Meta-Routing Paradigm For Robotic Ad-hoc Networks

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***Abstract*— With the increasing use of robotic networks, communication issues such as maintaining connections between nodes are becoming more prevalent. While previous routing protocols for wireless networks have been developed, they tend to address routing and link maintenance separately. Consequently, leading to increased costs and delays in network communication. Existing routing protocols typically focus on discovering links, connecting them, finding the most efficient path, and reducing costs associated with the path. However, their limitations have led to the development a new routing mechanism for robotic networks called Meta-Routing. Meta-Routing builds on existing routing protocols by incorporating regular routing of packets and maintenance of links in mobile agent environments. This approach aims to improve efficiency and reduce routing and link maintenance costs. In addition, meta-Routing seeks to minimize communication path costs and the overhead cost associated with discovering a route, repairing a link, or creating a new communication path among nodes. This paper presents a method for achieving Meta-Routing by controlling robot motion based on recognizing the radio frequency (RF) environment through Hidden Markov Models (HMMs) and gradient descent methods. Simulation results show that Meta-Routing, based on controlling individual robot motion, can provide self-healing capabilities in mobile robot networks, decrease network latency, and improve network performance.**

Keywords— Link Connectivity maintenance, gradient, RF mapping recognition, nod control movement

I. INTRODUCTION

Multi-robot exploration in Urban Search and Rescue (USAR) relies on routing protocols to efficiently transmit and receive information packets between robots (Voyles et al., 2009; Wu et al., 2020). These protocols are used to establish mobile ad hoc networks (MANETs), enabling the robots to work together effectively. (Devi et al., 2019). The routing process involves finding the most efficient path for transmitting information packets in a network by discovering links with the lowest cost. Routing protocols are responsible for identifying and connecting these communication links to form a path with the least possible cost. In the context of MANETs, the ability to establish a communication path between the source and destination nodes is essential for maintaining effective communication among a highly interconnected network of nodes, as shown in Fig. 1. Generally, routing protocols are responsible for two main activities: finding the optimal path with the lowest cost for transmitting data packets, and actually transferring the data packets along that path. The first activity involves determining the best route by identifying the lowest-cost links, while the second involves physically sending the data packets along that route. (Nabati et al., 2022). Routing protocols use a variety of metrics to determine the most efficient path for transmitting data packets to their destination. These metrics include the number of hops, path speed, packet loss, latency, path reliability, and bandwidth. Routing algorithms use these metrics to evaluate the network's performance and select the best path for sending data packets.

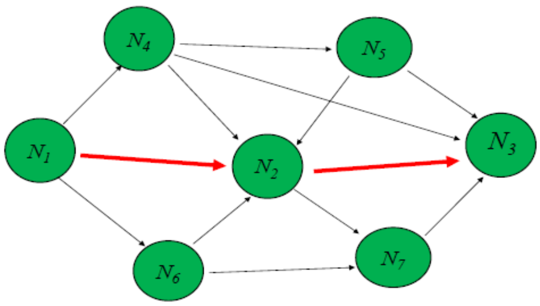


Fig.1. An interconnected network of communicating nodes.

The routing problem occurs when a device or node in a network needs to find a path to another node, but the path is unknown, and the path's complexity is also uncertain. It is a common problem in computer networks and routing algorithms while finding and maintaining the best routes, reducing network congestion, and preventing network failures. (Kumar et al., 2022). For example, Fig. 2 shows that node A attempts to connect to node B, but the path between them is undefined, and the network between node A and node B is unknown. In other words, not knowing the path between communicating nodes nor the complexity of the path are the key points of the routing problem. On the other hand, Link maintenance ensures that communication between a node and its neighboring nodes remains reliable by adjusting their operational characteristics. For example, In most cases of radio frequency (RF) communication, effective communication is typically achieved when the signal-to-noise ratio (S/N) is above a certain threshold. The S/N ratio is a measure of the strength of the signal compared to the amount of background noise, and a higher ratio indicates a more robust and precise signal. However, the ultimate goal of communication is that the robot can successfully transmit messages to its neighbor. Therefore, many reasons cause changes in the S/N ratio and lead to an adjustment of a node's operational characteristics. For example, in a static cell phone network, the mobile phone cannot move by itself, but it can increase its output power to increase the *S/N* ratio to regain communication with the base station. Another example is if it rains, the mobile phone must increase its output power to lift the S/N ratio above some threshold to maintain communication with the base station. In addition, tuning the antenna either by changing the direction of the antenna or manipulating the parameters characteristics of the antenna will vary the operating characteristics of a node.

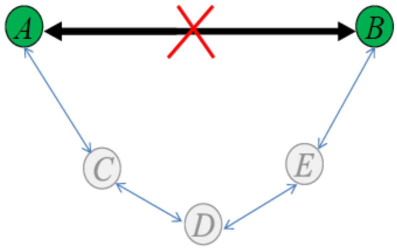


Fig. 2. Node A cannot communicate directly with node B, but it might have an indirect path.

In a wireless ad hoc network, devices communicate directly with each other without the need for a central router or access point. These networks can be helpful in situations where traditional infrastructure is unavailable or is challenging to deploy, such as in emergency response or military operations. They are also commonly used in personal area networks and in mobile ad-hoc networks (MANETs). Mobile nodes must be able to discover and connect with nearby nodes in order to establish communication and form the network. Due to the limited transmission range of wireless network nodes, it may be necessary for data to be passed through multiple intermediate nodes, or "hops," to reach its destination, which is called multi-hop communication. MANETs are composed of mobile devices that can connect and disconnect from the network at any time, creating a highly dynamic network topology. Because of this, they are well-suited for multi-robot systems and USAR (Urban Search and Rescue) scenarios, where mobility and flexibility are essential. In these scenarios, the robots can communicate with each other without the need for a fixed infrastructure, allowing for efficient coordination and information sharing. (Queralta et al., 2020). In MANETs, mobile robots act as both communication nodes and mobile platforms. They provide the network with a robust communication infrastructure by relaying data between other nodes and maintaining network connectivity. It allows for efficient communication and coordination among the robots, which is crucial in applications such as USAR, where the robots need to work together to accomplish a task. Additionally, the mobility of the robots allows them to move to areas with better connectivity or to avoid communication obstacles, which improves the overall performance of the network. In our case, if a mobile robot moves too far from the base station and causes a decreased S/N ratio, one solution would be to instruct the robot to move to a position within the transmission range to improve communication with other robots or the base station. Therefore, it ensures that the robot can continue to receive and transmit data effectively and perform its assigned tasks. Thus, the S/N ratio goes below some threshold when the robot is too far; consequently, the robot must move back into the communication signal coverage. These are examples of how the node can adjust its operating characteristics to maintain link quality above the noise threshold. This paper will focus on robot movement throughout the environment while not changing the output power, which is appropriate for static nodes.

MANETs are a type of wireless network where nodes can move around and connect to each other without needing a pre-existing infrastructure. These networks are useful in emergencies such as disasters or military attacks when traditional network infrastructure may be damaged or unavailable. Researchers have been working to improve the performance and security of these networks to ensure they can function well in critical scenarios (Tripathy et al., 2020). Another important characteristic of mobile ad-hoc networks is their ability to adapt to sudden changes in network topology. It is a critical feature as the nodes in the network are mobile and can move around, change positions and connect or disconnect from the network at any time. To handle these dynamic changes, routing protocols for MANETs are designed to be flexible and able to adjust quickly to new network topologies. These protocols are responsible for managing the routing of messages and maintaining links between nodes independently. Routing protocols for MANETs use route discovery to find new nodes in the network when connections are broken. However, this process can take a significant amount of time, especially when there is high contention for the communication medium. To address this issue, researchers have proposed the idea of combining self-mobile link maintenance with a traditional routing protocol. This approach utilizes the mobility of the nodes to improve the network more quickly or at a lower cost than the conventional route discovery process. This approach aims to reduce data delivery latency and enhance the network's overall efficiency by including link repair as a tool in the routing protocol. The key point in this paper is based on the fact that if self-mobile nodes exist in the network, in some cases, it is faster to relocate a node rather than discover an unknown node.

The discovery phase in routing protocols is time-varying, consumes a large amount of energy and bandwidth, and incurs latency that affects the network throughput. Research has shown that, in some cases, higher network performance can be achieved by focusing on link repair rather than running a node discovery phase. With this in mind, the idea of combining self-mobile link maintenance with a standard routing protocol was proposed to reduce discovery latency and improve network throughput. This approach aims to make the network more efficient by utilizing the mobility of nodes to repair links quickly rather than spending a lot of time, energy, and bandwidth searching for new nodes

This paper presents the Meta-Routing protocol, which is a new concept for managing mobile robots and ad-hoc network infrastructure. The Meta-Routing protocol is not only presented as a packet routing scheme but also as a new strategy for maintaining communication links. The main contributions of this paper are: Therefore, the main contributions of this paper are summarized as follows:

- Meta-Routing incorporates link maintenance directly into the routing protocols' cost function as an alternative to route discovery for robust network connectivity. It aims to reduce the total path cost compared to the standard routing protocols.

- The introduction of *hypothesized nodes* into the *augmented connection graph* implements a unified syntax of the message routing protocol and the link maintenance mechanism that allows the overhead costs of routing to be merged with the direct link costs of routing.

II. Related Work

Measuring network connectivity and signal strength are crucial for maintaining the quality of communication networks. Network connectivity refers to the ability of devices to connect and communicate with one another, while signal strength measures the power of the wireless signal being transmitted. These measurements are used to monitor and ensure the proper functioning of the network and to identify and fix any issues that may arise (Ayad et al., 2019; Thrane et al., 2020). Furthermore, maintaining node connectivity is crucial for robotic networks to ensure that data can be transmitted and received while the robots perform their assigned tasks. It is vital for the proper functioning of the network and ensuring that the robots can complete their duties effectively. Without proper node connectivity, the robots may not be able to communicate with each other or with the central control system, which could lead to delays or failures in completing their assigned tasks (Cardona et al., 2019; Ayad et al., 2022). In (Thiagarajan et al., 2017), an efficient routing protocol is presented for use in ad-hoc networks. The protocol utilizes a dynamic source routing scheme to transfer data from the source to the receiver node. The paper's authors have compared their proposed scheme with a conventional routing scheme to evaluate the performance in terms of throughput, energy consumption, and overhead. By comparing the two schemes, the authors aim to demonstrate the advantages and improvements provided by their proposed routing protocol. In (Malar et al., 2021), The authors proposed a multi-objective routing technique for MANET that uses Ant Colony Optimization (ACO) to find energy-efficient routes while considering constraints such as the residual energy of mobile nodes, number of packets in the path, and dynamic changes in the network topology. The technique, called MCER-ACO, aims to reduce transmission energy, adapt to changes in the network topology, and minimize path overhead. The authors of the paper evaluated the performance of the proposed MCER-ACO technique and compared it to two existing methods. The evaluation results showed that the MCER-ACO technique is more energy efficient and better at selecting optimal routes in a MANET than the other methods. In (Zhang et al., 2019), the authors proposed algorithm reduces the network's energy consumption, improves the delivery rate of data packets, reduces the network delay, and prolongs the network lifetime. In the greedy forwarding phase, the reliable communication area is calculated, and then the quality of the link is evaluated according to the relative displacement between the nodes and the maintenance time of the link. Then, according to the link quality, the distance between the candidate node and the destination node, and the number of the neighbor nodes, the metric value is obtained, and the node with the large metric value is selected as the next hop. Younis et al., 2021, present a comparison of existing routing protocols in MANET, indicating that overhead in Proactive and Geographic is competitive with delay in Reactive and *Delay Tolerant Network* (DTN) routing.

Alani et al.,2020, proposed the dynamically probabilistic route discovery scheme for MANET. The scheme aims to improve network performance and resolve the problem of frequent link breakage. The scheme selects the reliable node of the route discovery process to avoid the link break and eliminate redundant retransmission to achieve the lowest value of congestion, reducing the overhead in the network. Khudayer et al., 2020, proposed two mechanisms to enhance on-demand source routing protocols, a zone-based route discovery mechanism (ZRDM) and a link failure prediction mechanism (LFPM). ZRDM aims to control the flooding of route requests, and LFPM aims to avoid route breakages caused by node mobility. Raj, 2020, proposed a routing strategy suitable for dynamic and static environments as a hybrid optimization model that reduces link establishment issues. Nature-inspired bee colony optimization is used with conventional routing algorithms such as optimized link state routing protocol and Dynamic Source Routing Protocol to improve link discovery. The proposed routing scheme reduced the delay and communication overhead of the network. Zhu et al., 2020, presented an innovative, collaborative routing protocol with low delay and high reliability to accommodate mixed link scenarios. First, they establish a one-hop delay model to investigate the potential effects of Media Access Control (MAC) layer parameters. Then, forwarding, maintenance, and efficiency strategies are created to construct the basic functionalities for the proposed routing protocol.

III. Meta-routing Fundamentals

Network researchers address message routing of information packets distinctly from the link maintenance process, which is creating and keeping links. Meta-Routing combines the concept of message routing of information packets, which is finding the lowest path cost, and link maintenance, which is creating and improving paths (a path consists of links). Therefore, Meta-Routing integrates logical message routing and physical link maintenance to transmit information packets from node A to node B at the lowest cost.

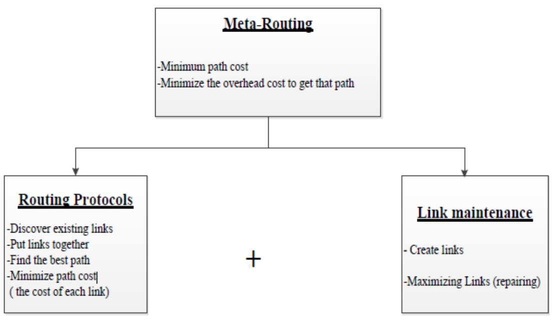


Fig.3. Meta-Routing cost diagram.

Algorithmically, Meta-Routing takes existing methods of computing path cost and augments them with the costs of overhead and maintenance to develop a more comprehensive cost metric. Meta-Routing includes links cost, route discovery cost, and link tuning/adjustment cost, as in Fig. 3. Meta-Routing applies to the entire gamut of available link maintenance mechanisms, including controlled motion of nodes, transmit power adjustment, antenna pointing, and other antenna tuning forms that vary the nodes' operating characteristics (Ayad et al., 2019). Regardless of the array of maintenance options available, the mechanism can be incorporated into the paradigm if the costs and likelihood of success can be quantified.

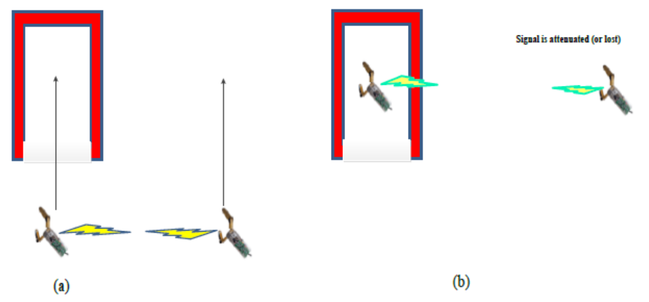


Fig. 4. Two crawler robots in an unknown environment, robots are (a) maintain signal and (b) signal lost.

A. *Meta-routing insight*

A particular scenario involving two crawler robots moving in an unknown environment, communicating and exchanging messages packets provided the insight from which Meta-Routing was born (see Fig, 4(a)). While these robots explore an unknown environment and exchange message packets, they approach a Faraday cage-like obstacle. As they move forward, the communication signal strength decreases until communication is lost (Ayad et al., 2019). Finally, the robots can not communicate anymore as a result of the RF obstacle effects on the communication signal, as shown in Fig. 4(b).

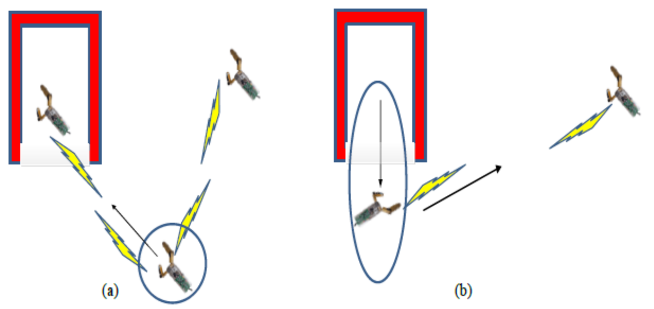


Fig. 5. (a) Discovering a new node (b) controlling the motion of an existing node.

There are two choices to reestablish communication between the two crawler robots: discover a new node that might re-connect the route or move existing nodes to re-connect the route. The first choice is to discover a new node in the network to act as a bridge between the two nodes that lost communication. This action requires performing the route discovery phase to find an intermediate node that acts as a bridge, as shown in Fig.5(a). In our work with Locally Selectable Protocol (LSP) over Bluetooth (Voyles et al., 2009), this process costs up to 39 *seconds* in the simulation experiment, as shown in Fig. 6. On the other hand, we realized that turning the robot around and crawling backward to regain signal was significantly faster (lower cost). Therefore, physically moving the nodes to regain the communication route is significantly lower cost than node discovery, in this case! Furthermore, node discovery is highly uncertain. If no new node is present, the cost is wasted.

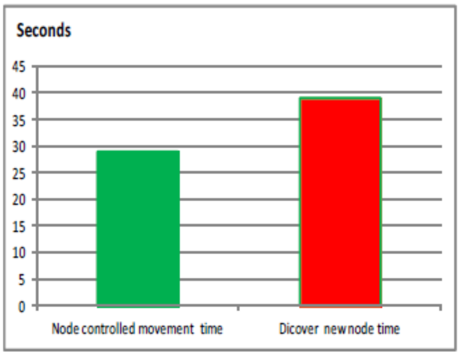


Fig. 6. Controlling the motion of an existing node and discovering a new node cost estimation comparison.

Meta-routing is best illustrated when a link disappears somewhere in the middle of the network and no known alternate route exists. In other words, the path the routing protocol thought was the best is now broken. Therefore, there is a subproblem; instead of going from node *A* to node *B*, it is going from node *C* to node *B*. Thus, the routing protocol does not know what the path is, and now we are going to compute both the total cost to that path (not only the individual links), but also what is going to cost us to find a path or create a new path or strengthen an existing path. Thus, this is what Meta-Routing is about. As a result, we will not change the basic routing protocols; we could use proactive, reactive, or hybrid protocols. The point is we will show how we will integrate link maintenance into a standard routing protocol. One of the advantages of the Meta-Routing approach is that we will include the cost of moving a node in the cost function of estimating the lowest total path cost. Therefore, all links are strong enough to have a path from node *A* to node *C*, then to node *B*. On the other hand, the cost of strengthening links is related to the overhead cost of node movement, which takes time and energy to move the node. In summary, using node movement and computing the gradient (Ayad et al., 2022) while robots move is one way to achieve the Meta-Routing protocol.

In Fig.7 (a), node *A* communicates with node *C*. There are two possible routes: $A - B - C$ and $A - D - B - C$. The lower cost route is $A - B - C$. In this scenario, we assume that node *C* wants to move to the right, as the arrow indicates, but node *D* also moves in the direction of its arrow, as shown in Fig.7 (a). As a result of this movement, node *C* has moved out of the range of node *B*, but node *D* has moved into the range of node *C*; consequently, node *C* and node *D* can communicate with each other *but don't know yet.* (The link between nodes C and D is not established until the link discovery protocol is initiated.) Besides, node *B* can not communicate with node *C*, as shown in Fig.7 (b). For this scenario, there are two possible solutions for maintaining communication between the mobile nodes. First, when node *C* moves out of the range of node *B*, node B triggers the route discovery algorithm to find a new link to node C, which is what traditional routing protocols do.

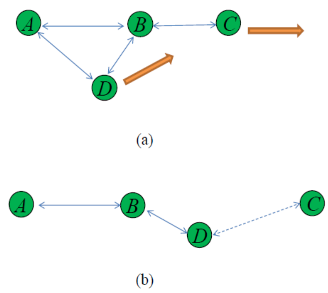


Fig.7. (a) Node *C* and node *D* are moving in the direction of the arrows (b) Node *C* moves out of the range of node *B*, but node *D* has advanced in such a manner that it is within range of node *C*.

Therefore, node B can communicate with node C through node D because node D and node C are within range and can communicate with each other, as shown in Fig. 8 (a). Second, node B can be moved along with node C (at half speed), so node B will remain in the range of nodes A and C and then maintain links, as shown in Fig. 8 (b). This is precisely what link maintenance does for the connectivity maintenance of the network.

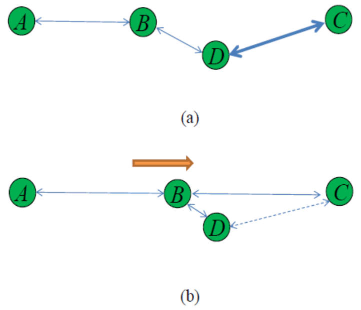


Fig.8. (a) Node D is in the range of node C (b) B moves toward node C.

B. Meta-Routing and the Conventional Routing Paradigm

Traditional routing protocols find paths (a series of links) in a connection graph, then choose the lowest-cost path to send information packets. Traditional routing protocols trigger an automatic route discovery when there is no direct path to the destination, as shown in Fig.8(a). In the Meta-Routing protocol, we are willing to augment the graph with hypothesized node, which will be our trigger to find paths in the augmented graph and compute the cost function for each path. Hypothesized nodes augmented in a graph are shown in Fig. 9, where φ_D represents the route discovery hypothesized node and φ_B represent the controlled motion hypothesized node.

C. Meta-Routing Protocol Path Cost

Fig.9 results from augmenting two hypothesized nodes φ_B and φ_D, which are virtual nodes, into the traditional routing protocol graph of Fig.7. The resulting graph in Fig. 9 represents the Meta-Routing augmented graph, where φ_D represents the route discovery hypothesized node (*virtual node*), which results from running the route discovery algorithm by node *B* to communicate with node *C*, and φ_B represents the controlled motion hypothesized node (*virtual node*), which results from moving node *B* to the position shown in Fig. 9, so that node *B* can communicate with node *A* and *C* (Ayad et al., 2019). Because both nodes φ_B and φ_D are hypothesized, they are uncertain. Hence, it is appropriate to consider their likelihoods of success of route discovery L_{Rd} and controlled motion L_{Mov}. Meta-Routing protocol total path cost represents the sum of the message routing protocol cost, which is the minimum links cost of a communication path (C_{Ls}), and the link maintenance path cost, which is the minimum overhead cost to find the path (C_{Oh}).

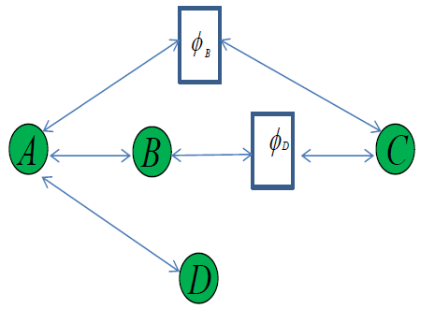


Fig. 9. Meta-Routing augmented graph with hypothesized nodes, φ_B, and φ_D.

In fact, Meta-Routing estimates the overhead cost of route discovery (C_{Rd}) and the overhead cost of node movement (C_{Mov}). Therefore, meta-Routing chooses the best total cost estimate, representing the lowest total path cost. In case the lowest overhead cost estimate is the cost of node movement, Meta-Routing uses the controlled motion algorithm when signal strength goes below some threshold, and a link failure occurs. The controlled motion algorithm moves communicating nodes in the field to a favorable position to regain a strong communication signal (Ayad et al., 2022). The controlled motion algorithm performs this to reduce the overhead cost that results from route discovery. Thus, the total path cost (C_{Tmeta}) is the sum of the node movement cost, which is the time and energy costs to move a node, and the minimum links cost (communication cost), which is the shortest path or a path with less hop count number. On the other hand, when the node movement cost is higher than a new node's discovery cost, Meta-Routing's total path cost will be the sum of the minimum communication links cost and the route discovery cost. Therefore, Meta-Routing's lowest total path cost is the sum of the minimum communication cost of links and the minimum overhead cost, as in equation 1.

$$C_{T_{meta}} = \Sigma C_{Ls} + \Sigma C_{Oh} \tag{1}$$

The graph in Fig. 9 shows two hypothesized nodes to create links from node *A* to node *C*, which is φ_B, and from node *B* to node *C*, which is φ_D. Traditional protocols trigger route discovery automatically when a link failure occurs. On the other hand, Meta-Routing goes to hypothesis mode to trigger the optimal cost choice based on the cost function and likelihood of success for discovery, L_{Rd}, or likelihood of success for movement, L_{Mov}. According to this, two hypotheses are discussed below.

D. Meta-Routing Hypothesis Generation

The novelty of Meta-Routing is in creating hypothesized graphs. Therefore, Meta-Routing is about hypothesizing new graphs and then applying the traditional routing protocols to the hypothesized graphs to choose the lowest path cost. Thus, Meta-Routing injects new hypothesized nodes into the graph to create different communication paths. For example, the hypothesized node could represent discovering a route, increasing the power, tuning an antenna, or moving a node, as shown in Fig.10. Consequently, Meta-Routing can trigger any hypothesized option using all types of link maintenance for all networks. In this paper, we will use the node movement and route discovery hypothesis.

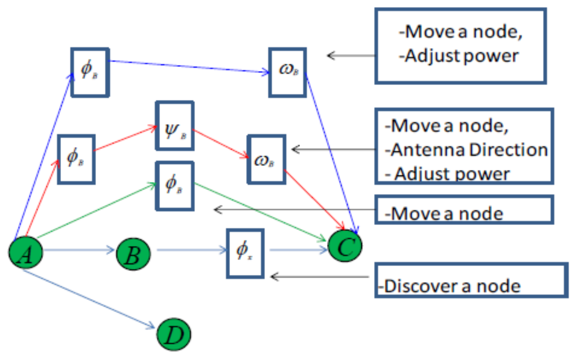


Fig.10. Meta-routing hypothesis generation graph.

*E. Link Discovery Hypothesis **H_1***

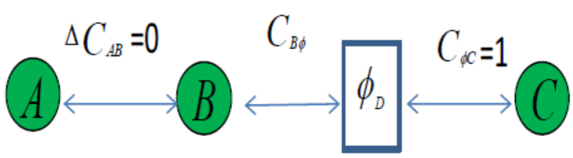


Fig.11. Hypothesized path for route Discovery.

In Fig.11, a hypothesized node φ_D is inserted between node B and node C. Therefore, the cost change of the link between node A and node B, ΔC_{AB}, equals 0 because node B does not move. Without loss of generality, we assume that the communication cost between the hypothesized node φ_D and node C is equal to 1. As a result, the Meta-Routing total cost of the first hypothesis H_1 is given by equation 2.

$$C_{T_{meta}}(H_1) = C_{AB} + \Delta C_{AB} + C_{B\phi_D} + C_{\phi_D C} + C_{Rd} \qquad (2)$$

Where C_{AB} is the communication cost between node A and node B, ΔC_{AB} = 0, $C_{B\varphi_D}$ is the communication cost between node B and node φ_D, $C_{\varphi_D C}$ is the communication cost between hypothesized node φ_D and node C and the overhead cost, which is the route discovery cost, C_{Rd}. C_{Rd} is the overhead cost that node B takes to discover the hypothesized node φ_D. To ensure that node B can find another node when it runs the route discovery process, we need to compute L_{Rd}, and then divide the route discovery overhead cost by the L_{Rd}; and that is a way to normalize that cost because we do not know that node B is going to find another node. Therefore, equation 2 is enhanced as in equation 3.

$$C_{T_{meta}}(H_1) = C_{AB} + \Delta C_{AB} + C_{B\phi_D} + C_{\phi_D C} + C_{Rd}/\mathcal{L}_{Rd} \qquad (3)$$

*F. Controlled Motion Hypothesis **H_2***

In Fig.12, a hypothesized node φ_B is moved between node A and node C. Therefore, the cost change of the link between node A and hypothesized node φ_B, $\Delta C_{A\varphi_B}$, is not equal to 0 because node B moves. Therefore, without loss of generality, we assume that the communication cost between the hypothesized node φ_B and node C is equal to 1. As a result, the Meta-Routing total cost of the second hypothesis H_2 is given by equation 4.

$$C_{T_{meta}}(H_2) = C_{A\phi_B} + \Delta C_{A\phi_B} + C_{\phi_B C} + C_{Mov} \qquad (4)$$

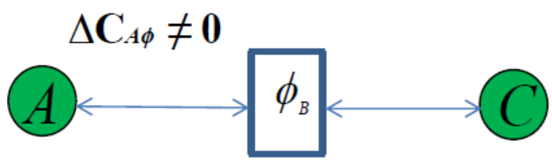


Fig.12. Hypothesized path for controlled motion of a node.

Where $C_{A\varphi_B}$ is the communication cost between node A and node φ_B, $\Delta C_{A\varphi_B}$ is the cost change between node A and node φ_B, $C_{\varphi_B C}$ is the communication cost between node φ_B and node C, and the overhead cost, which is the movement cost, C_{Mov}. C_{Mov} is the overhead cost that node B takes to move to the position of node φ_B. We have to compute the likelihood of success, L_{Mov}, when we control node B movement so that it will move in the right direction and not lose a connection with node A. In fact, there are some likelihoods of success to guarantee link repair when we move node B, so we have to consider the L_{Mov}. Therefore, we divide the overhead cost of movement by the likelihood of success, L_{Mov}, to normalize the cost. Consequently, equation 4 is enhanced as in equation 5.

$$C_{T_{meta}}(H_2) = C_{A\phi_B} + \Delta C_{A\phi_B} + C_{\phi_B C} + C_{Mov}/\mathcal{L}_{Mov} \qquad (5)$$

In summary, after computing $C_{Tmeta}(H1)$ and $C_{Tmeta}(H2)$, Meta-Routing will choose the lowest total cost and decide whether to control the movement of a node to repair a link or discover a new node to maintain the network connectivity.

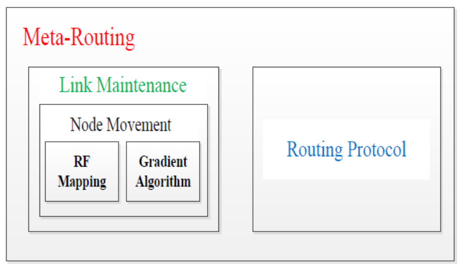


Fig. 13. Meta-Routing protocol block diagram.

IV. META-ROUTING DESIGN

The Meta-Routing combines routing protocol strategies such as proactive, reactive, hybrid, and link maintenance approaches. We believe the combination of routing protocol and link repair can achieve higher network performance than running the node discovery phase. Therefore, to incorporate link maintenance into the routing protocol to achieve Meta-Routing, as shown in Fig.13.

In a typical network situation, the Meta-Routing works and acts as a traditional routing protocol. Therefore, it infrequently applies a message routing protocol to the local network to transmit packet messages between nodes in the communication network. Meta-Routing computes the route repair and the route discovery cost functions and the likelihood of success for route repair and route discovery for achieving robust network connectivity and minimizing the overhead path cost. The Meta-Routing protocol triggers the hypothesis generation process when a critical error occurs on the communication path during message transmission and computes the cost function. Then, meta-Routing runs the route repair algorithm or the route discovery algorithm to maintain the network connectivity. It decides the route discovery or the route repair algorithm based on the estimated total path cost produced by the cost function and the likelihood of success for route repair, L_{Mov}, and route discovery, L_{Rd}. The Meta-Routing protocol will perform the route repair algorithm for link maintenance if the total path cost to repair a broken link is lower than the total path cost to discover a route and the L_{Mov} is higher than that of route discovery. Otherwise, Meta-routing performs the route discovery process. In summary, estimating the cost function and the likelihood of success are highly essential to decide whether the route repair or the route discovery algorithm will be executed (Ayad et al.,2019; Ayad et al., 2022). Fig.14 shows the flowchart for the Meta-Routing protocol.

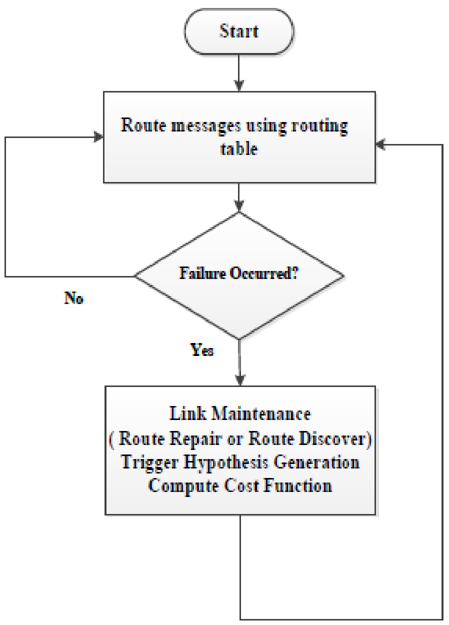


Fig.14. The Meta-Routing protocol flowchart.

A. *Movement in Meta-Routing*

A critical goal of Meta-Routing is to repair failed or broken links in an adverse environment. In fact, various locations will satisfy the criteria of a good-quality link. However, robots do not necessarily know where they are nor know when they last had a strong link signal. Therefore, Robots could go back to a known location; however, it is problematic because this requires having an accurate location. Robots need to know exactly where that place was and where they are now, which could mean there may have been an error as they moved along. Therefore, moving robots back is harder than it sounds because of air propagation and incidents where robots do not know where they were and do not know where they are now. As a result, robots try to move back to a wrong position from another wrong one and may be further away from the correct one. In fact, work from (Ludwig et al., 2006) demonstrates that the random walk is often better than moving back due to the uncertainty of where the back is, so moving in the reverse direction is one option, but it is sometimes dangerous.

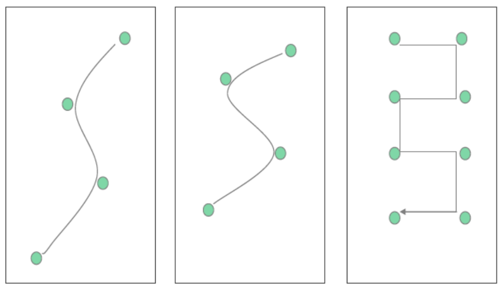


Fig.15.Different movement modes.

Meta-Routing uses movement back through free locomotion when the robot's signal strength goes down, and the robots start to lose communication signals. In typical scenarios, the robot would take the shortest straight-line path to reach the destination. However, this leads to unsuitable signal strength gradient estimates because the sampling locations cannot be co-linear (Ayad et al., 2013; Ayad et al., 2019). Therefore, rather than travel in straight-line trajectories, the robot introduces gentle oscillations to its path (see Fig.15). This makes the gradient estimate more potent than traveling in a straight line at the cost of greater distance traveled.

B. *Link Maintenance for Meta-Routing*

Despite the array of link maintenance options available for wireless communication, if the communication costs and likelihood of success can be quantified, the mechanism can be incorporated into the Meta-Routing mechanism. Traditionally, conventional routing protocols generate an automatic route discovery when there is no path to the destination. Meta-Routing protocol augments hypothesized nodes into the routing graph. It triggers the lowest cost path in the augmented graph by computing each path's cost function and the likelihood of success. In this paper, we will focus on the controlled motion of mobile nodes in experimental fields. Therefore, the Meta-routing protocol uses controlled node motion as one option to achieve link maintenance to maintain network connectivity while the network performs assigned tasks in a harsh environment. The controlled motion of the mobile robots is achieved by driving them to favorable link positions where they can maintain their connectivity (Ayad et al., 2019). Therefore, this will lead us to develop a routing control mechanism to control the node movement. This control mechanism requires knowledge about the direction of where the node should move while it is performing its task. One way to achieve this is to use the gradient descent method. The gradient method is used to determine the direction of movement of the mobile node in the field toward the most robust RF signal strength to maintain network connectivity (Ayad et al., 2022). To reduce the total path cost estimate, the node-controlled motion algorithm should utilize the knowledge that is learned from the RF environment recognition based on the RF signal strength measurements (Ayad et al.,2013). Therefore, this will guide us to explore the relationship between known RF obstacle types and their impact on RF signal strength measurements to minimize Meta-Routing total path cost. The information learned from the RF environment could be employed as the features for identifying the RF obstacle type, size, and the resulting RF environment. Once the robot determines the RF environment type and size, the node-controlled motion algorithm will drive the robot toward a favorable position predicted by the RF environment recognition method. Then, by applying the gradient method, which is used to extract the multi-dimensional gradient of the RF signals, a decision is made on the direction and control of the robots' motion (Ayad et al., 2019). The main steps of the node-controlled motion algorithm can be summarized as

1. Move robots to a favorable position in the field where they can gain strong RF signal strength to maintain their network connectivity.
2. Apply the gradient descent method to decide on the direction of the robot motion in the experimental field.
3. Utilize the knowledge learned from the RF environment recognition method to identify the RF obstacle type and size.

As mentioned in the previous section, robots will move back through free locomotion when the signal strength goes below some threshold, and a communication error occurs. The details of the gradient method used to drive robots to the most robust signal strength are discussed in detail in our work (Ayad et al., 2022). Also, the RF environment recognition method (RF mapping) used to identify different RF obstacle types and sizes is detailed (Ayad et al., 2013; Ayad et al., 2019). Lastly, the node movement, RF mapping, and gradient descent method are augmented into a controlled node motion algorithm to achieve Meta- Routing protocol to minimize the total path cost by reducing the overhead cost to maintain this path.

V. Gradient Descent for Intelligent Controlled Motion Algorithm

An essential part of Meta-Routing is the ability to move nodes intelligently, which maintains the communication links. Therefore, no assumption is made on the locations of RF obstacles or RF "dead zones." Instead, planned motions must be inferred from RF signal strength measurements. In our work, a multi-dimensional gradient approach is used to reduce the error in the signal strength because the robots estimate the signal strength gradient while they are moving (Ayad et al., 2019). The gradient method is applied in a way that helps minimize the total path cost function and increases the likelihood of success in controlling the direction and the robots' motion. Therefore, the gradient process significantly impacts the performance of the Meta-Routing protocol. The gradient method allows the robot to move in the direction of the strong RF signal strength; eventually, it affects the cost function of computing the total lowest path. Simultaneously, the likelihood of success L_{Mov}, in moving robots in the direction of communication coverage, becomes high. Therefore, the gradient descent method affects the overhead cost, C_{Mov}, which is a dominant part of the total path cost of the Meta-Routing protocol in our specific scenarios.

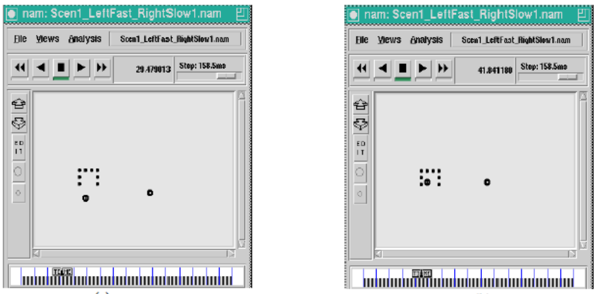
In summary, the gradient method significantly impacts C_{Mov} and L_{Mov}, which affects the overhead cost and would eventually affect the total path cost of the Meta-routing protocol. Different RF signal strength gradient scenarios were tested and examined. The overall results for all experiments showed that the gradient method could potentially support robots moving toward the direction of strong signal strength for their connectivity maintenance. Furthermore, the gradient results can help the robots map the RF obstacles and determine the direction of the robots' movements(Ayad et al., 2022).

A. *Gradient Algorithm Scenarios Using Network Simulator*

Table I. Simulation Environment.

Parameter	Value
Channel	WirelessChannel
Topology	2×2
Nodes	2
Mac layer	$\mathrm{Mac}/802-11$
Routing protocol	AODV
Traffic Type	FTP

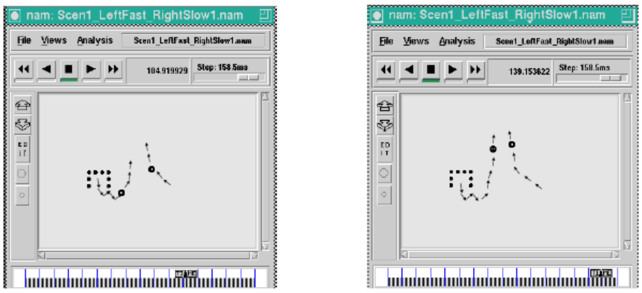
In this simulation scenario, an area of 2×2 m^2 was chosen. The freeway motion model of the nodes was defined as a movement model for our experiments. The simulation uses two nodes. The maximum speed was set to 2.2 *cm/s,* and the minimum speed was set to 1.5 *cm/s*. The traffic generated was the FTP (File Transfer Protocol) on the TCP (Transmission Control Protocol) agent. The MAC layer was set to MAC/802.11. The AODV protocol was simulated with a source-destination pair. Nodes generate packets at different times. After running the simulation, the network animator (NAM) was used to show the data transfer between nodes. The trace files were analyzed for moving nodes. Utilizing the trace file, the node movement time was calculated. The scenario in Figure 5.16 (a) shows two mobile nodes. One node moves at a speed of 2.2 *cm/s,* and the other node moves at a speed of 1.5 *cm/s*. The nodes are moving and transmitting data packets. The nodes and simulation environment parameters are shown in Table I. As the two nodes move, they approach an RF obstacle. The RF obstacle affects the communication signal between the mobile nodes. Therefore, the *S/N* goes down below the communication threshold. As a result, the nodes can not communicate anymore, as shown in Figure 5.16 (b).



(a) (b)

Fig.16. Two robots in (a) are transmitting data packets, and in (b) are losing communication.

In Fig.17 (a), the mobile trapped node has started to move back through free locomotion into a position where it can gain a strong signal strength to regain communication with the other node. According to the gradient algorithm, both nodes start calculating the gradient to decide the strong signal direction when the signal strength goes below some threshold. The node with the higher gradient would move first in the direction of its gradient, as shown in Fig.17(a). If the signal strength is above the threshold, the nodes would regain the communication signal and would start transmitting the information packet again; consequently, both nodes would move in the direction of their normal velocity, as shown in Fig.17 (b).



(a) (b)

Fig.17. The robots in (a) are moving back, and in (b)are regaining communication.

We run multiple scenarios where the trapped node moves at a lower speed than the rightmost node and when the two nodes move at the same speed. The conclusion is that the node movement velocity is scaled as the nodes calculate the gradient to determine the direction of motion to maintain the network connectivity.

Besides, the RF recognition approach based on partial signal strength measurements along the robot's trajectories is used to identify RF shadows in RF environments (Ayad et al., 2022). This approach assists with the utilization of fading characteristics of known RF obstacle types on the RF signal measurements. The gradient descent method in (Ayad et al., 2022), augmented with the RF recognition method, is developed to achieve the Meta-Routing.

B. Gradient and Node Movement based on RF Mapping and Classification

The robot-controlled movement can drive the robots to favorable positions in the field. Once the robots reach strong signal-strength positions, they can regain communication with the robotic network. The robot control mechanism performs this to accomplish tasks assigned to the robots and maintain their network connectivity. An appropriate robot-controlled motion algorithm can manage the network faster than discovering a new node when there is a network failure in some cases. Concerning robot-controlled motion, the gradient descent method is required for connectivity maintenance of the robotic network. The gradient descent algorithm will determine the trends of the strong signal strength for robots; eventually, the robots will move in the direction that supports their connectivity.

The proposed Meta-Routing relies on the node-controlled movement and the gradient algorithm by reducing the total path cost function and increasing the likelihood of success in repairing links to improve the quality of communication links and maximize the broken communication links. The robots can map the RF obstacles in a harsh RF environment a priori by knowing the gradient magnitude and direction. Therefore, if a robot starts moving into the RF obstacle shadow, can it realize that it is moving into a temporary shadow? In other words, can the robot move into the RF shadow quickly, or will the RF shadow go deeper? As a result, the robot will lose connection with the other robots. Knowing the depth of the RF shadow, it is possible to estimate and reduce the overhead cost, consequently increasing the likelihood of success of moving robots away from that shadow, and then this will lead to lowering the total path cost of the Meta-Routing protocol.

The RF shadow recognition and classification concern the mapping of RF obstacles in an RF environment for estimating the depth of an individual RF shadow to reduce the total path cost of the Meta-Routing protocol. The estimation process will minimize the routing overhead cost resulting from moving deeper into the RF shadow. Why do we need RF mapping? Another vital question arises. In fact, we can achieve Meta-Routing using node movement and applying gradient descent. However, we still need to find the best cost estimate for repairing a broken link or discovering a new connection or node. For example, when two robots are moving in an unknown environment and start losing the communication signal, could we know the effects of the environment (RF obstacle) on the communication signal between robots? Also, could we estimate the depth of the RF shadow affecting the communication? In addition, could we recognize and classify the RF environment so that we can put the best cost estimate of repair specifically on this link, but not the likelihood of average links like hybrid protocols did? The following sections will present the answer to the questions above and other questions. The RF environment recognition method, the robot-controlled motion algorithm, and the gradient method will help reduce the overall path cost estimate compared to the route discovery phase for achieving Meta-Routing.

C. RF Shadow Primitives Classification

The block diagram in Fig.18 summarizes the significant steps of our algorithm for achieving the RF environment recognition method from partial data. First, each measurement vector obtained from different robot trajectories is segmented into small segments (Ayad et al., 2022; Ayat et al., 2013). Each segment is then transformed into the frequency domain for extracting features using a fast Fourier transform (FFT). We use a subset of all feature vectors for training, and the remainder is used for testing. Next, the extracted feature vectors for training are clustered using a clustering algorithm to generate observation sequences. The generated observation sequences train three Hidden Markov Models (HMMs), one for each RF obstacle type. Each HMM model consists of five states, corresponding to five concatenated segments of the robot's movement through a specific trajectory. As described above, each model was trained using a set of observation sequences. Finally, the HMMs classification models were tested using the testing set of feature vectors. Using the trained HMMs results, the RF environment recognition is achieved and utilized by the robot-controlled motion algorithm aiming at robot connectivity maintenance (Ayat et al., 2013).

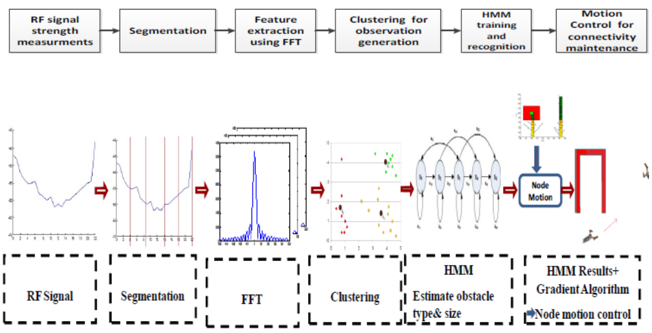


Fig.18. Block diagram of RF environment recognition processing steps.

D. Controlled Motion Mechanism for Meta-Routing

The controlled motion algorithm has two decisions for maintaining the robot's connectivity. The controlled motion algorithm takes the first decision; therefore, it drives the robots to move across the RF obstacle shadow toward a favorable position to maintain their connectivity based on the RF recognition through the HMMs results. On the other hand, suppose the controlled motion algorithm chooses the second decision. In that case, the robots move back through free locomotion and start computing the signal strength gradient to find the direction of the strong signal strength and then maintain their connectivity. We use the gradient-based controlled motion algorithm, which extracts the multi-dimension gradient of the RF signal measurements for controlling robot direction around the RF obstacle. In other words, depending on the HMMs results that estimate the type and the approximate size of the RF obstacle, the controlled motion algorithm decides whether to extend the movement through the RF obstacle shadow or to move back through free locomotion to a position in the field that has a strong enough signal strength and then it computes the gradient to determine the direction of robots' movements to maintain their connectivity. Algorithm 1 summarizes the main steps of the controlled motion algorithm. The whole picture of the Meta-Routing flowchart, including message routing protocol, link maintenance through node-controlled motion (link repair), and route discovery process, is summarized in Fig.19.

Algorithm 1 Controlled Motion Algorithm.

```
Input: RF environment recognition results.
Output: Maintaining connectivity of mobile robots.
Get RFRecognitionResults()

if (Obstacle type and size are estimated) then
    if Segments length ≥ (estimated width/2) then
        MoveCurrentPath()
        GradientDecsentAlgorithm()
    else
        MoveBack()
        GetStrongSignalPos()
        GradientDecsentAlgorithm()
    end if
else
    MoveBack()
    GetStrongSignalPos()
    GradientDecsentAlgorithm()
end if
MaintainConnectivity()
```

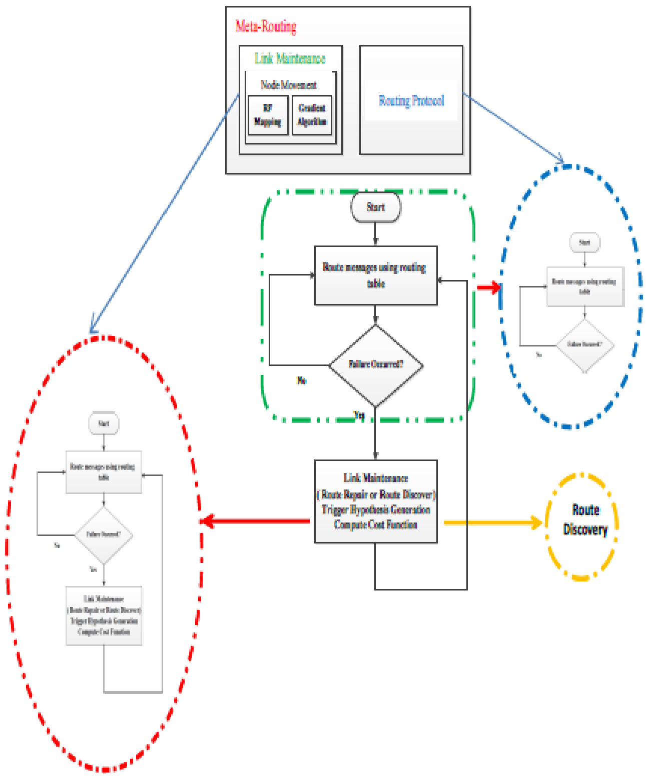


Fig. 19. Meta-Routing overall picture.

The controlled motion algorithm utilizes the HMMs results to drive robots to continue moving forward through the current trajectories if the length of the segment traveled by the robots are greater than or equal one half of the estimated RF obstacle size (Ayad et al. 2022; Ayat et al., 2013). Otherwise, the robots stop movement and move back through free locomotion to a position where it can gain strong signal strength. Then, the robots run the gradient algorithm to define the direction of the most robust signal strength. Afterward, the robots move in the direction of the gradient and attempt to regain communication (Ayad et al., 2022; Ayat et al., 2013).

VI. Link Maintenance based on RF Recognition Cost Estimation

The robot-controlled motion algorithm utilized the HMMs results to achieve robot connectivity maintenance. The time cost estimates for the link maintenance based on the RF environment recognition method are calculated in the following subsections.

A. *Estimated Cost of Link Maintenance*

The total estimated time for our link maintenance method $T_{(TOT)}$ is the sum of the segmentation time $T_{(SIG)}$ (the time to segment signal strength measurement vector), the FFT transform time $T_{(FFT)}$ (the time to perform FFT transform), the time for K-means algorithm T_k(the time to cluster the extracted feature vectors), the time for HMMs classification $T_{(HMM)}$ (the time for HMMs training and recognition), and the time for robot movement $T_{(MOV)}$, the time to move the robot back through free locomotion. The total estimated time is summarized as

$$T_{(TOT)} = T_{(SIG)} + T_{(FFT)} + T_{(K)} + T_{(HMM)} + T_{(MOV)} \qquad (6)$$

We created different MATLAB programs and functions to estimate the time cost for our link maintenance method. We ran these programs on a DELL desktop computer, model Optiplex980. The Desktop runs Windows, 64-bit Operating System. The Desktop uses the Intel(r) Core(TM) i7 CPU, which runs on 2.93 *GHz*. The installed memory (RAM) capacity for the Desktop is 8 *GB*. In the experiments, the segmentation and FFT transform times were $T_{(SIG)}$ + $T_{(FFT)}$=0.3 seconds, and the K-means and HMMs times were $T_{(K)}$ + $T_{(HMM)}$= 6 seconds. Therefore, for a crawler robot that moves back a distance of 0.5 meters at a speed of 0.022 meters/second, the total estimated time $T_{(TOT)}$ = 0.3 + 6 + 0.5 / 0.022 = 29.027 seconds, as shown in Figure 8.9. If the robot's speed increases to 0.15 meters/second, the total estimated time is T_{TOT} = 0.3 + 6 + 0.5 / 0.15 = 10 seconds. The results show that the time cost estimate is affected directly by the robot's speed in the field. Thus, as the robots move fast, the time cost decreases.

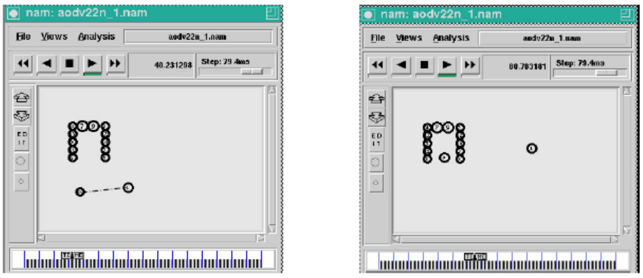
B. *Estimated Cost for Node Movement*

We will show a scenario on how node movement time can be estimated by explaining simulation environment specification and node configuration. The simulation was completed to assess the time required to move two disconnected nodes back through free locomotion to regain communication while running the AODV routing protocol. The simulation was performed on the NS2 simulator. In the simulation, an area of 2×2 m^2 was chosen. The freeway motion model of the nodes was defined as a movement model for our experiments. The simulation uses two nodes. The maximum speed was set to 2.2 *cm/s*. The traffic generated was FTP on the TCP agent. The MAC layer was set to MAC/802.11. The AODV protocol was simulated with a source-destination pair. They generated packets at different times. After running the simulation, the NAM was used to show the data transfer between nodes. The trace files were analyzed for moving nodes. Utilizing the trace file, the node movement time was calculated.

Table II. Simulation Environment.

Parameter	Value
Channel	WirelessChannel
Topology	2×2
Nodes	2
Mac layer	$Mac/802-11$
Routing protocol	AODV
Traffic Type	FTP

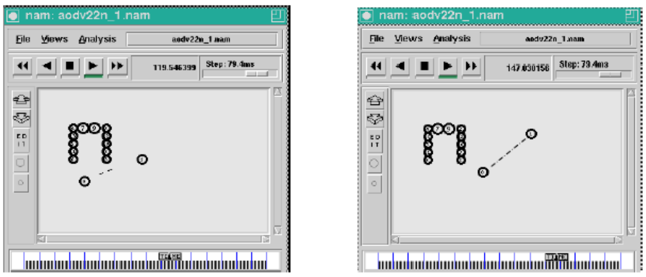
The scenario in Fig. 20(a) shows two mobile nodes. The nodes are moving and transmitting data packets. The nodes and simulation environment parameters are shown in table II. As the two nodes move, they approach an RF obstacle. The RF obstacle affects the communication signal between the mobile nodes. Therefore, the S/N goes down below the communication threshold. As a result, the nodes can not communicate anymore, as shown in Fig. 20(b).



(a) (b)

Fig. 20. Two robots in (a) are transmitting data packets, and in (b) are losing communication.

In Fig. 21(a), the mobile nodes are moving back through free locomotion into a position where they can regain the signal strength to communicate. The node movement time spent to retrieve the communication between the nodes was 29 seconds. Finally, the nodes regained the communication signal and started transmitting the information packet again, as shown in Fig. 21(b).



(a) (b)

Fig. 21. The robots in (a) are moving back, and in (b)are regaining communication.

C. Estimated Cost for Route Discovery

The route discovery time is a function of the distance to the destination, the size of the network, and the number of nodes in the network. The size of the transmitted data packet does not affect the route discovery time. A good route discovery process should have a short response time, which is how long the discovery mechanism takes to reach the destination, and should do so with a minimal time cost.

In communication networks, the total delay for the application data packet as it is transmitted from source to destination plus the route discovery time, which is the round trip time from sending a route request until receiving the route reply, is called the end-to-end delay. The total route discovery latency ($T_{(RDL)}$) is the sum of the request time ($T_{(req)}$), which is the time it takes for the first request message to traverse from the source to the destination, the reply time ($T_{(rep)}$), the time it takes for the first reply message to traverse from the destination back to the source, and the soft latency ($T_{(soft)}$), an extra waiting time happens at the source side after receiving the reply message. The total route discovery latency ($T_{(RDL)}$) is summarized in the Equation below:

$$T_{(RDL)} = T_{(req)} + T_{(rep)} + T_{(soft)} \qquad (7)$$

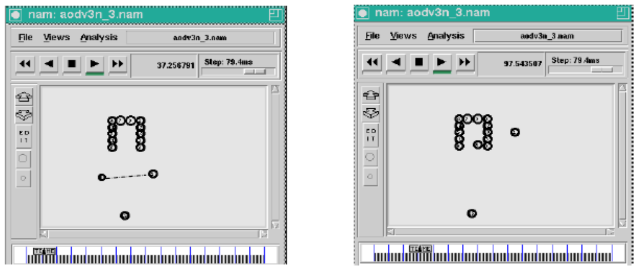
In the following sections, we will show a scenario of how to route recovery time can be estimated. First, the simulation environment specification and node configuration will be detailed. Then, the simulation is done to evaluate the route discovery time of the AODV routing protocol. The simulation was performed on the NS2 simulator.

In this simulation, the areas of the $2 \times 2\ m^2$ were chosen. The freeway motion model of the nodes was defined as a movement model for our experiments. The maximum speed was set to 2.2 *cm/s*. The traffic generated was FTP on the TCP agent. The MAC layer was set to 802.11. The protocol has been simulated with three nodes. They generated packets at different simulation times. After running the simulation, the NAM shows the data transfer between nodes. The trace files are analyzed for moving nodes. Utilizing the trace file, the node route discovery time is calculated.

Table III. Simulation Environment.

Parameter	Value
Channel	WirelessChannel
Topology	2×2
Nodes	3
Mac layer	Mac/802 – 11
Routing protocol	AODV
Traffic Type	FTP

The scenario in Fig. 22 (a) shows two mobile nodes. The nodes are moving and transmitting data packets. The nodes and the simulation environment parameters are shown in table III. In the beginning, two nodes move in the experimental field and approach the RF obstacle. However, the RF obstacle affects the communication signal between the mobile nodes. Therefore, the *S/N* goes down below the communication threshold. As a result, the nodes can not communicate anymore, as shown in Fig. 22 (b).



(a) (b)

Fig. 22. Two robots are (a) transmitting data packets and (b) losing communication.

(a) (b)

Fig. 23. A new node (a) moved to the network (b) Regained communication with other nodes.

In Fig. 23 (a), when the nodes lost communication, they started executing the route discovery phase. A third new node from the base station was moved to join the network. The trapped node detected the new node. The new node acted as a bridge between the disconnected nodes. Therefore, the disconnected nodes regained the communication signal and started to transmit information packets, as shown in Fig. 24 (b). The route recovery time spent to retrieve the communication between the nodes was 39 seconds, which is higher than the time cost of moving nodes back through free locomotion, as shown in Fig. 24. In summary, the time spent to move nodes back through free locomotion is shorter than the time spent to recover a new node. Thus, the node-controlled algorithm is more effective than the route recovery phase in some cases.

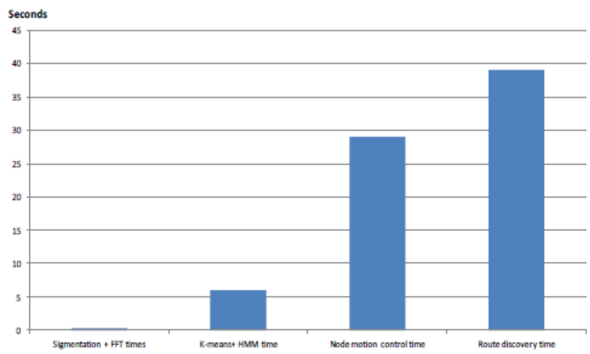


Fig. 24. Node movement and route discovery time comparison.

VII. Conclusions

This paper presents a new concept for a mobile robot routing protocol named Meta-Routing protocol. Meta-Routing merges a message routing protocol and a link maintenance protocol in mobile robot ad hoc networks. It achieves message routing using LSP hybrid routing protocol and performs link maintenance using the controlled motion of nodes. The motion control algorithm utilizes the RF mapping recognition and gradient algorithm results. The simulation results demonstrate the ability of the proposed Meta-routing protocol to achieve link maintenance through controlled node movement based on RF mapping and gradient algorithms. We expect that the proposed methods can be a competitive alternative for broken link replacement and maintaining robot connectivity in robotic networks.

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