REDUCING INTERRUPTS AMONG ROBOTS IN QUANTUM-BEHAVED SWARM EXPLORATION WITH MR-LEACH

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ABSTRACT

A quantum-behaved robot exploration algorithm such as the Quantum Robotic Darwinian Particle Swarm Optimization (QRDPSO) gives stable swarm movement in unstructured conditions but suffers from communication interruptions. This paper examines the Multi-hop Routing with Low Energy Adaptive Clustering Hierarchy (MR-LEACH) to improve the inter-connectivity in the QRDPSO. The MR-LEACH identifies partitions in the network into multi-hop network paths. The multi-hop network paths allow all robots to exchange information without unnecessarily restricting the swarm's range explicitly. As a result, the QRDPSO with MR-LEACH shows seamless inter-connectivity among the robots, lowering power consumption and increasing robots' lifetime. Interestingly, this paper also shows that the QRDPSO can reach a faster optimal solution when adopting other communication protocols such as the Ad-hoc On-Demand Distance Vector (AODV) communication schema. However, swarm endurance and reduced robot loss are considered vital resources over convergence speed for a swarm robot exploration in unstructured scenarios, such as search and rescue missions.

Keywords: Communication constraints, Swarm robotics, Fault-tolerance, MR-LEACH, AODV, robot communication

1.0 INTRODUCTION

Practical cooperation in swarm robotics stems from maintaining the communication network among robots in the swarm. For tasks such as the SAR mission, the swarm robots' requirement includes preserving interconnectivity even when the communication infrastructure risk interruptions. Maintaining interconnectivity is vital so that the robots can guarantee the continuous exchange of information within the multi-hop network paths, not to restrict the team's range unnecessarily.

The Ad-hoc On-Demand Distance Vector (AODV) is a pervasive communication schema in the PSO algorithms. Nevertheless, the AODV is an example of brute communication where all nodes broadcast messages to all other nodes in the swarm where some communication is long hops. Long transmission distance and multiple relays contribute to heavy communication traffic and do not encourage efficiency. The communication schema must follow a mission-related design, i.e., based on the behaviour that one should expect from the swarm robotics, to enhance the communication of the Quantum Robotic Darwinian Particle Swarm Optimization (QRDPSO) [13].

The Multi-hop Routing Algorithm with Low Energy Adaptive Clustering Hierarchy (MR-LEACH) offers a communication protocol towards coordination and cooperation between agents belonging to the multi-robot system. The MR-LEACH follows the design and architecture of a communication protocol that offers many distributed nodes, forming multi-hop wireless networks. Routing messages from one location to another, robots as nodes in MR-LEACH applications can act as hosts and routers. The MR-LEACH behaves differently over other communication networks because we cannot determine the connectivity and robustness as early as in MR-LEACH [2].

For this reason, enforcing the MR-LEACH protocol on the communication network can provide prevention from loss of connectivity [17]. The protocol also serves well as a fault tolerance strategy. Most significantly, the MR-LEACH allows node redundancy, which turns the topology dynamics into a multi-connectivity system. The definition of k-connectivity or k-fault tolerance, $k \in N$, is the exclusive communication pairing of one robot to another robot where each robot should be connected to at least k-robot disjoint paths [18]. The availability of this bi-connectivity means that in the worst-case scenario, a k connected MR-LEACH requires the failure of k robots to get disconnected.

Multi-connectivity is highly favourable for fault tolerance and boosts communication capacity. Establishing bi-connectivity is a critical contribution of MR-LEACH regarding multi-robot system application, and the approach is gaining popularity [19]. So the central aim of this paper is to describe the QRDPSO and the adoption of the MR-LEACH schema as a communication protocol towards robot interconnectivity and mobility, which conserve the robot's energy and extend the robot's lifetime during exploration.

In the next section, we present a review of the related work for this research. In section 3.0, we propose a method to extend the QRDPSO algorithm with the MR-LEACH schema. Experiment procedures are described in Section 4.0 and followed by discussions on experimental results. The paper is concluded in Section 5.0.

2.0 RELATED WORK

Communication is the practical resource in the network's resources where the performance improved robust collective communication. Development teams require autonomous communication between robots for surveillance missions. With MR-LEACH as protocol, the robots can maintain an explicit exchange of messages in the multi-hop network without restricting the team's range. In Baroudi [12], a wirelessly energy-charged (WINCH) protocol is proposed to maintain communication links with battery maintenance, combining low-energy adaptive clustering hierarchy-centralized protocol (LEACH-C) and the routing process wireless networks. The experimental results show the WINCH protocol has better energy consumption performance, network throughput, and coverage, demonstrating effectiveness than traditional protocols.

The multi-hop routes are established and used between the nodes to maintain the network's full connection [13]. This way, the communication link's quality can be measured, helpful in restricting the robot's movement. Kaur & Kumar introduced a LEACH optimization to the communication protocol where at initialization, nodes are randomly selected to become a cluster head (CH) [4]. When a node becomes CH, it is responsible for performing broadcasting advertisement messages. Upon receiving this advertisement message, other non-cluster nodes will decide to join a particular CH depending on the Received Signal Strength (RSS). The CH creates time-division multiple access (TDMA), i.e., a router table, to transmit each node's schedule in the cluster. The CH then compiles or aggregates the data from various nodes inside the cluster and sends it to the base station. At every other step, a different node is selected as CH. Except for the beginning, where nodes are randomly chosen as CH, at every other step, the node with the highest energy concentration wins the selection. Equation 1 is the formula used by the CH to distribute load among all participating nodes.

$$T(n) = \begin{cases} \dfrac{p}{1 - p * \left(r mod \frac{1}{p} \right)} ifn \in G \\ 0 \qquad\qquad\qquad otherwise \end{cases} \qquad (1)$$

Where,
P is the percentage of nodes to be elected as cluster heads in the whole network,
r is the current round (or step), and
G is the set of nodes that have not been cluster heads in the last $1/P$rounds.

Clustering is essential for wireless sensor networks [8], and in MR-LEACH, it is termed the multi-hop clustered algorithm. Jiang et al. proposed an energy-balanced unequal clustering (EBUC) communication protocol able to partition the sensor network and turns them into many uneven clusters [26]. Hence, one source communicates to the base station via a multi-hop channel [27]. This way, any node with the highest energy level can promote itself to become a CH. In equation 1, nodes that are CH in round r is limited from the selection in the next 1of P rounds. One issue associated with LEACH is that all CH must reach the base station in a single hop.

Depending on the signal transfer range between a sensor node and its receiver, a node can select a CH from the broadcasted list of available candidates. After the formation of CHs, different clusters will choose their base stations. The cycle is repeated until the completion of it. The varying size of clusters and the various cluster hierarchy level in the same network is challenging for scheduling. It is observed that the absence of TDMA leads to wastage of energy. For improvement, Lee et al. discussed the utility of an energy-efficient scheme call the Location-based Unequal Clustering Algorithm or LUCA [27]. LUCA localizes the nodes and forms CHs depending on the cluster's distance from the targeted sink. The farther a cluster from its sink, the more significant is the cluster size. Distant clusters take more energy than those nearer to the base station.

Protocols such as the Hybrid Energy-Efficient Distributed (RHEED) is introduced to support efficient clustering routing [9]. The main objective of RHEED is to spread out the energy consumption so the network lifetime can be extended and to minimize energy wastage during CH selection. RHEED can also reduce the control overhead of the network to a minimum. RHEED outperforms the HEED protocol by more than 20% in a network's lifetime and residual energy [9].

The efficient clustering protocols are offered to prolong the network lifetime. For example, the Energy Adaptive Cluster Hierarchy Mobile Enhancement or LEACH-ME is reported to contribute to network lifetime, energy consumption, and packet transmission stability [20]. Another example is MR-LEACH, which can enhance the network lifetime and reduce power consumption [21][23]. To summarize, the following are the MR-LEACH advantages:

1. Scalability: CHs are supposed to manage the network by listening and picking up data from the neighbourhood's communication traffic. Clustering topology can improve CHs performance by first dividing the sensor nodes into different classes of clusters, each with a particular assignment. In a clustering routing scheme, the clustering topology can set up a route from inside the cluster so that the routing table in each node are not overwhelmed. In comparison to flat topology, the clustering topology is more compact and more comfortable to sustain. The clustering topology is also more scalable than the flat topology when a larger node community is present [4].

2. Data Aggregation/Fusion: The CHs are responsible for aggregate data from within its clusters and other CHs. So internally, a member in the cluster only has to direct messages to its CH. The CHs will compile the data and transmit it to the sink or base station. Such an organization removes redundancy significantly and positively effective in saving network energy. With the introduction of this clustering data aggregation technique, the CHs multi-hop can form a tree structure for data transmission, significantly reducing energy wastage [20].

3. Less Load: With the elimination of redundant data transmissions, the network is given a new vantage point of view to review the problem (target) from other perspectives [21]. The network can trace and make a better estimation as data is cleaner with less noise.

4. Less energy consumption: Clustering of the intra-cluster and inter-cluster decreases the number of sensor nodes executing the task of long-haul communications, thereby making the entire network less energy consumed. CHs alone will manage the clustering system's data transfer function [6].

5. More Robustness: Clustering of the routing scheme helps manage network topology and suits network shifts such as node rise, node instability, and intermittent failures. A grouping routing scheme must respond only geographically with these shifts, making the whole network more resilient and more comfortable to handle. CHs are usually rotated between all sensor nodes to avoid a single point breakdown of the routing algorithms' clustering [9] to share the CH function.

6. Load Balancing: Load balancing can prolong the network lifetime in WSNs. Even distribution of sensor nodes among the clusters helps accomplish cluster construction where CHs must perform data processing and intra-cluster management. Generally, equal-sized clusters can sustain the CHs and prevent premature energy exhaustion. For the alternative, the multi-path routing can also lead to achieving load balancing [7].

7. Fault-Tolerance: In dynamic scenarios, sensor nodes suffer from energy depletion, transmission errors, hardware malfunction, and malicious attacks. Many small sensor nodes are deployed in some applications like hurricane modelling and vision tracking, with each sensor node's cost-constrained. With the cost constraints, quality of sensor nodes, and the hostile environment, the sensor networks are prone to failure. Fault tolerance is crucial to reduce data loss from key sensor nodes. Re-clustering is the most intuitive fault-tolerant method to recover from a cluster failure, albeit the mess created during ongoing operation. Assignment of CH backup is a crucial aspect for recovery from a CH failure [10].

8. Latency Reduction: When a WSN is divided into clusters, only CHs perform data transmissions out of the cluster, avoiding collisions between the nodes. Collision avoidance subsequently reduces latency. Usually, data transmission is performed hop by hop and flooding in a flat routing scheme, but in a clustering routing scheme, only CHs perform the task of data transmission. Data transmission by CHs decreases hops from the data source to the base station, reducing latency [12, 16].

The section next describes the QRDPSO and the adoption of the MR-LEACH schema as the communication protocol.

3.0 QRDPSO ALGORITHM

This section presents the robot team development for unstructured scenarios, describing one robot's communication and deployment to another robot within a multi-hop network path. The complete conversion of the QRDPSO algorithm from its predecessor, the Robotics Darwinian PSO (RDPSO)[1], can be found in [13]. The development of the QRDPSO revolves around parameters $is_{ij}(t)$ and $im_{ij}(t)$ into the term $(X_{i,n}^{j} - C_{n}^{j})$; thus, we obtain the QRDPSO as follows:

$$X_{i,n+1}^{j}(t+1) = P_{i,n}^{j} \pm \left(\alpha_1 \left|X_{i,n}^{j} - C_{n}^{j}\right| + \alpha_2 \left|X_{i,n}^{j} - im_{n}^{j}\right| + \alpha_3 \left|X_{i,n}^{j} - is_{n}^{j}\right|\right) \ln\left(\frac{1}{u_{i,n+1}^{j}}\right) \tag{2}$$

From (2), the coefficients αi, is given by $i = 1,2,3$, and μ is a random number between [0,1]. In the above formula, we can assign the avoidance component and network connectedness enforcement component to determine the new position. Each component's parameters are random vectors, which are mentioned as zeros and ones. $X_{i,n}^{j}$ represents the best position for the local, obstacle, and MR-Leach components [13].

The connectivity component X_2 is represented by the position where there is connectivity with its neighbour, connectivity function $im_i(t)$. The obstacle component X_3 which is represented by each robot's position is optimized monotonically by increasing or by decreasing obstacle sensing function $(s(x_i(t)))$ [13].

In short, the QRDPSO allows several complex groups of robots to be split into many smaller networks. Any group communication depends on the multi-hop clustering hierarchy to share information between robots. We assume that robots will communicate with the same community as the network, making the QRDPSO applicable to many robots spanning broad regions.

3.1 Communication between the robots

For the swarm robot to maintain communication, we describe the connectivity between robots (cluster head, non-cluster) using Multi Routing-Leach as a communication protocol, the following steps presented in [2,3]:

1. Every node randomly chooses to become a cluster head (CH), which determines a random number of n nodes (robots) between none and one. If the number obtained is less than a threshold $T(n)$, according to the previous Equation (1), the node becomes a cluster head.
2. A cluster head transmits "Hi" ads to the node surrounding it.
3. When each non-cluster node receives this message, it will agree to enter a specific CH based on the distance.
4. CH generates a TDMA (Multiple Access Time Division)-based transmission plan for each cluster node. The cluster headsets a contact time frame for any member node within the cluster based on the TDMA cluster heads; these members can only generate a signal for the transceiver at a given time frame for successful use of resources.
5. CH aggregates the data obtained from the nodes in the cluster and sends it to the CHs to find the best solution.

The link matrix $L = \{l_{i,f}\}$ which can be calculated as functions of either distance $_{Dmax}$ between cluster head and non-cluster. Together, they form the adjacency matrix $A = \{a_{if}\}$ and can be defined as follows [11]:

$$a_{ij} = \begin{cases} 1, nodes\ i\ and\ f\ connected \\ 0, no\ connection \end{cases} \tag{3}$$

Using the hop distances (CH's distances), i.e., the number of hops that interact with the zero-valued off-diagonal entries in the adjacency matrix, can be manipulated to create a multi-hop connectivity matrix$C^k = \{c_{i,f}^{k}\}$, where the entry (i, f) represents the least number of hop count needed to connect nodes i and f. k Represent the iteration with the number of varied hops of the network. The connectivity matrix can be defined as follows [11]:

$$c_{ij}^{k} = \begin{cases} h, i\ connected\ to\ f\ by\ h \le k\ hops \\ 0, otherwise \end{cases} \tag{4}$$

Regarding the MR-LEACH connectivity, when a robot corresponds to a node to monitor the connectionless system between them, we desire the position of each robot $X_{i,n+1}^{j}$ should be controlled since it influences the link matrix. To keep a good communication network or keep a good connection with a robot's nearest one, each robot must be forced and communicated accordingly. Since the connectivity is a lot influenced by the distance and connectivity of nodes, we compute the minimum or maximum value of each line of the adjacent matrix A, after excluding zero values and the (i,f) pairs that had previously been chosen. Therefore, a connectivity function $m\left(x_{i}(t)\right)$ is defined following recommendation in [3]. A higher $\alpha 2$ will enhance the ability to maintain a network connection.

3.2 Communication Optimization via MR-LEACH

The AODV is an example of brute communication where all nodes broadcast messages to all other nodes in the swarm where some communication is long hops. Long transmission distance and multiple relays contribute to heavy communication traffic and do not encourage efficiency. The communication schema must follow a mission-related design, i.e., based on the behaviour that one should expect from the swarm robotics, to enhance the communication of the QRDPSO. For the MR-LEACH schema adopted in this work, the implementation has the following steps:

1. Validate the proposed QRDPSO model with MATLAB simulation.
2. Compare the performance of QRDPSO MR-LEACH against another routing protocol such as AODV.
3. Validate the stability of QRDPSO MR-LEACH under various conditions.

Briefly, enhancing QRDPSO communication requires a strategy to handle the communication traffic in a more sustainable method. One approach to avoid brute communication is to look into clustering the swarm into multiple smaller groups. The following subsection describes this strategy.

3.2.1 Sharing information in the QRDPSO

The QRDPSO ensures connectivity of the network from $m(xi[t])$. Nevertheless, brute communication and long-hops create more traffic, which can overwhelm the network. Packet data structure shared between robots is defined to send messages (see Fig.1). The number of bytes needed for the critical message, i.e., data byte(s), would rely on the message itself. For example, if a robot needs to communicate its location and accept a planar situation, then two bytes might be appropriate to reflect the coordinates on-axis.

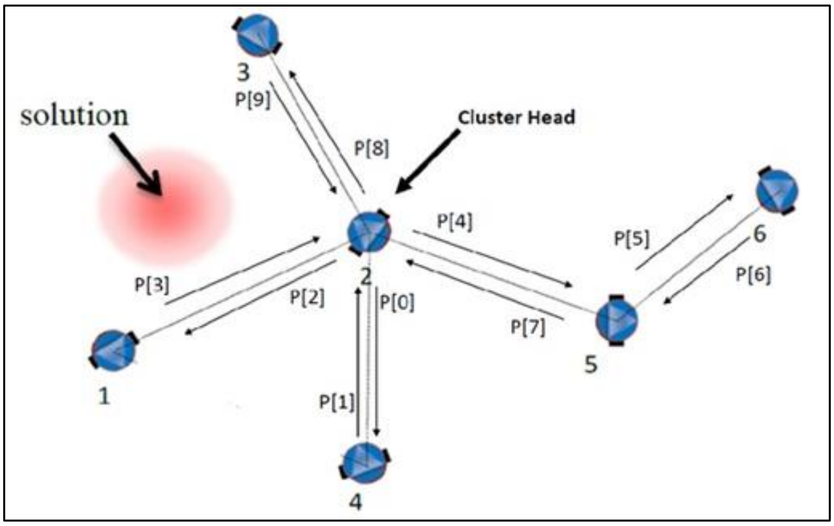

Fig. 1: General communication packet structure for a subgroup of Ns robots

A strategy to cluster the swarm network is introduced to the QRDPSO. The method includes labelling each robot with a robot ID and each swarm division with a cluster head ID. For the swarm robot to maintain communication, the connectivity between robots (cluster head, non-cluster) using MR-LEACH as a communication protocol is described as the following steps:

1. Each node automatically wants to become a cluster head (CH), where each node (robot) selects a random number between zero and one. Unless the amount obtained is less than the maximum T(n), the node must become a cluster leader,
2. The cluster head sends the "Hi" greeting to all the nodes surrounding it,
3. On receipt of this post, each non-cluster node agrees to enter a specific CH based on the smallest size.
4. CH generates a TDMA (Time Division Multiple Access) transmission schedules for every cluster node. The cluster head allocates the contact time slot for each member node in the cluster centred on the TDMA cluster heads; these members will obtain the transceiver signal only on a specified time slot for successful use of resources, and
5. CH aggregates the data obtained from the nodes within the cluster and sends it to the CHs to find the best answer for them.

Applying equation (4), the link matrix $L = \{l_{i,f}\}$ can be calculated as functions of either distance $_{Dmax}$ between a cluster head and a non-cluster. Together, they form the adjacency matrix $A = \{a_{if}\}$. Equation (5) can be adopted, and the connectivity matrix can be defined similarly to calculate the cluster head hop distance. A connectivity function $m(x_i(t))$ is then defined. A higher $\alpha 2$ will enhance the ability to maintain a network connection. To further understand how the QRDPSO supports the MR-LEACH connectivity, considers the topology in Fig. 2.

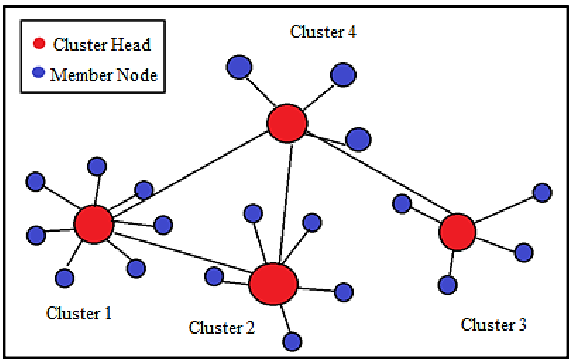

Fig. 2: MR-LEACH connectivity topology

Fig.2 shows an illustration of the MR-LEACH schema with multi-hop clustering routing. A swarm can be divided into smaller divisions so long a CH is appointed, and the robots are labelled. However, each pair of nodes must be at least two disjoint routes between the network, so the network partition is not influenced by a single node's failure. We propose a clustering hierarchy fault-tolerant system so, at any time, the CHs can use an exclusive channel to send messages between the robots.

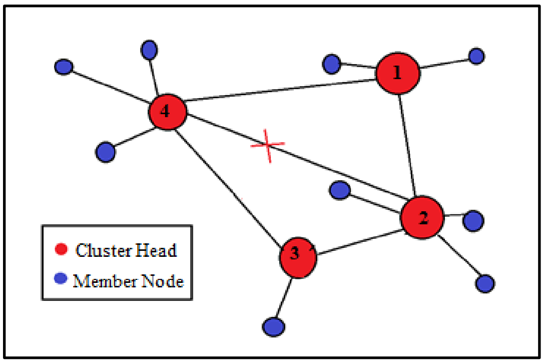

Fig. 3: Clustering hierarchy for MR-LEACH connectivity

Fig. 3 shows CH robot 2 is the nearest neighbour to CH robot 1. The nearest neighbour of CH robot 2 is CH robot 3. However, the distance between them is smaller than CH robot 2 and CH robot 4. Finally, the nearest, not previously chosen, a neighbour of CH robot 4 is robot 1 and 3. If a robot fails due to energy depletion, for example, CH 2 fails, robot 1 will be unable to communicate with robot 3, but robot 3 can connect to another channel with robot 4. Here, the bi-connectivity that is $k = 2$ will be enough to get the desired performance in simple exploration (e.g., to find a gas leak in a room in military application) then the necessity of more connected MR-LEACH can be increased ($k > 2$). Algorithm 1 is the MR-LEACH algorithm for cluster formation.

Algorithm 1: Cluster formation with MR-LEACH

```
Node = Sensing Node
S= Set of all Sensing Nodes in the Network
Neighboring Nodes = Null; // When no neighbors discovered
for $\forall$ Nodes $\in$ S
      Broadcast _ HELLO (nodeID, Energy);  // nodeID = Robot ID
for $\forall$ Nodes $\in$ S
      begin
          Re cv _ BroadCast _ MSG(nodeID, energy)
          ID= NeighbouringNode.searchNodeID(nodeID)
      if (ID$\neq$ nodeID)
         NeighbouringNode.insert(nodeID, energy)
end
for $\forall$ Nodes $\in$ S
       begin
          nodeWithHigestEnergy = neighbouringNodes.getHighestEnergy()
       if (nodeWithHighestEnergy < nodesEnergy)
           BROADCAST _ HEAD _ MSG(nodeID)
       end
       for $\forall$ Nodes $\in$ S
           begin
           Rev _ Head _ MSG(ID)
            Cluster _ Head.insert(ID, ReceivedSignalStrength)
      end
       for $\forall$ Nodes $\in$ S
          begin
              Select Cluster Head; //non-cluster node will decide to join a CH following smallest distance
              Send _ Cluster _ Join _ MSG(ID);
        end
      for $\forall$ ClusterHeads $\in$ S
         Recv _ Join _ MSG(ID)
end
```

3.2.2 Converging to the Optimal Solution

In section 3, $P\ (i, n)^\wedge j$ reflects the optimal location of the system. Robots with the same successful sub-group, i.e., not in the socially removed sub-group, also ought to exchange their best cognitive solution $[t]$ and current status $xn[t]$ location robot with the best social solution. For example, in locating a survivor, the most effective robot would be the one with the highest solution. Even if the active sub-group robot were unwilling to progress, the details of its response would be meaningless to the community, i.e., the collective actions would not alter.

As a rule of thumb, however, a robot wants to communicate its current solution and role if it can develop the best cognitive solution, i.e., $fn[t + j] > fn[t]$. Otherwise, the robots must memorize the best answer of the subgroup and the corresponding location. This data needs to be shared amongst all teammates by distributing it to the whole sub-group through MR-LEACH, thus raising robots' energy and increasing their lifetime.

Fig.4 represents the packet structure sent from a robot that was able to improve its solution. This communication packet structure allows robots from active sub-groups to cooperatively converge to the solution. The packet is only sent if a robot improves its best cognitive solution. The following sub-section evaluates the MR-LEACH communication using the MR-LEACH Simulator.

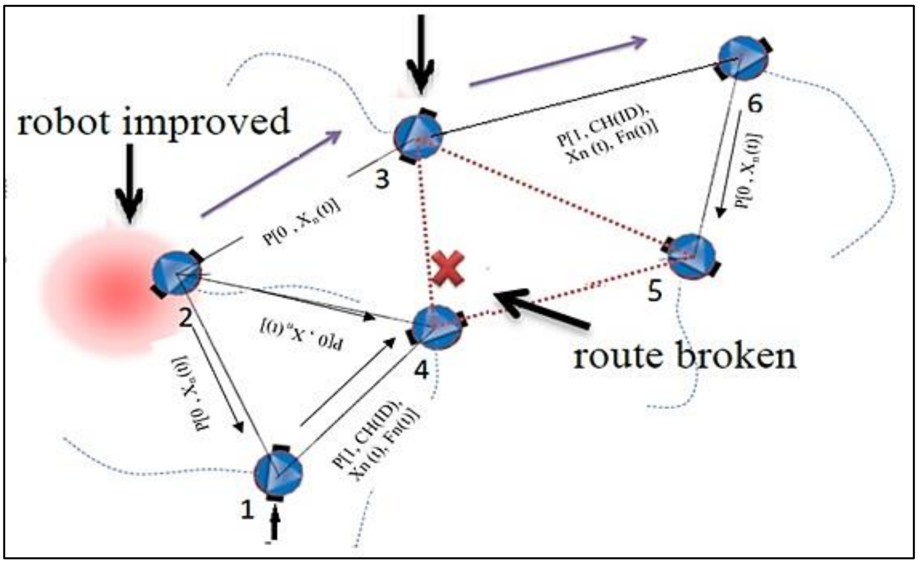

Fig. 4: Communicating the packet structure to a robot to get the best solution

3.2.3 MR-LEACH SIMULATOR

Testing the nodes' energy consumption by adaptively increasing the clustering hierarchy and testing nodes' lifetime can be done in three steps. Using the MR-LEACH simulator, the steps are:

1. Remove the sink. Sink means single-hop. However, a swarm needs multi-hop to continue searching (fault tolerance system). Multi-hop avoids issues when single-hop crashes [5].
2. Encourage dynamic neighbouring. Pair mobile nodes with the mobile cluster heads, and connect each node with neighbouring CHs with the smallest distance. See Fig. 5.
3. Test the MR-LEACH control with new evolutions, evaluate rounds with dead nodes, and perform energy consumption. See Fig. 6.

Fig. 5 shows the experiment with five dynamic CHs, with each CH connecting to 25 dynamic nodes. Fig. 6 shows the first experiment (see left) with three dead nodes reported at around 300. The number of nodes killed keeps increasing until round 450, where all the nodes are reportedly dead. In the second experiment (see right), the nodes' energy consumed decreases when the number of rounds increases; at round 0, all the nodes have 50 energy, which means full strength. The nodes consumed energy so much that at around 450, all nodes' energy level is depleted (dead).

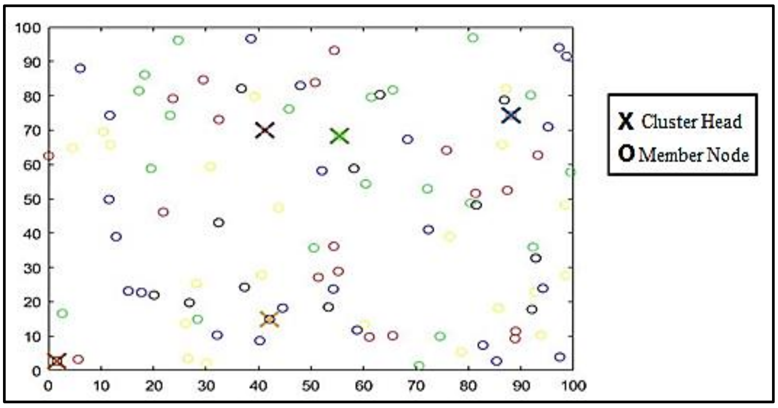

Fig. 5: MR-LEACH simulator of a 100 x100 Area

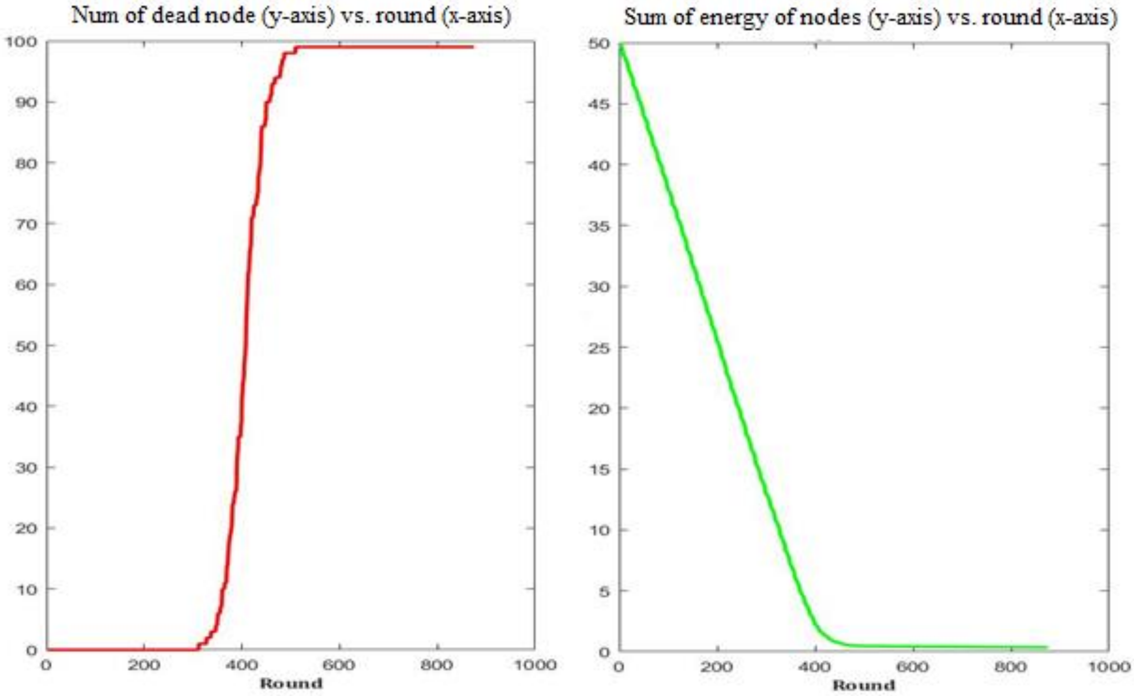

Fig. 6: MR-LEACH control with new evolutions

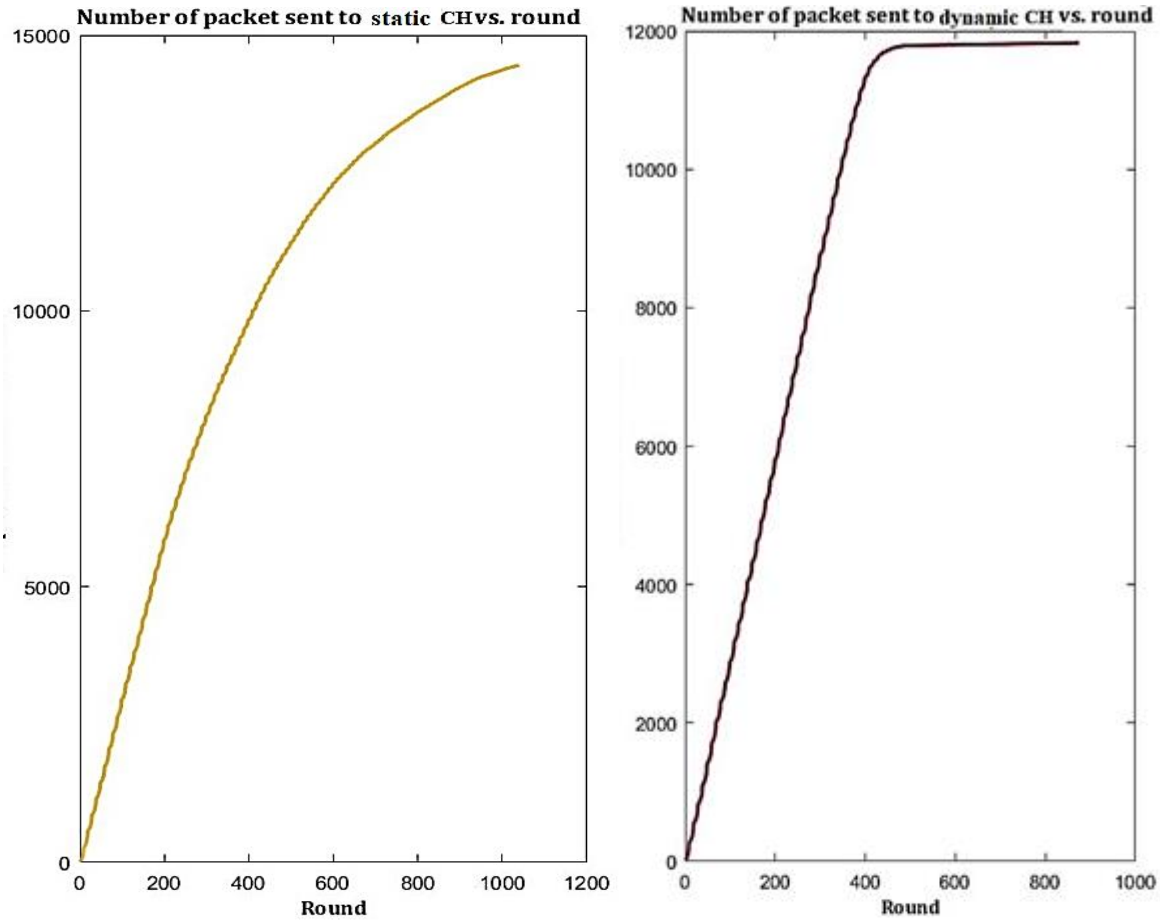

Fig.7: the number of messages sent between to (static or dynamic) cluster head and non-cluster

An experiment comparing packets' performance to convey the entire subgroup through multi-hop contact via dynamic and static routing is done. Fig. 7(left) shows increasing packets via dynamic routing reaching 11,900, slowing after round 430, where all the nodes are reportedly dead. Fig. 7(right) shows increasing packets via static routing reaching 13,000, slowing after round 800, where all the nodes are reportedly dead. Even though the static routing packets are more than the dynamic routing, it took about 800 iterations, which means the static routing could have repetitive packets (not applicable) to CH. The dynamic routing shows it can carry the volume and quality of packets over smaller iterations.

Optimizing the coordination protocol between the nodes under the MR-LEACH via dynamic routing is essential. The enhancement is inspired by the desire to utilize large robot teams without dramatically raising overhead connectivity. Note that the sum of usable knowledge can differ based on various factors, e.g., the number of robots, situation, and task goals. Section 4.0 present the experimental results and discussion.

4.0 RESULTS AND DISCUSSION

This section examines the results of two communication protocols considered for the QRDPSO, the AODV and the MR-LEACH. In the AODV protocol, the communication between robots shows interruptions. For example, in Fig. 8(a), robot no. 1 receives no communication with robot no. 4 but connects with robot no. 2, 3, and 5. In comparison, the communication in QRDPSO using MR-LEACH shows no interruption between robots, so all robots maintain a connection with each other (see Fig. 8(b)).

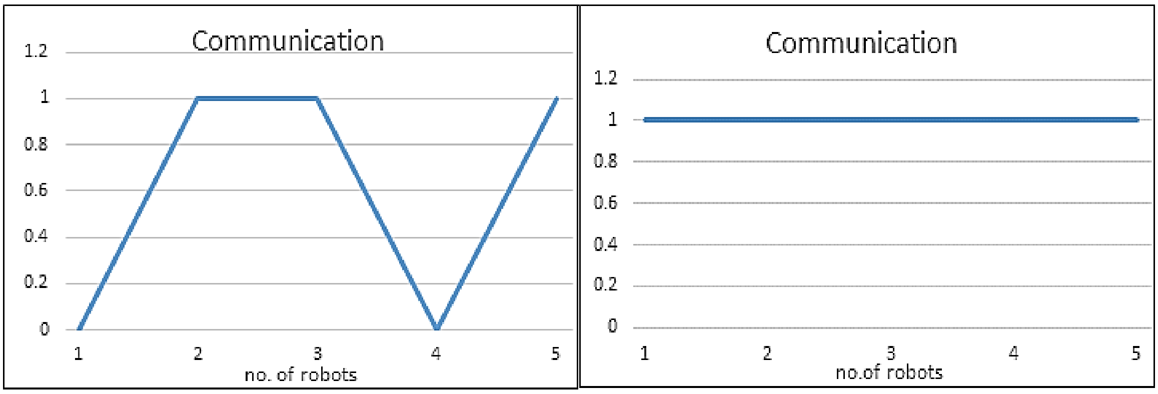

Fig 8: The AODV protocol connectivity (left) and the MR-LEACH protocol connectivity (right)

Fig. 9 shows that increasing the number of robots to 5, 10, 15, and 20 decreases the time needed to find the optimal solution. In QRDPSO with AODV, five robots can reach the optimal solution in 366 iterations. On the other hand, the QRDPSO with MR-LEACH needs 375 iterations. Interestingly, the QRDPSO with AODV can reach the optimal solution in 319 iterations, whereas the QRDPSO with MR-LEACH needs 329 iterations. A similar pattern is observed with the increasing robot population. When fifteen robots are deployed in QRDPSO with AODV search to find the victim, it needs 207 iterations, whereas the QRDPSO with MR-LEACH needs 220 iterations. Finally, when 20 robots are deployed to search the victim (or the optimal solution), the QRDPSO with AODV requires 180 iterations and QRDPSO with MR-LEACH needs 202 iterations to reach a victim. These results show that even with interrupts, the AODV performs better when it comes to convergence speed.

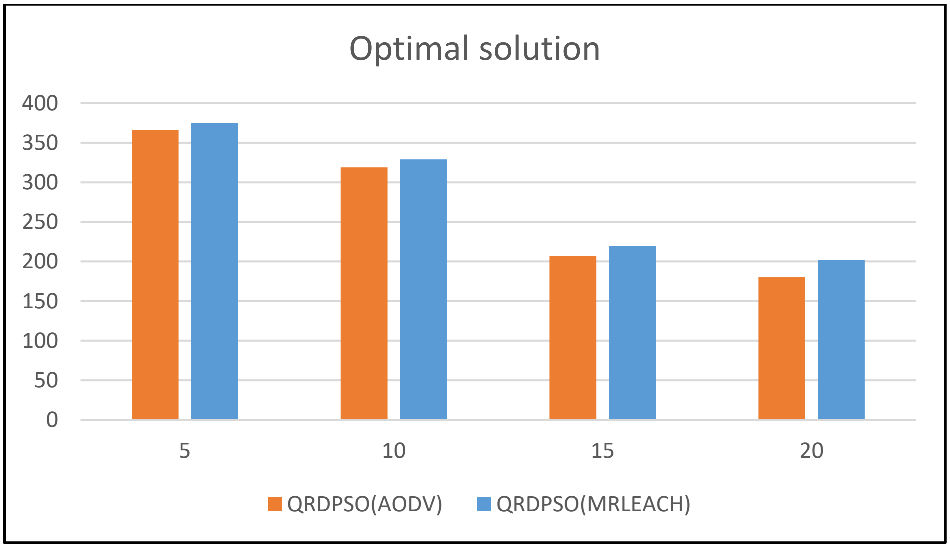

Fig. 9: ComparisonQRDPSO between the AODV and MR-LEACH convergence performance

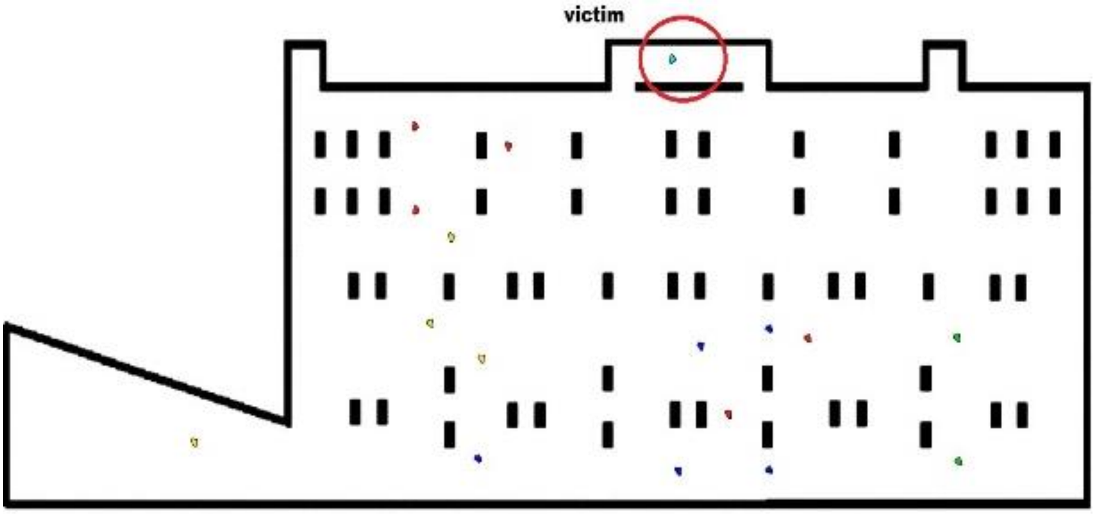

Fig. 10: A 300x300m environment used in the experiment

Fig. 10 shows the environmental design to examine the number of robot kills between the QRDPSO with AODV and MR-LEACH. In Fig.10, the rectangular blocks represent random obstacles generated. The triangular markers represent robots. The triangular marker marked in the red circle represents the victim at a random location unknown to the robots.

Fig. 11 shows the environment shown in Fig. 10 when the AODV communication protocol is adopted for the QRDPSO. A group of robots, shown by triangular markers in the simulation, successfully located the victim marked by the red circle. One robot marked in a blue circle is facing some trouble navigating and gets stuck in local optima. Three robots marked in the black circle have lost communication with the swarm. The lost robots are moving randomly in the hope of regaining range and communication with the swarm. These robots can rejoin the swarm to reach the victim if they can receive signals from any of the robots in the swarm.

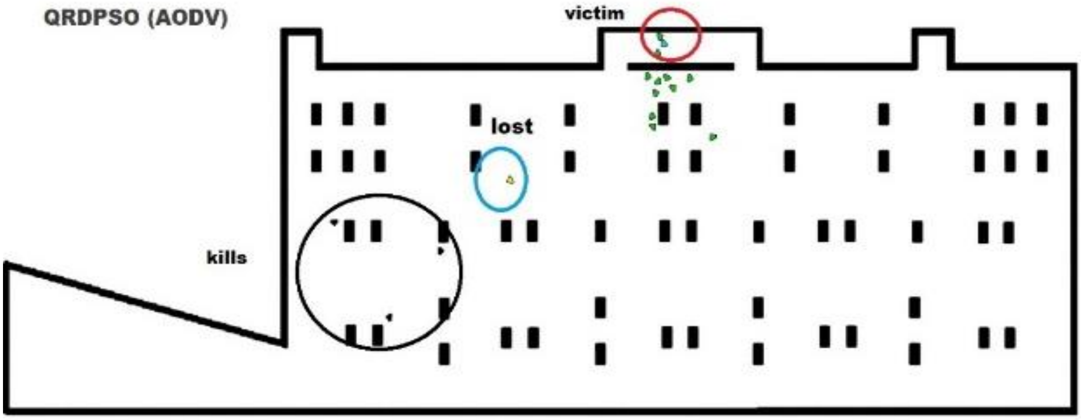

Fig. 11: An experiment showing the QRDPSO algorithm with AODV schema.

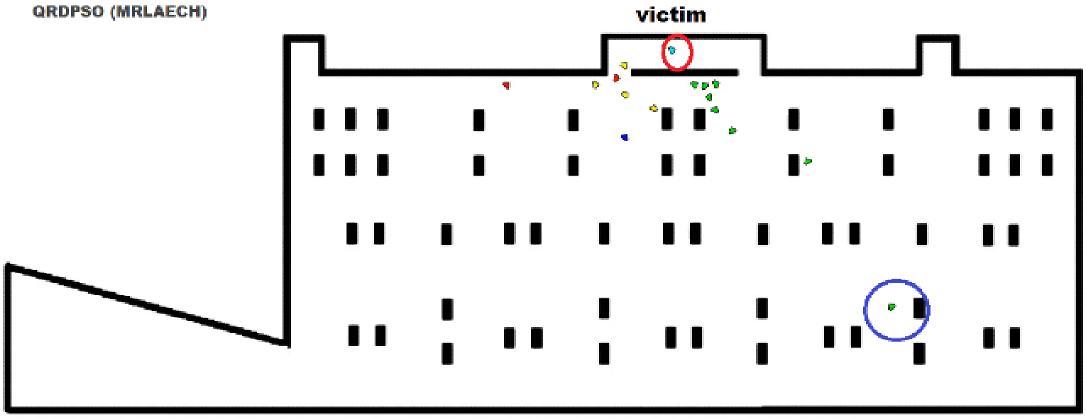

Fig. 12: An experiment showing the QRDPSO with MR-LEACH schema.

Fig. 12 shows the environment in Fig. 10 when the MR-LEACH schema is used to extend the QRDPSO. Similar to the setup in Fig. 11, triangular markers are used to denote robots. The victim is marked using the red circle, and a wandering robot is marked in the blue circle. In Fig. 12, only one robot is stuck in the local optima, and the rest can successfully reach the victim. Note that none of the robots is lost when the MR-LEACH is adopted. The MR-LEACH can maintain inter-connectivity among the robots in the swarm and reduce communication interruptions.

Fig. 13 shows a comparison between the QRDPSO running AODV and the QRDPSO with MR-LEACH. It is observed that increasing the number of populations of robots to 5, 10, 15, and 20 increases the number of robots lost when QRDPSO with AODV is used. When the MR-LEACH is used, the QRDPSO can find the optimal solution without robot loss.

Another attribute that is investigated in the experiment is channel availability for fault tolerance. Autonomous mobile robots have difficulty carrying out complex mission in a dynamic environment. In this study, a fault-tolerant system is designed for autonomous mobile robots using channel availability. Fig. 14 shows a design clustering hierarchy with cluster heads (CHs) and cluster nodes representing autonomous mobile robots. The CHs can exchange messages with each other by using any channel. Fig. 15 shows that all the mobile robots were connected, meaning they continue sending messages without interruption even when one or more clustering hierarchy components fail.

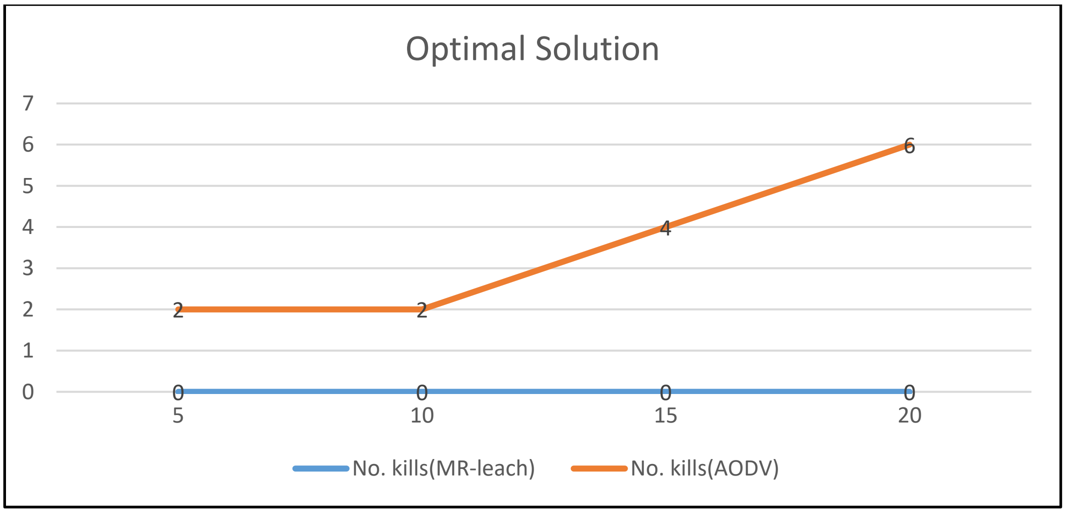

Fig. 13: Several kills robots that used the QRDPSO with AODV and the MR-Leach protocol

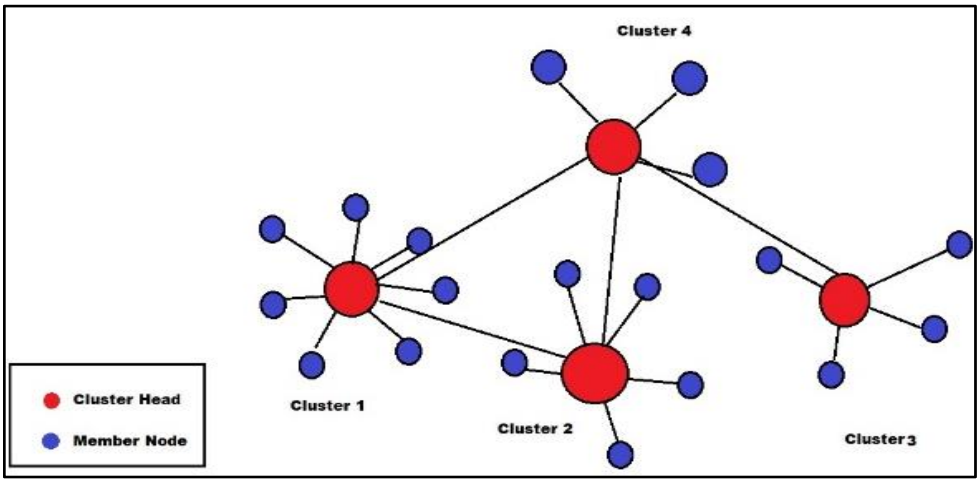

Fig. 14: Cluster hierarchy (MR-LEACH)

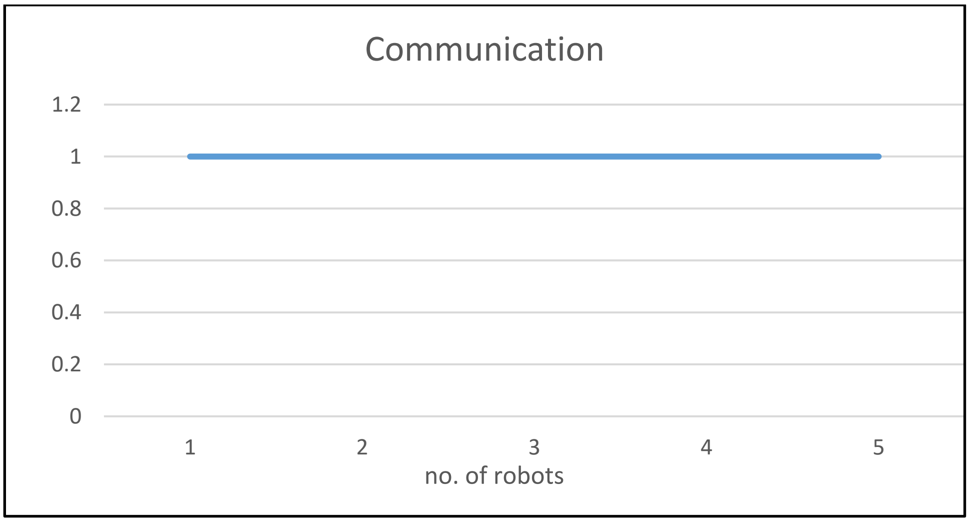

Fig. 15: Communication using MR-LEACH showing no interruptions

The number of local and global broadcasts is evaluated in Fig. 16 within each subgroup. Fifty trials are carried out to understand better how the robots develop within the quantum-behaved swarm through monitoring the local and global broadcasts. Fig. 16 represents the total number of local and global broadcasts for each subgroup order. The local broadcast increment is almost proportional to the number of robots in both QRDPSO using AODV and MR-LEACH. The key difference is seen in the number of global broadcasts between robots belonging to various social statuses, indicating a dependency on communication quality to improve the subgroups' social activities. When the total number of socially active robots decreases, the number of socially excluded robots increases. Therefore, the possibility of success also decreases, affecting the opportunity to enhance the current solution. As a consequence, this decreases the necessary number of global broadcasts from excluded subgroups.

It is observed that socially active robots using the AODV usually have a higher amount of messages flooding than the MR-LEACH through the whole subgroup. The CH creates the messaging pattern by collecting the same cluster nodes' data and sending it to the other CHs. The messaging is interesting because the global broadcast is connected to enhancing subgroups that need the population's global consent. As a result, such global broadcasts diminish over time. It appears that this kind of global messaging has significantly less recurrent in socially excluded subgroups. Notice that this dramatically decreases communication difficulty as data needs to be shared between all teammates, i.e., broadcasting multi-hop communication to the subgroup.

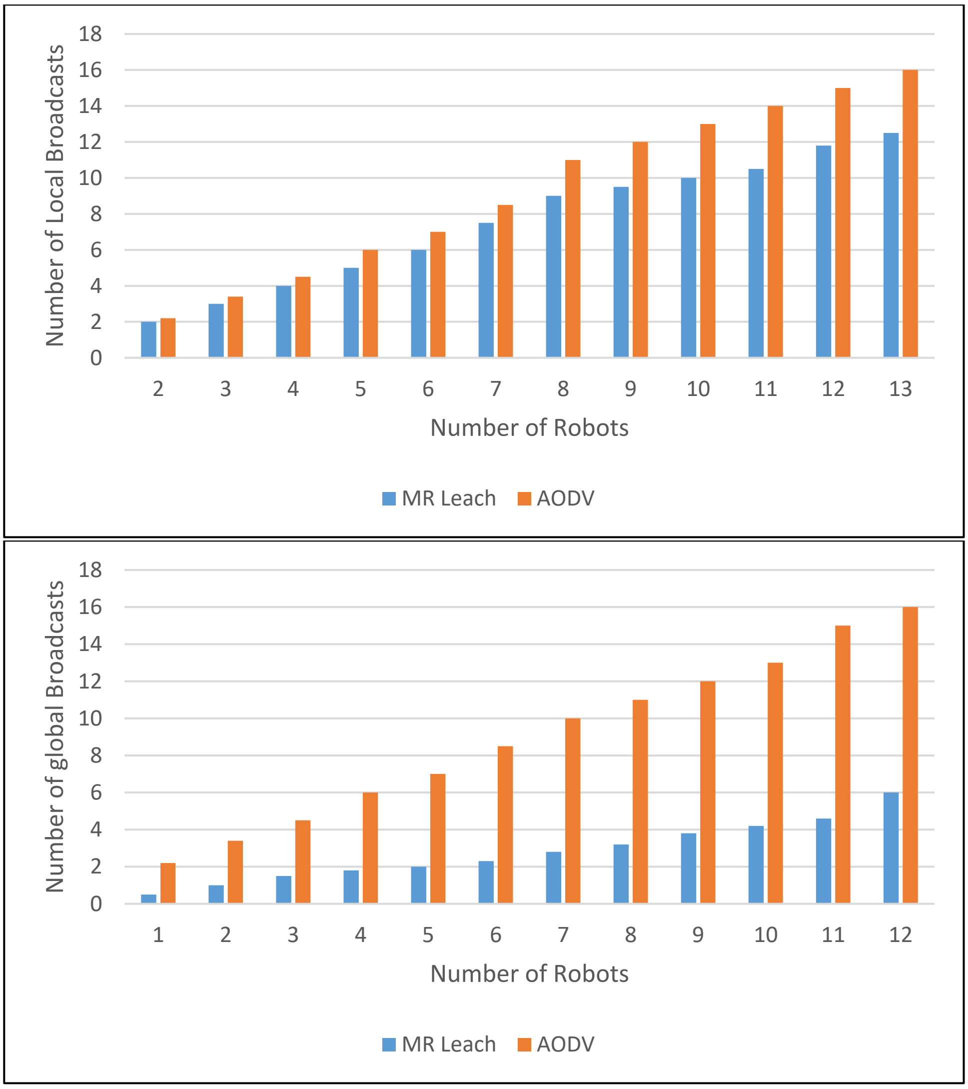

Fig. 16: The normalized average number of local and global broadcasts over time.

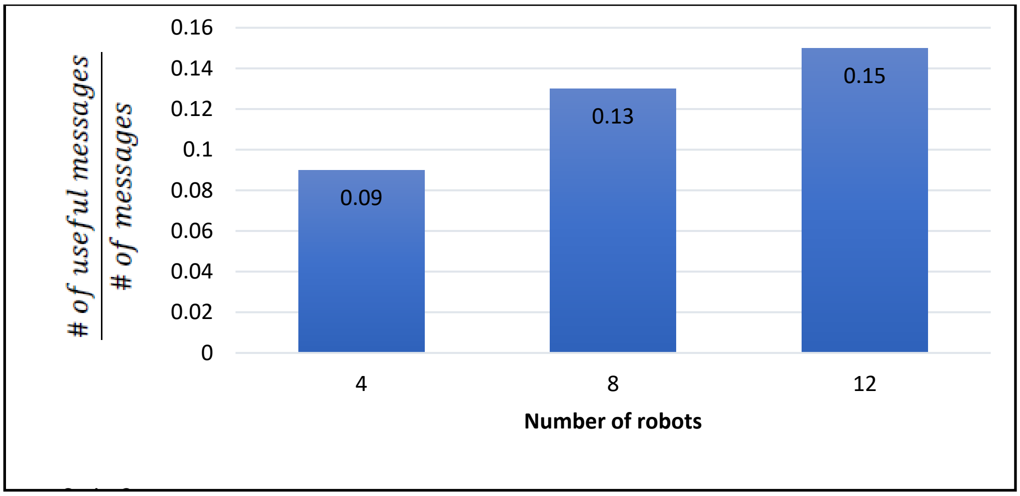

Fig. 17: The ratio between the number of valuable messages and the total number of messages received from the experimental evaluation

Fig. 17 depicts the ratio between the number of valuable messages and the total number of messages received when twelve robots are deployed. The experiment's purpose is to represent the critical condition tested to the chances that the subgroup has to improve. The experiment, involving 80 trials, observes that a robot can only improve approximately 15% of the iterations. The percentage means only about 15% of the shared information is helpful collectively. If the number of robots decreases in the same situation, the possibility of a robot improving also decreases slightly, reducing the amount of useful information slightly.

The energy consumption of nodes should be minimized to increase the lifetime of the nodes. Fig. 18 shows the different energy consumed by 20 nodes concerning the simulation time between the AODV and the MR-LEACH protocols. Based on the results obtained, it is shown that the QRDPSO running MR-LEACH consumes less energy than the QRDPSO running AODV. The result also showed that the power consumption kept increasing in both protocols when the simulation time increases. The simulation output indicates that the MR-LEACH can significantly increase the nodes' lifetime more than the AODV.

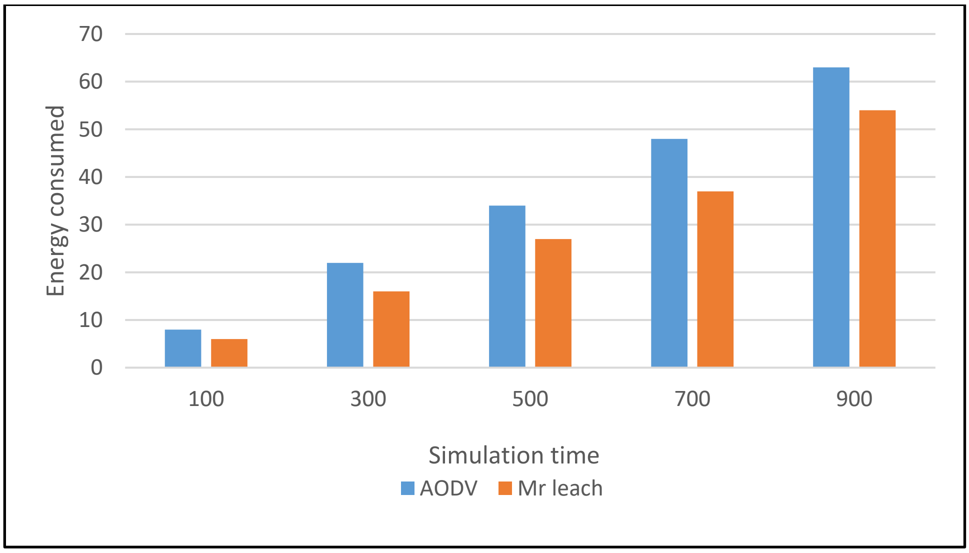

Fig. 18: Comparison between AODV and MR-LEACH energy consumption performance

Fig. 18 shows the energy consumption between the AODV and the MR-LEACH protocols, with the MR-LEACH, consumed consistently lower energy than the AODV. For example, in 700 iterations, the AODV consumed up to 55% energy compared to 38% of the MR-LEACH. When 900 iterations are executed, the AODV consumed 63% energy compared to just 48% of the MR-LEACH. So, the MR-LEACH increases the lifetime for the nodes more than AODV during search and rescue exploration.

5.0 CONCLUSION

Communication is essential for robotics swarm to maintain cooperation. This work reports an improvement in connectivity among individual robots in the QRDPSO swarm when communication protocols are introduced. Nevertheless, there is still much to explore regarding enhancing the QRDPSO swarm communication for robot energy conservation and prolonged lifetime during search and rescue exploration. In this work, adopting a multi-hop clustering routing protocol using the MR-LEACH minimizes the entire sensor nodes (robots). Interestingly, the performance analysis shows that even though the QRDPSO with MR-LEACH performs well compared to the QRDPSO with AODV in terms of the increased lifetime of robots and reduce interrupt communication, the QRDPSO with AODV can reach the optimal solution faster than QRDPSO with MR-LEACH.

6.0 ACKNOWLEDGMENT

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