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Improved Communication Strategy Based on Optimization Algorithm For Unmanned Multi-Robot Open Area Exploration

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Abstract*: This correspondence presents a communication strategy for multi-robot systems (MRS) deployed for open area exploration and map making, which is improved using optimization algorithm. One of the noteworthy application of MRS is exploration of unknown environment. The crucial problem of MRS is reliable exchange of data between different robots and efficient communication with data collection centre. However in the real world, mobile robots have limited communication range and energy, which in turn impose constraints in the design of communication strategy for effective coordination. The biggest challenge in this domain is to formulate an appropriate exploration and communication framework, which helps robots in achieving their goal of exploring maximum area with minimum energy loss and transmitting the full exploration data, while working as a team. Here, a framework for multi-robot communication is proposed, using Flower Pollination Algorithm for efficient transmission and routing of data to base station, which is utilized by simultaneous localization and mapping (SLAM) protocol for exploration and map making. Comparisons of proposed protocol are made with other clustering based routing algorithms available in the literature. Simulation results depict that the proposed strategy outperforms other communication techniques in terms of energy efficiency and network life time. The minimized energy usage helps robots to stay alive for more time, which in turn helps in exploring large areas with similar conditions.

***Index Terms*: Multi-robot system, Optimization, Routing protocol, Unmanned exploration**

I. INTRODUCTION

Unity is Strength" is a very insightful proverb which holds true for humans as well as robots in present times. Similar to humans, robots working together in proper coordination and cooperation perform better in various challenging situations. Multiple interacting dynamic objects or a group of robots functioning in an environment possessing some collective behaviour is known as a multi-robot system (MRS) [1]. Team of several simple robots is always beneficial over a complex single robot, as they offer higher degree of reliability through resource repetitiveness and effectiveness by parallel task execution. Moreover, MRS also delivers better fault tolerance and flexibility because of dynamic reformation and coordination.

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Recent progress in robotic research has allowed roboticists to use MRS for solving various real world problems in areas like agriculture, natural resource monitoring, emergency response and rescue, maintenance of heavy machinery and many more. Researchers around the globe have developed many projects of MRS catering to various applications [3-7]. Based on the research projects, the type of MRS applications can be further classified into unmanned ground vehicles (UGV), unmanned aerial vehicles (UAV), unmanned surface vehicles (USV) and unmanned underwater vehicles (UUV). Various articles have been published in the area of MRS regarding survey analysis, review of research, frameworks, application domains and taxonomies. Based on the literature available [2, 8, 9, 10, 11, 12], MRS is a constitution of five groups i.e. structure, re-configurability, size, communication linkage and communication configuration, as depicted in Fig. 1.

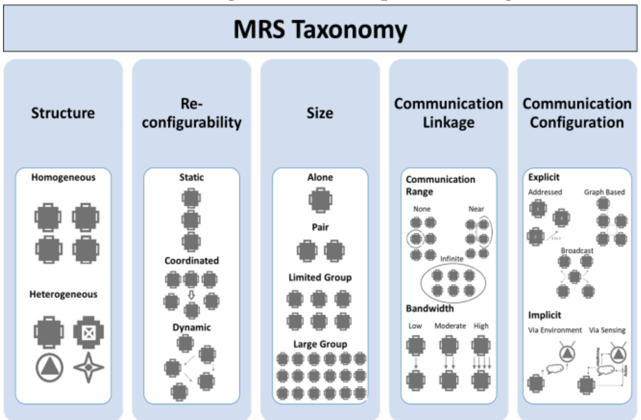

Fig. 1: MRS Taxonomy

Structure, or in other words composition, is defined as the type of hardware and software used for robot team, which can be homogeneous (team of exactly same robots) or heterogeneous (robots with different specifications). Re-configurability refers to the way of coordination among robots. It extensively depends on the application domain and the environment in which the robot team is operating. It can be static where no movement takes place, or coordinated where complete team is led by a single robot, or dynamic in which the decision process is autonomous for every individual robot. Size of the MRS is defined as the number of robots involved in a particular task. It is totally application dependent. It can be a pair of robots, small team having 10-12

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robots or a large group (swarm) of robots. Communication is a process in which data is transmitted and received between robots in order to accomplish the tasks. Further communication linkage or network refers to range/distance and bandwidth by which robots can connect to each other and configuration/pattern defines the process of communication i.e., explicit (indirect communication where information flow is through cloud) and implicit (direct connection between peer robots and BS) methods. The key factor for accomplishment of any task in an application is coordination among robots. Coordination can only be achieved by establishing communication between robots. Since from the inception of MRS, there have been constant developments in communication strategies to enhance battery life and bandwidth utilization [13, 14]. This article is primarily focused on enhanced MRS communication technique for the applications of field surveillance as well as search and rescue in military and urban domain. The same can be used/modified for forest fire detection, habitat monitoring and other surveillance applications [15].

This correspondence is organized as follows. The preceding section discusses real world communication constraints in stable and collaborative layout domain for MRS. Section 3 reviews routing protocols for MRS which are classified based on various parameters. Furthermore, meta-heuristic algorithms for MRS are compared followed by outlining of Flower pollination algorithm. Section 4 formalizes the exploration scenario and framework considered in this paper. Section 5 describes the proposed protocol and strategy in detail. Section 6 discusses the performance of the proposed protocol and its performance advantages over other approaches. Finally, in Section 7, conclusions are drawn and possible future directions are described.

II. REAL WORLD COMMUNICATION CONSTRAINTS FOR MRS

One of the biggest and vital challenge in MRS is effective communication among robots. The quality of communication degrades in exploration domain because of distance between peer robots or base station (BS), obstacles and many other geographical factors. Wireless network with large bandwidth provides satisfactory communication [16]. However, this is not true for real world conditions and network must be intelligently planned to overcome overloading and conservation of energy because of large number of robots.

Communication support is a costly affair in terms of energy consumption, as more payload will drain the battery faster. Some of the potential parameters that must be considered while transmitting data from a robot are individual state, task data and environmental state. Individual state represents battery level and robot identification, task data refers to task specific information provided by sensors and environmental state characterizes hazardous variations in environment, which can constrain reliable communication between robots [17]. The communication standards such as Wireless Fidelity (Wi-Fi), Radio frequency (RF), Infra-Red (IR) to be deployed for MRS, must be considered depending on factors like geography, distance, line of sight etc., for a particular application. The type of communication configuration, which can be implicit or explicit, is also important for efficient information sharing in MRS for geographically reliant applications. Moreover, type of communication strategy used, plays a crucial role in dissemination/reception of information to/from robots in a timely manner, in order to reduce conflicts and delay. Hence, the cost of communication is a function of parameters like transmission time, collision with other robots and energy consumed in order to fix communication range and strategy [18, 19]. On the whole, real world communication constraints must be taken into account before deciding communication technology, bandwidth allocation and communication strategy.

In this section, communication constraints in the example scenarios of field surveillance, search and rescue and monitoring systems, have been discussed. MRS are deployed in these setups to achieve higher efficiency, economical deployment and redundancy which is beyond the scope of single robot systems [20].

A. Example Scenario 1: MRS in Stable Layout Domain

This kind of scenario arises in applications like forest fire detection, habitat monitoring, aerial robotics and other monitoring systems. Robots maintain specific kind of formation in these applications, as shown in Fig. 2, and are controlled by BS. Robots establish recurrent connectivity, which refers to connectivity activated due to occurrence of an event or timeout, so bandwidth required is low. Peer to peer connection is established between robots in dynamic environment, where only location coordinates are shared to maintain formation. The BS has to plan the communication path (robot-robot and robot-BS) in an optimized manner in order to reduce transmission time and battery consumption, for maximum network lifetime.

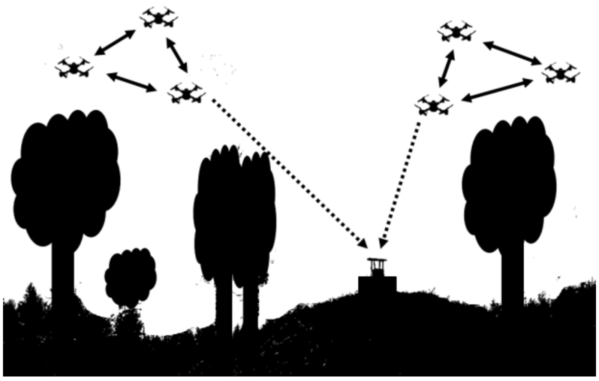

Fig. 2: MRS in stable layout domain (Aerial Robotics)

B. Example Scenario 2: MRS in Collaborative Layout

This scenario is common to applications like search and rescue operations, underwater exploration, map building for houses, factories and other unknown environments. Since, geographical topology is not/ partially known to MRS, robot location and path cannot be planned in advance, as depicted in Fig. 3. In this case, robots share information with peer robots and BS continually. The delay in information reception, in these applications, result in failure of the system. For search and rescue operations, robots must send real time images/data

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to BS, so that effective decisions can be taken timely. So, a higher bandwidth is required for efficient data transfer between robots and BS. As the terrain is unknown, robots have to communicate through various obstacles/scatterers, which makes the use of omnidirectional antenna with higher communication ranges necessary for robots. The key factors that limit the system performance are continuous connectivity, higher bandwidth and network congestion.

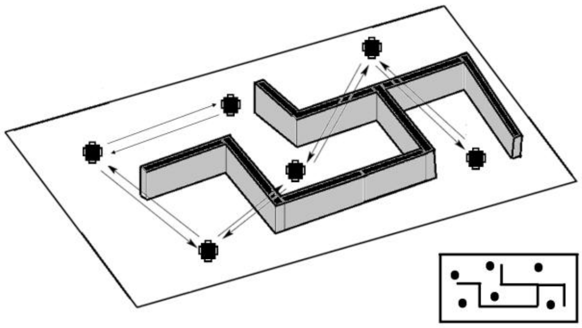

Fig. 3: MRS in collaborative layout domain (Map Building)

III. ROUTING PROTOCOLS FOR MRS COMMUNICATION

The research in cluster-based routing protocols mainly focuses on three objectives: energy saving, reducing delay and enhancing accuracy. This means that a routing protocol offers a good performance for MRS data aggregation, if it is able to collect the maximum number of packets with minimum energy consumption and delay. However, these objectives are defined and optimized according to the consumer/application requirements. For example, a protocol that is able to reduce delay and increase accuracy is well-suited to real-time applications, even if it does not optimize energy efficiency [21]. In addition, routing protocols should consider and balance the potential correlations between energy, delay and the number of collected data samples. For example, collecting a greater number of packets increases energy consumption and delay, especially when the data sources are randomly scattered in the network. Reducing delay by utilizing direct communication (instead of multi-hop) increases energy consumption, whereas using multi-hop routing will increase data collection delay. For this reason, the issues of energy conservation, reducing delay and/or increasing the unit of collected data items, need to be addressed to design data aggregation routing protocols and enhance their performance in MRS.

Energy consumption needs to be reduced as a robot usually have limited power. Energy squandering hinges on the number of transmissions, dissemination stretch and data aggregation computation overhead. For this reason, data aggregation protocols should minimize the network traffic and path leap count. Data aggregation routing delay should be minimized for data freshness. In other words, routing delay may change the meaning and impact of collected data on further processing at BS. Data aggregation delay depends on network congestion (network traffic), transmission distance and communication delays. Increasing the count of captured data samples enhances data collection robustness. Indeed, the data consumer is able to make precise decisions on the collected data, if a greater number of data samples are collected. Data accuracy depends on the routing algorithm's effectiveness to report data samples to the BS. Now, from above discussion it is quite evident that one single common default protocol will not suit each application and choosing appropriate parameter settings is necessary for stabilizing the energy dissipation with other competing metrics such as delay and data accuracy. Therefore, an approach that can effectively and automatically choose an appropriate protocol parameter is always sought by roboticists. Network layer in MRS routing protocol stack performs data routing and self-configuration of network. It finds the best route so that energy consumption of mobile robots is minimized. It is also responsible for the updation of network topology, if any link failure occurs [21]. Energy-aware routing algorithms for network layer can be classified into different categories, as given below:

- Based on mode function: Proactive, Reactive and Hybrid
- Based on participation style: Direct, Flat and Clustering
- Based on network structure: Data centric, Hierarchical, Location based and QoS aware

In recent years, various investigators have used heuristic computation based clustering protocols. These protocols exhibits a vital system, by finding the ideal arrangements regarding optimal size of cluster and selecting best robots as CHR's [22, 23]. Various techniques of computational intelligence (CI) and evolutionary algorithms (EAs), have been employed by researchers. Swarm intelligence (SI) and EA are meta-heuristic algorithms, have two key components: diversification and intensification. Various optimization techniques such as Particle Swarm Optimization (PSO) [25], Genetic Algorithm (GA) [24], Harmony Search Algorithm (HSA) [27] and Ant Colony Optimization (ACO) [26] have been used in this regard. These techniques utilize distinctive parameters in wellness capacity to achieve their goals. The arrangement of bunches and group based steering are some challenging issues encountered while implementation. In tackling these issues, the time of merging is an imperative metric in addition to energy efficiency. Details of the above said meta-heuristic algorithms based routing protocols, with an aim to prolong network lifetime along with the optimization criterion and effect is given as below:

- **PSO** [28]: Optimization Criteria: Minimum intra-cluster distance

Effect: Extended network lifetime and throughput.

- **GA** [29]: Optimization Criteria: Consumption of energy, number of clusters, size of cluster, direct distance to sink and cluster distance

Effect: Increase in network lifetime, better performance in terms of energy consumption, rate of convergence and execution time.

- **ACO** [30]: Optimization Criteria: Energy consumption for communication, Residual energy, Path length

Effect: Prolong network lifetime, energy consumption balance among nodes and reduction of avg. energy consumption.

- **HSA** [31]: Optimization Criteria: Minimum intra-cluster mean distance and maximum network energy.

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Effect: Lower energy consumption and extended network lifetime.

There are chances that a robot with low energy can become CHR, considering the point selection of CHR is probabilistic, as revealed by literature. So, there is a requirement to consider CHR selection in a deterministic way along with residual energy of robots. Other factors can also be considered to balance the load of robots such as distance from BS and distance of other robots from CHR. Therefore, the elementary requirement for energy efficient routing protocol foe communication is proper selection of CHR in appropriately formed cluster. In the majority of the conventions, CHR are expected to have a long correspondence empowering them to send information straightforwardly to the BS. This supposition that isn't constantly practical, because of signal propagation problems and BS is directly inaccessible to all robots. Therefore, there is a requirement to consider communication between CHR and BS in a multi-hop manner to handle this problem. The literature reveals that many evolutionary algorithms have done better than deterministic methods in many problems related with CHR selection in MRS. Appropriate selection of evolutionary algorithms alongside proper fitness function can proficiently balance the depletion of energy depletion in robots and hence uplift the lifetime of network. Flower pollination algorithm (FPA) is recently developed heuristic approach, that mimics the pollination process of flowers [32] and has been successfully applied for problems of forest fire detection [33] antenna design [34] etc. In this article, potential of FPA has been exploited for resolving the problem of load balancing in clusters in order to proficiently balance the consumption of energy in robots and maximize the period of stability for communication network.

A. Flower Pollination Algorithm

FPA is a unique bionic evolutionary algorithm that was proposed by Yang [32]. The motivation for FPA originates from the natural pollination process that happens in flowering plants. To emulate the pollination procedure, there are two distinctive pollination strategies for each flower to pick: worldwide/global or neighborhood/local pollination, with phase switch probability p.

Global pollination phase: For each individual, a random number $\mathfrak{X}$ is generated. If $\mathfrak{X} < p$, then global pollination is done. In the worldwide/global pollination process, each flower modifies its position as per following expression [32]:

$$X_{\varkappa}^{\mathfrak{d}+1} = X_{\varkappa}^{\mathfrak{d}} + \gamma L(\lambda)(X_{best}^{\mathfrak{d}} - X_{\varkappa}^{\mathfrak{d}}) \qquad (1)$$

where $X_{\varkappa}^{\mathfrak{d}}$ and $X_{\varkappa}^{\mathfrak{d}+1}$ are the old and new positions of $\varkappa^{th}$ flower, respectively, $X_{best}^{\mathfrak{d}}$ is the best flower at current iteration $\mathfrak{d}$, which has the best fitness value among whole population, and the step size of global pollination is controlled by γ the scaling factor. Parameter (λ), the L'evy flight, is used as the strength of pollination in the basic FPA, and the step size (λ) obeys the L'evy distribution:

$$L(\lambda) \sim \frac{\lambda \Gamma(\lambda) \sin\left(\frac{\pi\lambda}{2}\right)}{\pi} \frac{1}{s^{1+\lambda}}, (s \gg s_0 > 0) \qquad (2)$$

where $\Gamma(\lambda)$ is the gamma function. The pseudocode/ calculation steps of this algorithm is given below:

```
Start:
    Initialize a population of ϰ random
    flowers
    Define switch probability, p
    Define objective function
    Identify current best solution X_best^ƌ
    while ƌ < max(ƌ)
    for i = 1: ϰ
      if 𝔛 < p
        perform Global Pollination:
        X_ϰ^(ƌ+1) = X_ϰ^ƌ + γL(λ)(X_best^ƌ − X_ϰ^ƌ)
      else
        perform Local Pollination:
        X_ϰ^(ƌ+1) = X_ϰ^ƌ + r(X_p^ƌ − X_q^ƌ)
      end if
      evaluate X_ϰ^(ƌ+1)
      if X_ϰ^(ƌ+1) is better than X_ϰ^ƌ
      update position
      end if
    end for
    Find the Current best
    end while
    Update Final best
End
```

Pseudocode 1. Pseudocode of FPA

Local pollination phase: If $\mathfrak{X} > p$, the local pollination process is be carried out. Flower $X_{\varkappa}^{\mathfrak{d}}$ obtains its new position $X_{\varkappa}^{\mathfrak{d}+1}$ according to the difference between its old position and the position of two neighboring flowers $X_p^{\mathfrak{d}}$ and $X_q^{\mathfrak{d}}$. This process is considered as local search, and the updating equation [32] is defined as

$$X_{\varkappa}^{\mathfrak{d}+1} = X_{\varkappa}^{\mathfrak{d}} + r(X_p^{\mathfrak{d}} - X_q^{\mathfrak{d}}) \qquad (3)$$

where r is drawn from uniform distribution [0, 1], and it is considered as a local random walk. After pollination is completed, the new individuals update their positions by comparing fitness values. If the fitness of $X_{\varkappa}^{\mathfrak{d}+1}$ is enhanced than that of $X_{\varkappa}^{\mathfrak{d}}$, the new position of $\varkappa^{th}$ flower will be exchanged by $X_{\varkappa}^{\mathfrak{d}+1}$. Otherwise, $\varkappa^{th}$ flower remains at $X_{\varkappa}^{\mathfrak{d}}$.

In MRS, selection of CHR is binary-coded problem. So, one cannot straightforwardly use the basic FPA to handle this problem. For MRS, when position of the flower is modified, the position is discretized by following expression:

$$Flag_{\varkappa} = \begin{cases} 1, if\ (X_{\varkappa} \geq 0.5) \\ 0, \quad otherwise \end{cases} \qquad (4)$$

where $X_{\varkappa}$ indicates the position of $\varkappa^{th}$ flower.

IV. PROBLEM FORMULATION

The problem addressed in this correspondence is effective communication for the application of unknown open

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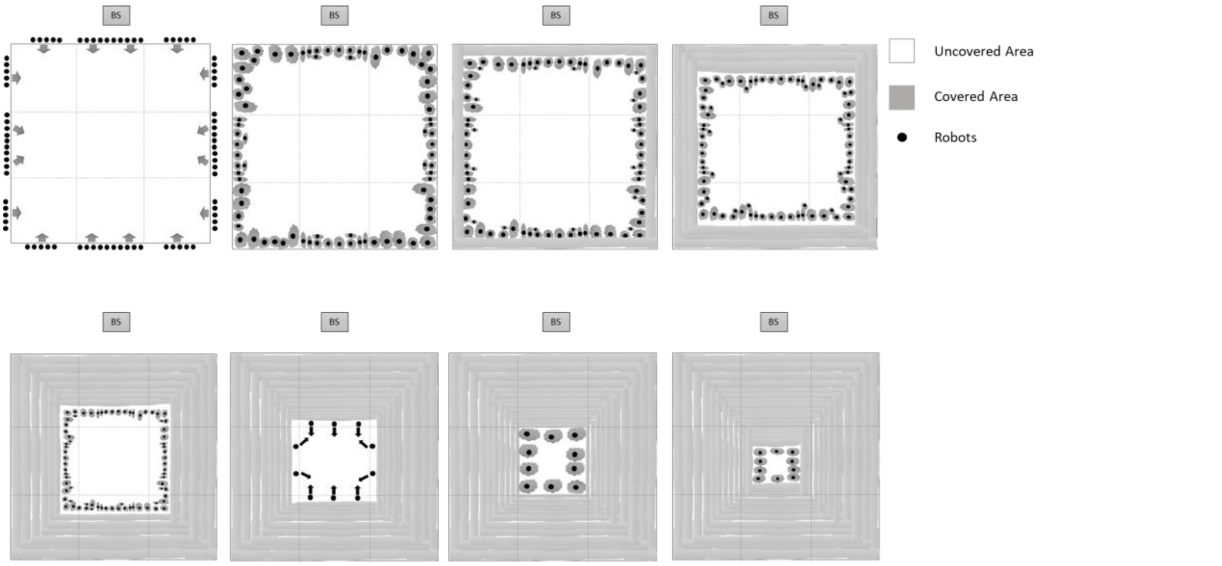

Fig. 4: Robots navigation in 3x3 field

environment exploration, for the generation of maps and/or search-and-rescue missions. An initially unfamiliar, circumscribed, continuous two dimensional area $\text{Ʉ} \subset \mathbb{R}^2$ is considered, where $\mathbb{R}^2$ signifies that the locations on Ʉ which is represented by x and y referring to latitude and longitude coordinates of global positioning system (GPS). A team of M mobile robots $X = (X_1,\ X_2, \ldots, X_M)$ will send data to principal control center called as base station (BS) located at a fixed location outside the bounds of Ʉ. Each robot integrates various types of sensors, such as ultrasonic, LIDAR, thermal, image, GPS, etc. to perceive the environment, and transceivers (Texas CC1120, Microchip RN2483, Semtech SX1272 etc.) for long range data transmission and reception. Each robot is capable of exchanging data with BS and other robots over an ad-hoc wireless network governed by proposed algorithm (discussed in subsequent section). The BS plans the path and pose for each robot through simultaneous localization and mapping algorithm (SLAM) [35, 36], in order to safeguard the autonomy of robot. The progression of time is considered in discrete steps i.e., $t \in \{1, 2, \ldots, \mathrm{T}\}$, where last time step of the mission is denoted by T. The speed, position, direction and transmission range of robots is represented by a pose function of robot, given as

$$\psi_m^t = f(\text{Ʉ}_m(x, y), \mathcal{v}_m, \theta_m, \mathcal{L}_m) \qquad (5)$$

where, $\text{Ʉ}_m(x, y)$ is the position, $\mathcal{v}_m$ is the speed, θ_m is direction and $\mathcal{L}_m$ is the transmission range of robot X_m at time t.

A.Exploration

As per the system paradigm described above, exploration of unknown territory is processed as follows. Area to be explored is divided into $g \times h$ matrix where g and h are whole numbers. Every element of the matrix is called zone, which is given as

$$\text{Ʉ} = \bigcup_{g,h} z(g, h) \qquad (6)$$

Considering $g = h = 3$, Ʉ is divided into 3×3 matrix i.e. 9 zones. A number of robots (ten in our case) are placed at boundaries of peripheral zones of Ʉ . At a particular time t, the deployment of robots is given as

$$\mathfrak{D}^t = (\psi_1^t, \psi_2^t, \psi_3^t, \ldots . \psi_M^t) \qquad (7)$$

In order to cater to the challenge of map building, SLAM algorithm is used because of its high convergence and ability to handle uncertainty efficiently [37]. A graph-based SLAM approach is being followed to represent map in terms of finite vector $\mathcal{b}$ by m^{th} robot to record corresponding observations e_m^t from LIDAR sensors. Odometry measurements q_m^t are executed at time steps t to register new pose function ψ_m^{t+1} of robot which is given as

$$q_m^t = \begin{pmatrix} \psi_m^t \\ \psi_m^{t+1} \end{pmatrix} \qquad (8)$$

where, ψ_m^t and ψ_m^{t+1} refers to before and after movement poses of m^{th} robot. At time t, the appraised joint posterior over the map, in probabilistic form, is given as [36]

$$\wp(\psi_m^{1:t}, \mathcal{b} \mid e_m^{0:t}, q_m^{0:t-1}, \psi_m^0) \qquad (9)$$

The integration of sensor data to find maximum likelihood is re-appraised for whole map in each iteration to store overall data, as expressed below:

$$\wp(\psi_m^t, \mathcal{b} \mid e_m^{0:t}, q_m^t, \psi_m^0) = \int\int \ldots \int \wp(\psi_m^{1:t}, \mathcal{b} \mid e_m^{0:t}, q_m^{0:t-1}, \psi_m^0)\, d\psi_m^1\, d\psi_m^2 \qquad (10)$$

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Map construction in graph-based SLAM is a two-step procedure, where first step is to describe and integrate constraints which is highly sensor dependent, named as front-end and second step is abstract depiction of data which is sensor agnostic, named as back-end [32, 38]. So the objective function to find configuration of robots is given as

$$\mathfrak{f}(\psi_m^1, \ldots, \psi_m^t) = \sum_{u,v} e_{u,v}^T \mho_{u,v} e_{u,v} \quad (11)$$

where $e_{u,v}$ is difference of appraised and observed poses and $\mho_{u,v}$ represents information matrix. At a particular time interval $t = t_o$ decided by base station, robots stop moving and transmit their data to their respective ZCH (zone cluster head), which further transmits the data to BS. SLAM algorithm is computed at BS in order to update uncertainty grid [39], which in turn calculates the updated pose function ψ_m^t, for all robots. This information is transmitted back to ZCH which forward the same to its zone member robots (ZMR) for further navigation. All robots will be made to converge towards central zone i.e., $g = h = 2$, as shown in Fig. 4. At central zone, ten robots with maximum energy will be selected by BS from all of the robots and same process is repeated again for central zone.

B. Radio Energy Dissipation Model for Communication

As robots have limited energy, power consumption is a crucial factor for designing communication protocol, since robots consume energy for sensing, navigation, data processing, and wireless communication. The network energy is consumed on both sides during communication (sender and receiver) as per wireless energy consumption model [40]. The model consists of two parts reflecting transmission and reception as depicted in (12) and (14) respectively [40]. Robot consume energy E_{TX} to run the transmitter circuit and E_{amp} to activate the transmitter amplifier, whereas a receiver consumes E_{RX} amount of energy for running the receiver circuit. Energy consumption in wireless communication also depends on message length l. Thus, the transmission cost for a l -bit message having transmitter-receiver distance d, is calculated as:

$$E_{TX} = \begin{cases} lE_{elec} + lE_{friis\_amp}d^2, & if\ d < d_0 \\ lE_{elec} + lE_{two\_ray\_amp}d^4, & if\ d \geq d_0 \end{cases} \quad (12)$$

where d_0 is crossover distance and is given by:

$$d_0 = \sqrt{E_{friis\_amp}/E_{two\_ray\_amp}} \quad (13)$$

The term E_{elec} signifies the energy consumed per-bit for transmission, the parameters E_{friis_amp} represent the energy consumed and $E_{two\_ray\_amp}$ represent the energy consumed in two ray ground propagation by radio. The cost of reception for the l-bit data message is given as:

$$E_{RX} = lE_{elec} \quad (14)$$

V. PROPOSED PROTICOL FOR COMMUNICATION

Various tasks are performed by robots are sensing, computing, transmitting, and receiving. Few of these robots are ZCH or leaders, they collect and process the data and then forward it to BS. The task of robots i.e. zone member robots (ZMR) other than ZCH is to sense the surroundings and send the data to the ZCH of their respective zone. The complete process of exploration and communication is performed in three phases i.e. Navigation phase in which robots sense the environment till particular time interval $t = t_o$ decided by base station and stop moving till next instruction by BS. The second phase is Set-up phase where ZCH selection is performed followed by Steady-state phase which is responsible for routing. Once steady-state phase is over BS again initiates navigation phase. The complete process of exploration and communication is shown in Fig. 5.

In this correspondence, **FPA** based **E**nergy **E**fficient **R**outing **P**rotocol (FPA-EERP) is proposed for energy efficient communication between robots and BS. The protocol process is bifurcated into rounds consisting of set-up and steady-state phase as illustrated in Fig. 6. The optimum ZCH selection is done in set-up phase and the optimum route is established in steady state phase, both using FPA.

The ZCHs are selected by BS from the alive robots having residual energy more than a threshold level, using FPA, which is basically average energy of all robots that are active, in set-up phase. Firstly, the BS makes announcement of a short communication in order to get the identifications (ID), energy levels and locations of every robot present in particular zone. Based on received data by robots, BS makes use of FPA to elect the ZCH per zone, on the basis of minimization of fitness function given by (15)**.** The whole process is to minimize the fitness function and ZCH selection, which is formulated as Pseudocode 1. When ZCHs are elected and their associate members i.e. ZMRs are determined, then a communication broadcast is launched by BS to inform robots in various zones about their respective ZCH and ZMRs in association. A time division multiple access (TDMA) schedule is generated by elected ZCH to assign time slot to ZMRs and further notify with schedule through broadcasting in their zone. Schedule of TDMA is used to avoid intra-group interference and provides a facilitation to every ZMR for shutting down their radios when not in operation, for energy conservation. Furthermore, to reduce inter-zone interference a distinctive code division multiple access (CDMA) code is chosen by each ZCH chooses and notification is sent to all associated ZMRs present within the zone to make use of this code to send their information.

Fitness Evaluation: Lets consider a network of M robots deployed in area $\mho$. Let $X = (X_1, X_2, \ldots, X_M)$ denote the population vector of a robots with M robots, where position of m^{th} robot in j^{th} zone is $X_m(j) = \{0, 1\}$. ZMRs and ZCHs are represented by values 0 and 1 respectively. The Np solutions (size of population) is initialized randomly in terms of 1s and 0s and one ZCH is selected per zone. The robots are deployed into Z zones where $Z = z(g, h)$ and g and h are whole numbers. The fitness function for ZCH selection is defined as:

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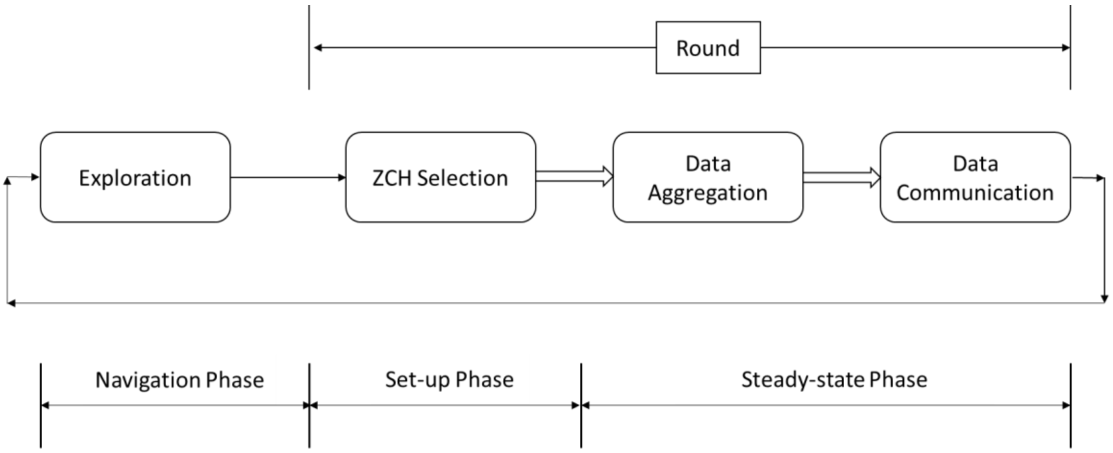

Fig. 5: Process of exploration and communication

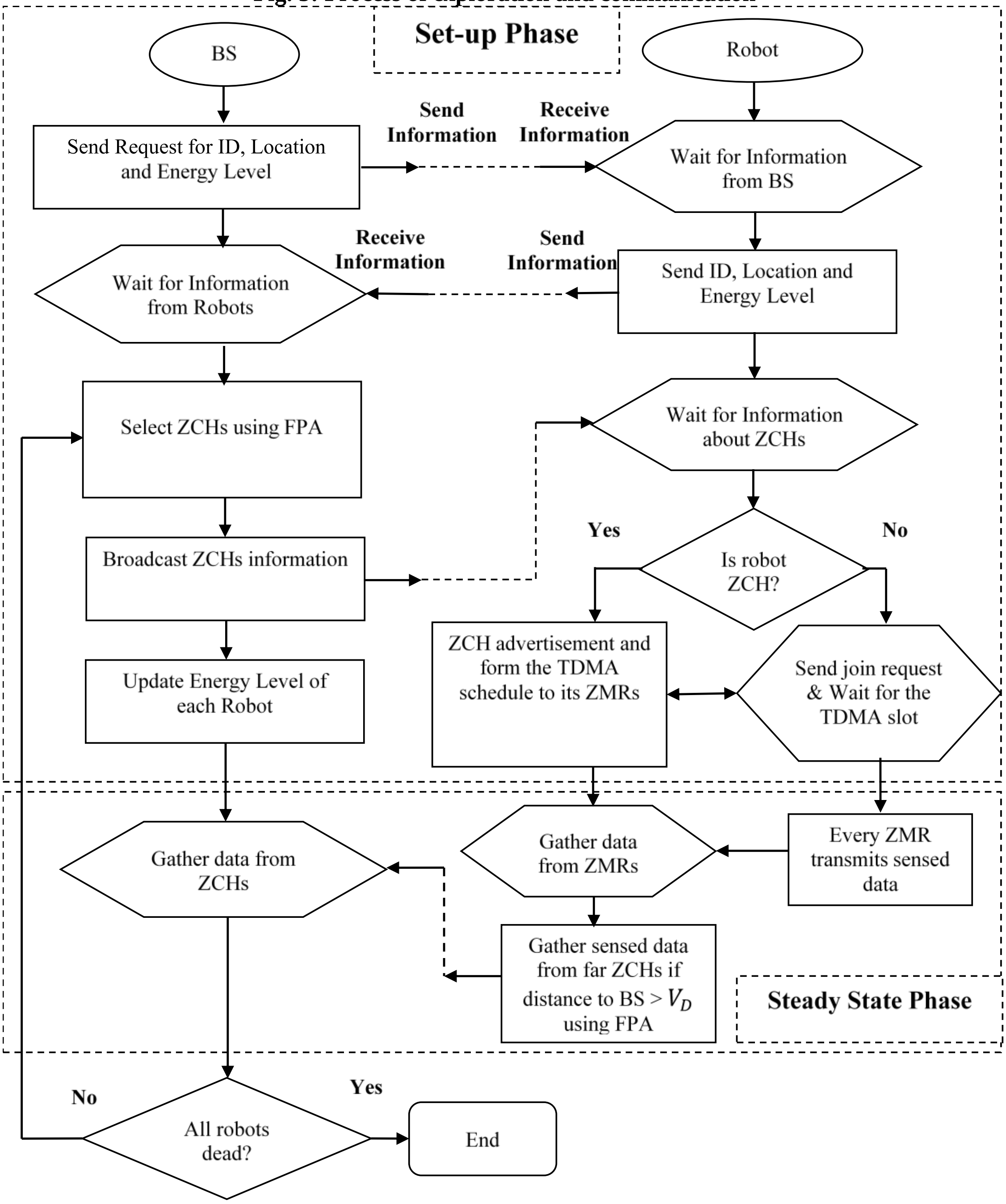

Fig. 6: Working of proposed FPA-EERP protocol

$$f_{obj\_ZCH} = \sum_{i=1}^{2} w_i f_i \quad (15)$$
$$\text{subject to: } \sum_{i=1}^{2} w_i = 1.$$

In order to accomplish the better stability period, reduction of standard deviation of remaining/residual energy of each robot is very crucial. The standard deviation (σ_{RE}) aids to measure the quality of even dissemination of the load between robots per Z, which is given as

$$f_1 = \sigma_{RE} = \sqrt{\frac{1}{M}\sum_{m=1}^{M}\{\mu_{RE} - E(X_m)\}^2} \quad 16)$$

where $\mu_{RE} = \frac{1}{M}\sum_{m=1}^{M} E(X_m)$ and $E(X_m)$ is the remaining/residual energy of m^{th} robot.

The second objective concerns with aggregation of residual energy level $E(X_m)$ and average distance value A_D for selection of ZCH.

$$f_2 = ZH_{EV}(m) = 0.5E(X_m) + 0.5(1/A_D(m)) \quad (17)$$

where A_D is average distance of a robot from all the other robots in same zone as given in (18). The chance of a robot to become ZCH is elevated with its lesser average distance A_D.

$$A_D(m) = \frac{1}{M-1}\sum_{m=1}^{N} d(m,n), m \neq n \quad (18)$$

where N is total number of robots in a zone, $d(m,n)$ is distance of m^{th} robot from n^{th} robot in its zone, as

$$d(m,n) = \sqrt{(m_x - n_x)^2 + (m_y - n_y)^2} \quad (19)$$

Steady-state phase: Steady-state phase is divided into two parts named as Intra-zone data transmission phase and Inter-zone data transmission phase. Since, interval for data transmission in this phase is far lengthier than the set-up phase, so there is scope of energy dissipation reduction in this phase as well. In intra-zone data transmission, the member nodes send information to the ZCH at a certain time interval t and perform exploration for rest of the time, being a part of reactive protocol. During inter-zone data transmission phase, ZCH receive data from other ZCHs & sends the aggregated data to next hop. Next hop depends on distance in BS and ZCH (d_{ZCH-BS}) at the slot of time that is allocated by the ZCH of the upper level.

Intra-zone data transmission phase: During this data transmission phase, energy of active robots will be dissipated while sensing, navigation, packets transmission, receiving, and aggregation. For ZCHs, energy will also be consumed with packets reception and aggregation. Thus, in this phase, the energy of the ZMRs and ZCHs can be formally modified according to the following expression:

$$E(X_m) = E(X_m) - E_{sensing}(X_m) - E_{TX}(X_m, ZCH_k) \quad (20)$$

$$E(ZCH_k) = E(ZCH_k) - (E_{RX} + E_D) \quad (21)$$

where, $E(X_m)$ and $E(ZCH_k)$ denotes current energy of m^{th} ZMR and k^{th} ZCH respectively, $E_{TX}(X_m, ZCH_k)$ is energy expenditure for transmitting data from ZMR to ZCH. E_{RX} is energy dissipated for reception of data at ZCH and E_D is the energy dissipated in data aggregation for ZCH.

Inter-zone data transmission phase: During this phase, the energy of ZCHs in the network will be modified according to the dissipated energy required for packets transmission to BS. Energy is also dissipated for relay ZCHs i.e., ZCH_R to receive the message packets from distant ZCHs and transmission to next ZCH. Thus, in this phase, the energy of the ZCH can be formally modified according to the following

$$E(ZCH_k) = \begin{cases} E(ZCH_R) - E_{TX}(ZCH_k, ZCH_R) & \text{if } d(ZCH_k, BS) \geq V_D \\ E(ZCH_k) - (E_{RX} + E_D + E_{TX}(ZCH_k, BS)) & \text{if } d(ZCH_k, BS) < V_D \end{cases} \quad (22)$$

where, $d(ZCH_k, BS)$ is the distance between ZCH and BS and ZCH_R is the relay ZCH that lie within the transmission/reception range V_D and $E(ZCH_k)$ is the residual energy of ZCHs. In the proposed routing algorithm, a multi-hop communication is used to improve communication efficiency and reduce long communication cost using FPA. If the distance $d(ZCH_k, BS)$ is greater than V_D there is a requirement to consider an adjacent ZCH as a relay to send its data to BS. To achieve load balancing, relative distance factor (D_f) is considered, defined as

$$f_3 = D_f = \frac{d(ZCH_k, ZCH_R)^2 + d(ZCH_R, BS)^2}{\max_{k,R}(d(ZCH_k, ZCH_R)^2 + d(ZCH_R, BS)^2)} \quad (23)$$

Distance factor D_f is associated to the total sum of distance in-between the source ZCH and relay ZCH and relay ZCH and BS. If ZCH_k is away from the BS, then it chooses a ZCH_R as a relay node. ZCH_R with the least cost of link will be selected to relay the data sensed by ZCH_k.

VI. SIMULATON RESULTS

In order to optimize energy consumption of robots in MRS, the design of network scenario which executes FPA for ZCH selection and optimal route establishment is demonstrated via computer aided simulation. The simulation results of FPA-EERP have been analysed in terms of performance metrics such as energy efficiency and network lifetime, and are compared with LEACH [41], hierarchical cluster-based routing (HCR) [42], evolutionary based clustered routing protocol (ERP) [43], distance-based residual energy efficient stable election protocol (DRESEP) [44] and harmony search algorithm based energy-efficient routing protocol (HSAERP) [45]. The mobile robots are considered to be powered by a

Table I Dead robot round history for E_{01} = 6.66 kJ and E_{02} = 13 kJ

% dead Robots	LEACH		HCR		ERP		DRESEP		HSAERP		FPA-EERP	
	E_{01}	E_{02}	E_{01}	E_{02}	E_{01}	E_{02}	E_{01}	E_{02}	E_{01}	E_{02}	E_{01}	E_{02}
1 (FRD)	971.6	1806.2	871.4	1727	1039.1	2114.3	1563.8	4102.6	2439.5	4902.8	**2513.85**	**5052.1**
10	1006.4	2021.8	1008.6	2049.6	1159.5	2277.3	2263.4	4505.2	2621.5	5266.8	**2744.45**	**5517.3**
20	1038.2	2068.3	1061.6	2188.6	1199.7	2365.4	2464.9	4768.9	2734.75	5493.3	**2818.4**	**5665.2**
30	1061.5	2142	1114.2	2316.3	1238.6	2439	2561.4	4882.4	2776.45	5576.7	**2894.2**	**5812.8**
40	1074.9	2168.4	1164.9	2421.2	1266.9	2508.5	2681.6	4984.5	2832.55	5688.9	**2986.1**	**5996.6**
50 (HRD)	1168.6	2216.2	1229.6	2525.6	1293.9	2581	2781	5127.7	2877.3	5778.4	**3093.25**	**6208.9**
60	1207.9	2281.1	1266.9	2628.9	1318.8	2649.9	2842.9	5295.2	2977.85	5983.5	**3199.95**	**6424.3**
70	1266.6	2347.3	1307.2	2753.2	1361.1	2745.8	2881.4	5396.4	3051.1	6128	**3268.9**	**6566.2**
80	1317.5	2395.8	1354.6	2917.8	1411	2838.3	2981.9	5622.1	3138.8	6305.4	**3425.1**	**6874.6**
90	1368.2	2486.6	1412.9	3108.1	1478.3	2984.3	3081.5	5771.7	3321.9	6667.6	**3633.95**	**7293.3**
100 (LRD)	1671.8	2764.5	1742.3	3575.3	1608.8	3306.9	3201.3	6403.2	3543.2	7108.2	**4075.15**	**9174.7**

Lithium-Polymer (Li-Po) battery (2200mAh = 88 kJ), which drives motors, control system and sensors. Also, it is assumed that a portion of energy (330mAh = 13 kJ) is used for powering LoRa module (Microchip RN2483) for transmitting and receiving data. Here, three cases are simulated at different initial energy levels for communication i.e., E_{01} = 6.66 kJ (50%) and E_{02} = 13 kJ (≈100%). The parameters used for the protocol simulations in network are given below:

- Number of robots = 80
- Area =100m×100m
- Location of BS = (50, 120) (Outside Area)
- Length of data packet: 40,000 bits
- Initial energy, E_{01} and E_{02} = 13 kJ and 6.66 kJ
- Radio energy, $E_{TX} = E_{RX}$ = 500 µJ/bit
- Energy for data-aggregation, E_D = 50 µJ/bit
- Radio amplifier energy, ε_{friis_amp} = 1000 nJ/bit/m^2
- Radio amplifier energy, $\varepsilon_{two\_ray\_amp}$ = 0.013 J/bit/m^4

Simulation results are produced by deploying 10 robots per outer zone, making a total of 80 robots. The network consist of robots having initial energy E_0 and BS is located at (50, 120) i.e., outside the area to be explored. FPA-EERP protocol performance is evaluated in terms of stability period (the time interval or the rounds before the first robot becomes inactive due to energy depletion) and network lifetime and further, compared with the other algorithms. The simulation results of total network lifetime for competitive protocols with initial energy E_{02}=13 kJ are shown in Fig. 7. It can be seen that FPA-EERP has maximum network lifetime, because of the reason optimal selection of ZCHs and routing path by making use of FPA, on the basis of energy and distance. The performance advantage of FPA-EERP in terms of the total network lifetime is approx. 4% as compared to HSAERP & approx. 11% as compared to DRESEP, when 50% of robots are alive. The performance improves drastically till last robot is alive i.e. approx. 20% as compared to HSAERP and approx. 27% as compared to DRESEP.

To verify the performance of proposed algorithm, the simulations are performed with different initial energy of robots. Table I shows the dead robots round history for E_{01} = 6.66 kJ (50%) and E_{02} = 13 kJ (≈100%) respectively. For the total network lifetime (i.e., time until last the robot dead (LRD)) and the stability period (i.e., time until the first robot dead (FRD)), the proposed protocol outperforms against all other protocols. Effect of robot density is evaluated the in each approach by varying the number of robots from 100 to 500 with initial energy 13 kJ. In the same parameters are used to form a simulation model, and the results are presented in Table II. The performance of FPA-EERP confirms that the consistency, firmness, and scalability of the proposed algorithm is brilliant and is appropriate to large scale MRS communication in exploration tasks.

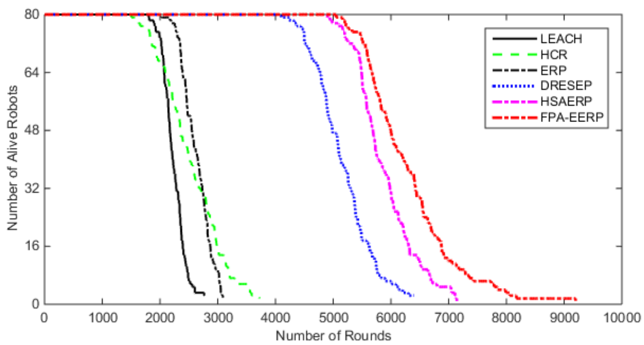

Fig. 7 Comparison of no. of alive robots per round wrt different protocols for E_0 = 13kJ

Table II Effect of robot density on the performance of FPA-EERP

Protocol	100	200	300	400	500
LEACH	2874.5	3038.8	3317.2	3593.5	3849.1
HCR	3685.3	4004.2	4218.7	4433.1	4683.3
ERP	3406.9	3571.4	3714.2	3825.6	4016.8
DRESEP	6513.2	7491.6	8015.9	8977.7	10144.7
HSAERP	7218.2	7821.1	8446.7	9091.75	10228.5
FPA-EERP	**9272.7**	**9546.8**	**9846.5**	**10748.2**	**12248.5**

VII. CONCLUSION & FUTURE SCOPE

In this correspondence, various approaches for multi-robot communication were reviewed, considering the

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communication constraints involved in the field of multi-robot communication. This paper addresses the problem of routing of data by robots, which are spatially dispersed in zones, to BS at specific time instants, while ensuring an efficient communication and increased network life time. A framework for multi-robot communication using FPA is proposed for transmission and routing of data between ZMR to ZCH, ZCH to ZCH and ZCH to BS. This information is further utilized by SLAM protocol at BS for efficient exploration and map making. Periodic communication helps BS to generate updated poses for ZMRs in order to empower exploration process, which in turn saves robot's energy. Simulation results shows that the proposed protocol i.e. FPA-EERP can be effectively applied in MRS for unknown environment exploration as it outperforms other methods (available in literature) in terms of energy efficiency and network life time, which leads to more freedom to explore.

In future, the investigation and applicability of proposed protocol on hardware [46] for communication in indoor and outdoor map making applications will be explored. Finally, this development will also incorporate open source codes, in order to empower researchers around the globe to develop hardware for these applications.

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