j \in R \tag{20e}$$

$$\sum_{u \in K \cup N} \left(X_{DP_i\left(ku\right)} + X_{DP_i\left(uk\right)}\right) - W_{jk} \leq 1, \quad \forall k \in K \tag{20f}$$

$$\sum_{k \in K} W_{jk} = 1, \quad \forall i \in N \tag{20g}$$

$$\sum_{k \in P} P_k W_{jk} = \sum_{k \in P} div_k W_{jk}, \quad \forall\, i \in N, \ \forall\, j \in R \tag{20h}$$

$$\sum_{k \in K; i \in N} X_{DP_i\left(jk\right)} \leq q, \quad \forall\, j \in R \tag{20i}$$

$$\sum_{j \in R; k \in K} P_k X_{DP_i\left(jk\right)} \leq Q, \quad \forall\, i \in N, j \neq k \tag{20j}$$

$$\sum_{j \in R; k \in K} div_k X_{DP_i\left(jk\right)} \leq Q, \quad \forall\, i \in N, j \neq k \tag{20k}$$

$$\sum_{j \in R; k \in K} \left(t_{jk} + Sn_i\right) X_{DP_i\left(jk\right)} \leq T, \quad \forall\, i \in N, j \neq k \tag{20l}$$

$$\sum_{j \in R} \left(t_{jk} + \ell_{j\left(DP_i\right.}\right) X_{DP_i\left(jk\right)}, \quad \forall\, i \in N, \ \forall\, k \in K \tag{20m}$$

$$H_{sd} = \min \sum_{t \in T} \sum_{(j,k) \in L} X^t_{DP_i\left(jk\right)} \times H_{jd} \leq H_{max}, \quad \forall\, t \in T \tag{20n}$$

$$d_{jk} = d\left(j, S_{ink}\right) - d\left(\left(k\right)_{relay}, S_{ink}\right) \leq 1, \quad \forall k \in K \tag{20o}$$

$$d_u S_{ink} = d\left(F_{relay\left\{\left((j,k) \subseteq n\right)\right\}}\right) \leq d_{max} \tag{20p}$$

$$d_u S_{ink} = d \times F_{relay_{(n)}} \in Up_{stream} \tag{20q}$$

$$0 \leq \rho_{b\left(pd(i)\right)} < 1 \tag{20r}$$

$$\sum_{j \in R; k \in K} X_{DP_i\left(jk\right)} \left(sd\right) \leq 1, \quad \forall\, i \in N, j \neq k \tag{20s}$$

$$\sum_{j \in R; k \in K} X_{DP_i\left(jk\right)} \left(ds\right) \leq 1, \quad \forall\, i \in N, k \neq j \tag{20t}$$

$$\sum_{j \in R; k \in K} d_{jk} X_{DP_i\left(jk\right)} < \infty, \quad \forall\, i \in N, j \neq k \tag{20u}$$

$$\sum_{j \in R; k \in K} d_{jk} X_{DP_i\left(jk\right)} < \infty, \quad \forall\, i \in N, k \neq j \tag{20v}$$

$$P_t \times X^t_{DP_i\left(jk\right)} \leq P_{t\left(maxi\right)} \quad \forall i \in N, \ \forall j \in R, \forall k \in K \tag{20w}$$

$$\sum \left(j, k\right) \in LD_{jk} \times X^t_{DP_i\left(jk\right)} \leq D_{min}, \tag{20x}$$

$$\forall i \in N, \quad \forall j \in R, \ \forall k \in K. \forall t \in T \tag{20y}$$

$$X^t_{DP_i\left(jk\right)} \in \left\{0, 1\right\}, \quad \forall j, k \in L, \ \forall t \in T \tag{20z}$$

Constraints in (20a) and (20b) state that the link between source node i and destination node k along a routing path will remain the same in the network. Thus, the data packets (DP_i) will be continuously forwarded over a chosen routing path to a forwarding node runs out of its energy or congestion or link quality issues. Constraints in (20c) express that the data packets over a link between the source node i

and destination node k must visit the same number of nodes in both upward and downward direction over a data path in UWSNs. Constraints in (20d) and (20e) indicate that the resource limitations of the acoustic relay sensor nodes along a data route in UWSNs. Constraints in (20f) express that the data packets are forwarded to the acoustic sensor node u only if it is associated to the routing path in UASNs. Constraints in ((20h) are supporting constraints, which assures that each data packet pickup from the source node or delivery to the destination node, is only serviced by the relay node that is linked to a particular routing path in UWSNs. Constraints in (20g) show that the total packets received by the destination node (P_k) over a distance d_k from the source node j must be equal to the total number of packets forwarded to the next hop node, which guarantees there is no holding inventory. In (20i), the constraints show that there are at most q number of relay nodes in every routing path in UWSNs. Constraints in (20j) and (20k) are the data capacity limitation (Q) of each acoustic sensor node in the network. In (20l), the constraints show that the total time spent by a data packet over a routing path consists of a set of relay nodes (t_{jk}) should be less than or equal to the maximum defined time T. In (20m), constraints represent that the leaving time of a data packet $\left(\ell_{j(DP_i)}\right)$ from a forwarding node j to the receiving node k over a link jk should be equal and the time needed to travel from j to k. Constraints in (20n) verify the number of forwarding hops along a data route. The number of forwarding hops over a data route should equal or less than the defined maximum number of relay nodes in the network, which support the constraints in (20i). In (20o), constraints verify that the distance d of a relay node k in single-hop packet progress is always less than the sender node j towards the sink. In (20p), constraints ensure that the distance of a relay node is less or higher than the predefined minimum distance d_{max} and d_{min} in UASNs.

In (20q), constraints guarantee that during the packet transmission process, the minimum and maximum distance are bounded in upward directions UP_{stream} towards the sea surface sink. However, the downwards links (denoted by black colour lines) during forwarding packets in upwards direction are prohibited as shown in Figure 3. Thus, these constraints verify the constraints in (20i) and (20n). The congestion indicator values varies between 1 and 0 for each ASN in UWSNs. In (20r), constraints guarantee that the congestion is avoided along a routing path by setting the congestion indicator value (CIV) of each forwarding node lower than 1 in UASNs. In other words, the CIV of each relay node always must be lower than 1 in order to prevent data packet loss due to buffer overflow in UASNs. Consequently, the constraints in in (20s) and (20t) guarantee that there is no cycle in the routes between the source and destination in the network. In (20u) and (20v) constraints ensure that the packets forwarding cost between the source and the destination along a routing path is not infinite. Thus, these constraints verify and support the constraints in (20s) and (20t). Hence, it is guaranteed that forbidden routes will not be the part of the final routing solution in the network. In (20w), the constraints guarantee that the transmission power (P_t) of a packet transmission should not be higher than the predefined maximum value $P_{t(maxi)}$ in the network. Constraints in (20x) assure that the delay to reach a data packet from the source node to the destination node along a selected routing path should not be more than the predefined value of the threshold in UWSNs. The constraints in (20y) are supporting equation (20x). Similarly, the constraints in (20z) state that the delay is set to 1 if the delay constraint of the data packets is satisfied, otherwise is 0. In addition, the terms $X_{DP_i(ij)}, Y, W_{jk}, p_k$ and div_k are, the data packet (DP_i) passes through the link (ij) or (jk) is 1, otherwise 0, the max capacity of each relay acoustic node along a routing path, the next-hop relay node k is used is used to satisfy the request of an acoustic sensor node j is 1, otherwise 0, the number of packets load quantity in pickup acoustic sensor node k, and the unloading quantity in delivery node k in the network.

IV. SIMULATION MODEL

In our study, the path loss [39] is calculated as

$$10 \log A(d,f)/A_o = k \times 10 \log d + d \times 10 \log a(f)^d \quad (21)$$

The absorption coefficient $a(f)$ using the Thorp's formula [40] is given as

$$10 \log a(f) = \frac{0.11 \times f^2}{1+f^2} + \frac{44 \times f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \quad (22)$$

The noise originated from site-specific and ambient sources in the ocean can be modelled using four factors, namely thermal noise (N_{th}), turbulence (N_t), waves (N_w) and shipping (N_s) as in (23), as shown at the bottom of the next page, in which, the wind wi is in m/s and the shipping s is ranging from 0 to 1 indicating the light to dense in the UWEs. Thus, the signal to noise ratio (SNR) of an emitted acoustic signal at the receiver acoustic sensor node is computed as

$$SNR = SL - A(d,f) - N(f) + DI \geq SINR_{th} \quad (24)$$

The factors transmission loss $A(d,f)$ and noise level $N(f)$ are functions of the distance d and frequency f. In UWEs, the average signal to noise ratio (SNR_{avg}) of an emitted underwater signal over distance d is computed as

$$SNR_{avg}(d) = \frac{E_b/A(d,f)}{N_o} = \frac{E_b}{N_o d^k a(f)^d} \quad (25)$$

in which $SNR_{th}, DI, SL, N_o, E_b$ and k are, the decoding threshold, the directivity index, the source level, and constants indicate that the noise power density, the average transmission energy per bit in a non-fading additive white Gaussian noise channel, and the spreading factor with values $k = 1$ for cylindrical spreading and $k = 2$ for spherical spreading, respectively. In Eq. (26), the SL is related to $I_t(\mu Pa)$ and $1m$ apart from the source can be computed as

$$SL = 10 \log \frac{I_t}{1 \mu Pa} \quad (26)$$

Generally, the spreading factor is used to illustrate the geometry of propagation for a practical scenario in the UWEs. Solving Eq. (26), the intensity of the transmitted signal (I_t) is computed as

$$I_t = 10^{\frac{SL}{10}} \times 0.67 \times 10^{-18} \quad (27)$$

In UWEs, acoustic channel bandwidth highly relies on radio frequency, transmission distance and transmission power. Thus, the transmitted signal power P_t at a distance of $1m$ to achieve the intensity of a transmitted acoustic signal at the receiver acoustic sensor node is computed as

$$P_t = 2\pi \times I_t \times H \quad (28)$$

Consequently, the low and high energy consumption during sending and receiving data size K bits for a small distance d_s and large distance d_l can be computed as

$$E_{T_x}(k, d_s) = E_{elec} \times k + E_{amp} \times k \times d^2 < d_0 \quad (29)$$

$$E_{T_x}(k, d_l) = E_{elec} \times k + E_{amp} \times k \times d^4 \geq d_0 \quad (30)$$

$$E_{R_x}(k) = E_{elec} \times k \quad (31)$$

in which the constant converts μPa to W/m^2 while H is the depth of the ocean in meters, d_0 is the threshold distance of the acoustic nodes and, E_{elec} and E_{amp} are the power consumptions of the received E_{R_x} and transmitted signals E_{T_x} in UWEs, respectively. To compute the probability of bit error $P_{b(error)}$ over distance d by employing binary phase shift keying modulation is computed as

$$P_{b(error)}(d) = \frac{1}{2}\left(1 - \sqrt{\frac{SNR_{avg}(d)}{1 + SNR_{avg}(d)}}\right) \quad (32)$$

Thus, the packets delivery probability of a packet with size k bits with distance d for any pair of nodes can be computed as

$$P_b(d, k) = \left(1 - P_{b(error)}(d)\right)^m \quad (33)$$

In the experimental studies, we employ the most common energy consumption model presented in [41]–[45] to evaluate the performance of FFRP against MERP [31], LRP [22] and QERP [26] schemes in UASNs. These routing schemes are implemented using network simulators called NS2 and AquaSim 2.0 in random network topologies to simulate the continuous events monitoring in UASNs. Table 2 shows the rest of the simulation parameters and their values in UASNs.

TABLE 2. Parameters and their values used in FFRP.

Parameters	Value
Simulator	NS2 and AquaSim 2.0
Channel	Underwater channel
Network topology	Random
Deployment area	$1000\times1000 \times 500m^3$
Initial energy of the ASN	100 Joules (J)
Initial energy of the sink	100 kilojoules (kJ)
Node density	300
Number of female fireflies	85
Number of male fireflies	225
Male mating with the same female	1 time
High transmission power	1.6 Watts (W)
Low transmission power	1.2 W
Reception power	0.70 W
Idle power	0.12 W
Data aggregation power	0.35W
Transmission range of ASN	120 meters (m)
Communication range of the sink	150 m
Spreading values	1.5
Frequency	40 kilohertz (kHz)
Maximum Bandwidth	35 Kbps
Packet size	30 bytes
Size of a control packet	5 bytes
Rate of packets generation	0.01 packets/s
Memory size	6 MB
Average ocean depth	I mile (1.6km)
Direction of antenna	360 degrees
Location of sea surface buoys	middle
Simulation time	130 seconds
Maximum number of iterations	55

V. PERFORMANCE ANALYSIS

This section analyzes and compares the performance of various routing protocols for UWSNs. In the experimental studies, we observed that when the interference is low around 13%, the PDR in FFRP, MERP, LRP and QERP schemes is increasing rapidly in UWSNs. In fact, this low interference does not affect the transmission of the packets and thus result in high data reception rate for MERP, QERP and LRP schemes around 93.4%, 92.6%, and 91%, respectively, in the first 40 seconds. However, the PDR decreases rapidly over time when the interference level increases from 13% to 35% in UWSNs. Consequently, the average packets reception rates rapidly decreased up to 90%, 91.3%, 91.9% for LRP, QERP, and MERP schemes in the next 30 seconds. However, the data delivery rates were found low around 90% in MERP compared to 87.2% and 88.5% in LRP and QERP schemes. At the same time, the packet loss rate also increased up to 9.1%, 8.8%, 10.2%, respectively, for LRP, QERP, and MERP schemes. Throughout the simulation period, this rate

$$N\left(f\right) = \begin{cases} 10\log N_t(f) = 17 - 30\log f \\ 10\log N_s(f) = 40 + 20(s - 0.5) + 26\log f - 60\log(f - 0.03) \\ 10\log N_{wi}(f) = 50 + 7.5(wi)^{\frac{1}{2}} + 20\log f - 40\log(f - 0.4)m \\ 10\log N_{th}(f) = 15 + 20\log f \end{cases} \quad (23)$$

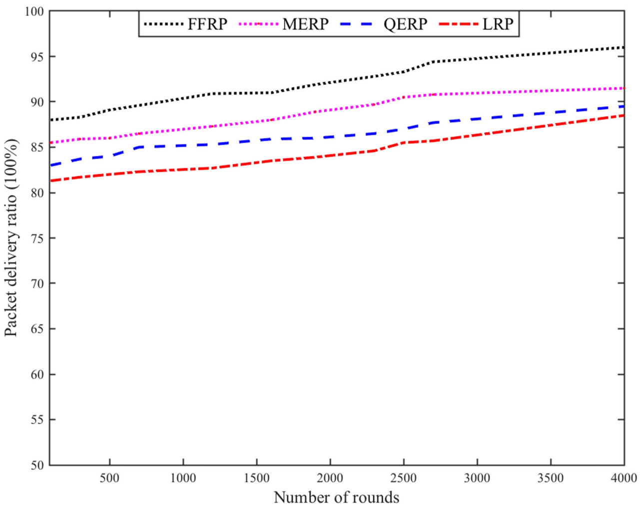

FIGURE 4. Packets delivery ratio vs number of rounds.

was found low around 4% in the FFRP scheme compared to all the other schemes in UWSNs. On the contrary, the overall PDR in MERP is observed nearly 91.4% compared to QERP and LRP schemes, which is recorded around 89.6% and 88.5%, respectively, in UWSNs. At the same time, the overall PDR in the FFRP protocol is observed high up to 96% compared to other schemes in UWSNs. In FFRP, the sum of data packets delivered to the sink is recorded up to 98.3% when the interference level is extremely low around 13% in UWSNs. However, this level drops up to 96% when the interference level is around 51% in UWSNs. In FFRP, one of the main reasons for achieving high data rates is due to its packets forwarding over highly reliable links between forwarding ASNs in UWSNs. In FFRP, the link quality is estimated by considering the residual energy and the rate of successful packet transmission of the next-hop forwarder over a link in the previous rounds. The other main reason for the high data rates is because of packets forwarding over a set of relay nodes with a closer distance towards the sink. This low distance between acoustic relay nodes with high signal to noise ratio significantly improves the link quality during packet transmission in UWSNs. This mechanism avoids packets forwarding over excessive relay ASNs and thus increases the chance of successful packets delivery in UWSNs. Also, in FFRP, the entire observed data is routed over different relay nodes, which significantly balances the data traffic load evenly and also increases the successful packet delivery rate in UWSNs.

Initially, the throughput of each routing scheme is witnessed high around 89%, 90% and 92.9%, for LRP, QERP, and MERP schemes. This is because of the small size network where each routing protocol efficiently manages the routing paths in the network. However, the network throughput is decreasing rapidly overtime when the network size grows linearly involving above hundred acoustic nodes in the data gathering process. In the medium-sized network, the throughput performance is recorded up to 88.7%, 90%, 88% for MERP, QERP and LRP schemes. Finally, the average network throughput performance in the large size network involving up to 300 ASNs is recorded up to 87%, 88.7% and 85% for the MERP, QERP and LRP schemes, respectively. On the other hand, the network throughput performance is recorded high around 97% when the network size is small in the FFRP scheme in UWSNs. However, this level drops up to 96% when the network size is medium-sized involving a hundred ASNs in the data gathering process in UWSNs. The average network throughput performance in the large size network is observed around 94% in FFRP in UASNs. In the experimental studies, we observe that the LRP, MERP and QERP schemes show a deteriorated reception rate in UWSNs. One of the main reasons for this is their poor fitness functions, which fail to find the best routing paths between source and destination in the network. Therefore, the forwarding nodes in these protocols drop most of the data packets since they do not have the ability to retransmit packets over the same link because of extremely low interference recovery time in the network. On the contrary, the PDR performance is found better in the MERP scheme since it has more time to retransmit packets compared to the LRP and QERP schemes in UWSNs. On the other hand, the better performance of QERP is due to its employing dynamic genetic operators, which provide a better solution compared to the LRP scheme.

The other reason for the packets loss is increase in network congestion due to retransmissions of packets by the acoustic nodes. Over time, the nodes stop receiving data packets from the neighbouring nodes along a distinct routing path since they do not have enough available memory to hold the incoming packets. This results in congestion in the network. However, the packets forwarding over different relay nodes can solve the congestion issue in the network. The congestion management performance of QERP is observed to be better than MERP and LRP routing protocols in UWSNs. This is because of forwarding packets over the least number of hops away to the central regions. However, this provides a trade-off between energy consumption and network throughput in QERP. The other main issue of these routing protocols is the data path loops occur during forwarding packets from the source towards the sea surface sink. This is because of involving a huge number of relay ASNs with a short distance in the network. This mechanism may help to balance the energy consumption, but increases the opportunity of data packets lost due to not reaching the sea surface sink in the predefined time. The data path loops are found more in the LRP routing protocol compared to all other routing schemes. Therefore, it shows a low packet delivery ratio and high latency as shown in Figure 6. It clearly shows that the overall delay performance of the FFRP routing protocol is recorded up to $0.81s$. The delay value in both LRP and MERP schemes is observed high up to $1.035s$ and $0.91s$ compared to $0.975s$ in QERP scheme. In fact, the robust route finding in the case of a route failure leading to low latency in QERP compared to LRP and MERP schemes in UWSNs. On the other hand,

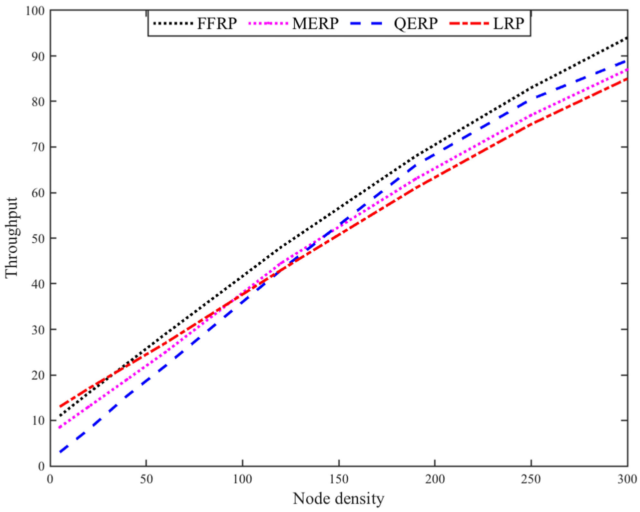

FIGURE 5. Throughput vs number of acoustic nodes.

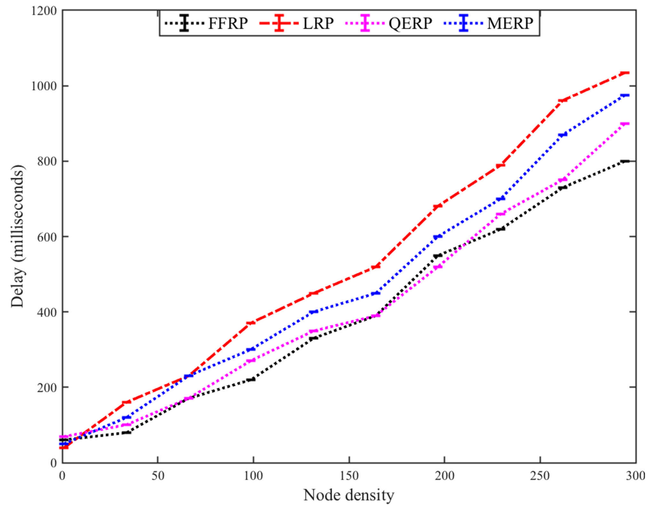

FIGURE 6. Delay vs number of acoustic nodes.

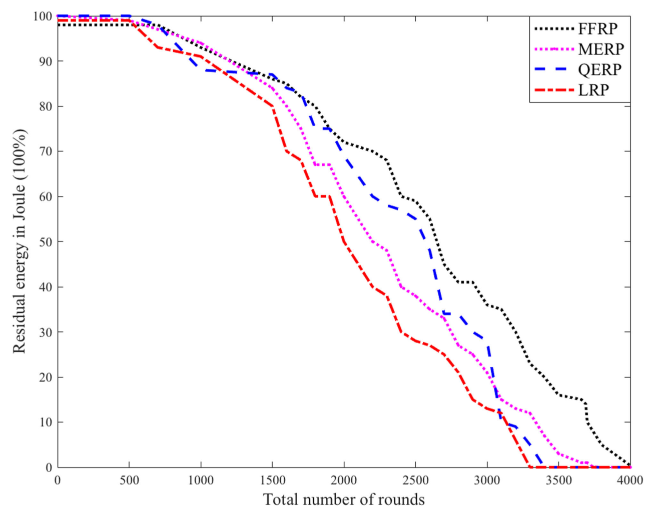

FIGURE 7. Residual energy vs number of rounds.

the delay value in MERP is relatively better than the LRP scheme because of its handling congestion issues in less time during conveying packets towards the sink. In FFRP, to keep the reception of the packets high, the sender ASN stops to forward the packets to the nodes that are suffering from high noise and interference problems. In this respect, the routing table plays a key role in which the nodes suffering from high noise and interference problems are assigned a low priority level for a predefined amount of time to avoid packet loss in UASNs. In this way, it guarantees that the remaining neighbouring ASNs are using the low interference channels during packet transmission in UWSNs. Therefore, the FFRP periodically orders the neighbouring nodes in the routing table by following their priority values before deciding on the packets forwarding to escape from the harmful interference effects on the data transmission reliability in UWSNs. Therefore, the ability of FFRP in terms of finding the best routing path enhances significantly, which leads to high throughput up to 94% compared to LRP, MERP and QERP routing protocols as illustrated in Figure 5. In FFRP, the best routing paths obtained by employing the intelligence of firefly mating optimization is another main reason for the high packet delivery ratio and network throughput. The designed mating procedure with multiple genetic operators helps to find a set of alternative paths towards the sea surface sink. Therefore, the proposed scheme achieves better performance in terms of avoiding local optimization problems as shown in Figure 8. It indicates that the proposed scheme achieves efficiency to avoid local optimization problems up to 97% during packets forwarding over reliable links in UWSNs. On the other hand, the MERP and QERP schemes overlap each other as the number of rounds increase in the network. However, the overall performance of MERP to avoid local optimization problems is found a little better up to 94% than QERP and LRP routing protocols recorded up to 92% and 88.9%. Consequently, among the available, the best path is selected by the sender based on the minimum angle information, distance and residual energy in the network. Besides, its ability to monitor the congestion occurrence during relaying packets significantly reduces congestion issues in the network. As soon as the congestion is reported at a node, the packets are forwarded to alternative paths.

Figure 7 depicts the residual EC of LRP, MERP, QERP and FFRP routing schemes in UASNs. The low EC profile of FFRP is observed better than the LRP, MERP, QERP schemes. One of the main reasons is it's finding the best next-hop relay nodes during packets forwarding towards the sink. In this way, it ensures that there is no specific node is being used excessively along an alternative routing path in the network. Thus, the data packets forwarding over a narrow routing path containing a set of optimal forwarders with shorter distances and minimum angle information in both upward and downward directions significantly, which helps to reduce the overall transmission EC in UWSNs. This

TABLE 3. The packet delivery ratio, delay, throughput and energy consumption performance in various routing schemes in UWSNs.

No.of rounds	Packet delivery ratio(%)				Delay (seconds)				Throughput (%)				Energy consumption (rounds)			
Protocols	FFRP	MERP	QERP	LRP	FFRP	MERP	QERP	LRP	FFRP	MERP	QERP	LRP	FFRP	MERP	QERP	LRP
1	0.953	0.931	0.911	0.878	0.795	0.915	0.971	1.042	0.941	0.882	0.887	0.862	3997	3730	1964	1908
5	0.959	0.925	0.905	0.872	0.815	0.925	0.981	1.048	0.946	0.875	0.898	0.845	4008	3728	1970	3398
10	0.968	0.891	0.891	0.895	0.818	0.918	0.960	1.018	0.937	0.863	0.887	0.853	3998	3721	1962	3390
15	0.967	0.912	0.879	0.902	0.819	0.910	0.980	1.003	0.936	0.851	0.865	0.861	4004	3718	1959	3388
20	0.949	0.903	0.869	0.844	0.800	0.889	0.983	1.057	0.942	0.893	0.894	0.883	3999	3720	1964	3379
25	0.960	0.883	0.885	0.865	0.819	0.902	0.972	1.048	0.935	0.851	0.879	0.871	3996	3719	1952	3372
30	0.956	0.931	0.901	0.903	0.818	0.931	0.969	1.029	0.938	0.846	0.910	0.826	3995	3735	1968	1908
35	0.963	0.919	0.914	0.911	0.824	0.911	0.982	1.025	0.943	0.848	0.889	0.838	4005	3740	1975	3388
40	0.966	0.926	0.919	0.926	0.779	0.899	0.977	1.011	0.946	0.889	0.902	0.849	4004	3738	1950	3379
45	0.960	0.909	0.889	0.879	0.799	0.900	0.975	1.039	0.939	0.895	0.885	0.835	3999	3727	1964	3385
50	0.959	0.900	0.892	0.873	0.818	0.908	0.980	1.047	0.937	0.874	0.880	0.854	3998	3740	3360	3389
55	0.959	0.909	0.894	0.874	0.822	0.922	0.973	1.059	0.940	0.869	0.863	0.840	3999	3730	3549	3390
Avgerage (≅)	96%	91.4%	89.6%	88.5%	0.81s	0.91s	0.975s	1.035s	94%	87%	88.7%	85%	4000	3730	1960	3391

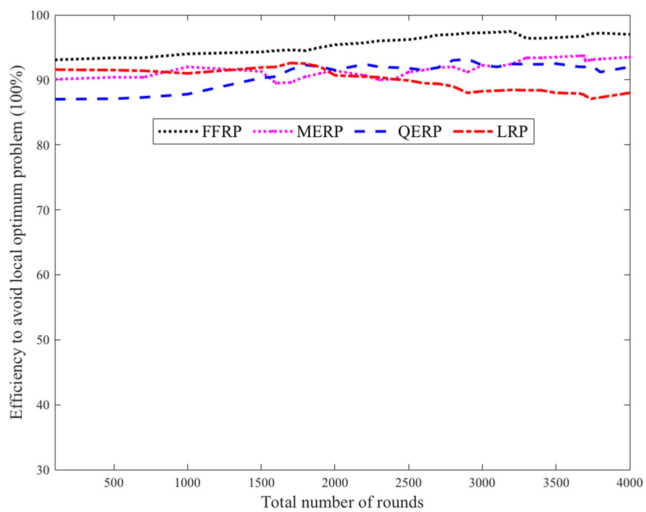

FIGURE 8. Efficiency to avoid local optimum vs number of rounds.

mechanism notably minimizes the chance of data path loops occurrence and thus invalid data packets are also reduced in the network. Thus, it avoids excessive rerouting due to providing good quality routing path between the source and the destination, which significantly reduces the control message overhead, which in turn helps to reduce the overall EC in UASNs. In addition, timely measuring the buffer occurrence of each relay node in the priority list help to reduce the impact of congestion occurrence in the FFRP scheme. To do so, in FFRP, each relay node periodically monitors its buffer occupancy level to prevent the congestion occurrence in UASNs. The congestion avoidance process starts if the buffer occupancy exceeds a defined threshold level. The key aim of the congestion avoidance process is to inform the sender node by sending a congestion occurrence message to divert the data traffic to other neighbouring relay nodes. Thus, a node dynamically switches to the alternate next-hop forwarder closer to the destination if the current path is unavailable or congested in the network. The entire procedure extremely minimizes the packets retransmission EC in the network. However, this is not the case in the LRP, MERP and QERP schemes. Generally, these schemes do not consider the link quality of the forwarders during conveying packets towards the sink. In addition, they fail to choose an alternative route if the existing path becomes unavailable or congested in the network. However, the EC performance is found extremely poor in LRP protocol compared to the QERP, FFRP, and MERP schemes because of excessive packet retransmission caused by excessive route failures. Though, the LRP scheme can find the next-hop relay node to convey packets when the current path becomes unavailable in UWSNs. However, most of the time, it selects the next-hop relay node with longer distance away to the sink. In addition, the QERP scheme performs poorly compared to the MERP scheme due to the lack of an appropriate congestion management mechanism, which results in excessive packet retransmission in UASNs. In addition, the data path loops are other main issues of both LRP and QERP schemes, which results in excessive packet retransmission in UASNs. However, this rate is observed lower in MERP compared to LRP and QERP schemes. In sum, the performance of FFRP routing scheme is observed remarkable in terms of low latency, EC, local optimum problem, and high throughput and PDR for the underwater monitoring applications. Table 3 summarizes the performance of FFRP, MERP, QERP and LRP schemes in UWSNs.

VI. CONCLUSION

Designing a routing protocol for energy efficient and reliable information gathering is the major concern in UASNs. This research proposed a novel dynamic firefly mating inspired routing scheme for UASNs-based time-critical marine monitoring applications. The developed mechanism during the events data gathering employs a self-learning based dynamic firefly mating optimization intelligence to find the highly stable and reliable routing paths to convey gathered information in voids or shadow zones in UASNs. The designed scheme significantly minimizes energy consumption, latency, and local optimum issues by balancing the data traffic load evenly in the network. In addition, the data transmission over highly stable links between acoustic nodes improves the PDR and throughput in UASNs. The simulation results obtained in a realistic underwater channel model with NS2 and AquaSim 2.0, verify the best performance of our proposed scheme against all other routing schemes in UWEs. In the future, we are planning to focus on dynamic mating and mobility issues with the increasing number of nodes for many practical time-critical applications of UASNs.

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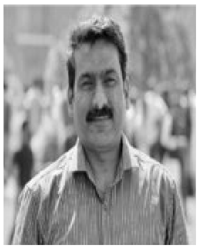

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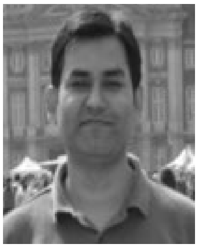

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