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A Hybrid Routing Protocol For Communications Among Nodes Withhigh Relative Speed In Wireless Mesh Networks

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A HYBRID ROUTING PROTOCOL FOR COMMUNICATIONS AMONG NODES WITH HIGH RELATIVE SPEED IN WIRELESS MESH NETWORKS

by

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ABSTRACT

Wireless mesh networks (WMN) is a new promising wireless technology which uses already available hardware and software components. This thesis proposes a routing algorithm for military applications. More specifically, a specialized scenario consisting of a network of flying Unmanned Aerial Vehicles (UAVs) executing reconnaissance missions is investigated. The proposed routing algorithm is hybrid in nature and uses both reactive and proactive routing characteristics to transmit information. Through simulations run on a specially built stand alone simulator, based on Java, packet overhead, delivery ratio and latency metrics were monitored with respect to varying number of nodes, node density and mobility. The results showed that the high overhead leads to high delivery ratio while latency tends to increase as the network grows larger. All the metrics revealed sensitivity in high mobility conditions.

to my

PARENTS and my lovely BROTHER

with love

ACKNOWLEDGMENTS

I would like to specially thank my advisor Dr. Damla Turgut who has helped me throughout these two years of my Master's degree duration and has also provided me with an interesting and realistic research topic. I would also like my committee members, Dr. Mustafa Bassiouni and Dr. Lei Wei for spending their valuable time in assisting me.

Needless to mention that without my parents none of this effort would have become reality. Special acknowledgments go to them for giving me the opportunity to continue my studies in graduate school.

Finally, I would like to dedicate this thesis to my little brother and I hope it will serve as an inspiration for his future.

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CHAPTER 1 : INTRODUCTION

As technology evolves, wireless networks are becoming more and more widespread since they play an essential role in providing better services in every day life. A new key technology called wireless mesh networks (WMN) is estimated to contribute significantly in the next generation of wireless computing.

Generally mesh networks can be considered to be part of the same family of networks as the ad hoc networks. However, mesh networks have substantially more advantages [17]. They are dynamically self organizing and self configuring networks, with nodes that automatically establish ad hoc connection between themselves in order to maintain mesh connectivity [6]. They consist of two types of nodes: mesh routers and mesh clients. The routers form the backbone of such a network and they can perform conventional operations similar to any wireless router. What differentiates a mesh router is its capability of having multiple wireless network interfaces operating on multiple channels which can maximize the throughput and the overall network performance. Power consumption is not an issue anymore, as most of the routing decisions are made by the mesh routers and as a result the users' devices are relieved of the power consuming procedure of routing. Mesh routers are also responsible for making the different radio technologies (WiFi, WiMax, etc.) compatible with each other. On the other hand, there are the mesh clients which can be any well-known devices such as laptops, PDAs, pocket PCs, IP phones, etc. A mesh client usually has one network interface and they are much simpler that a mesh router. Clients can easily connect to the network by being automatically detected and they disconnect without affecting the network reliability and performance.

1.1 Mesh Architectures

There are three types of mesh architectures [6]. First, there is the infrastructure or backbone architecture, where wireless mesh routers provide a backbone topology which is used by the clients to connect and operate. Communication between the routers is accomplished through wireless protocols such as 802.11. One or more routers can function as a gateway for providing internet connection to the entire network.

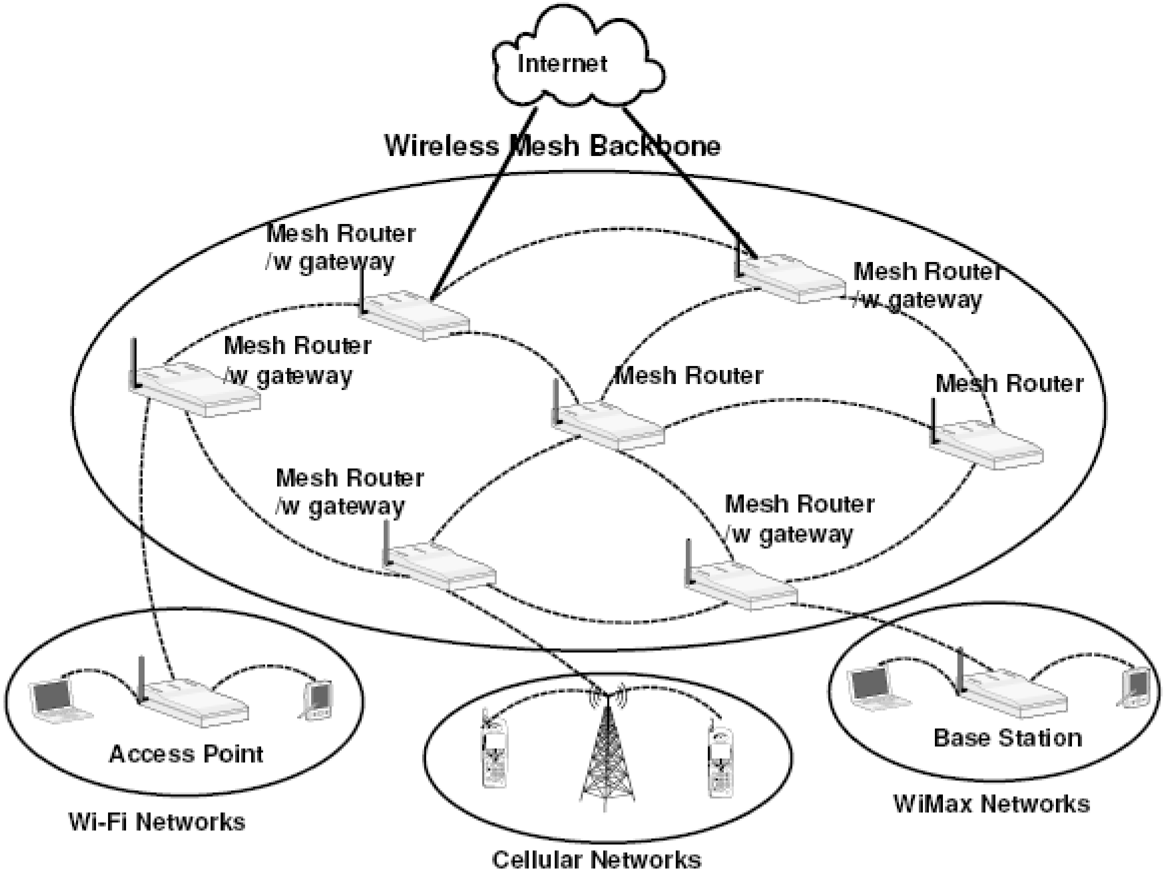


Figure 1.1: Backbone/Infrastructure WMN.

The second type is the client architecture which is a peer-to-peer way of communication where data is transmitted directly from one node to another. If the sender does not have the destination within its transmission range then the data is transmitted through other intermediate clients. In other words, client architecture is very similar to multi-hop ad hoc network topology. The specialized scenario investigated in this thesis corresponds very well to this type of architecture, with the UAVs being the client nodes.

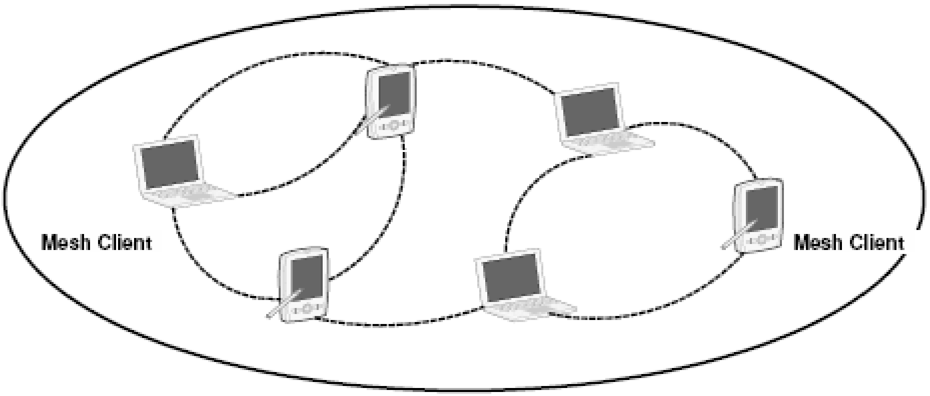


Figure 1.2: Client WMN.

Finally, there is the hybrid mesh architecture which combines characteristics of both of the previous two types of setups. In other words, there is the backbone section of the network which supports part of the clients; however there are also clients which communicate among themselves in a peer-to-peer mode.

Regardless of the way a mesh network is deployed, various applications will be enhanced by the realization of WMN, such as home and enterprise networking, building automation and networking unreachable urban areas. The main advantages of this new technology are the ease and low cost of deployment. Most of the components required are already available in the networking community and that consists both hardware components as well are established and tested protocols such as 802.11 MAC protocol.

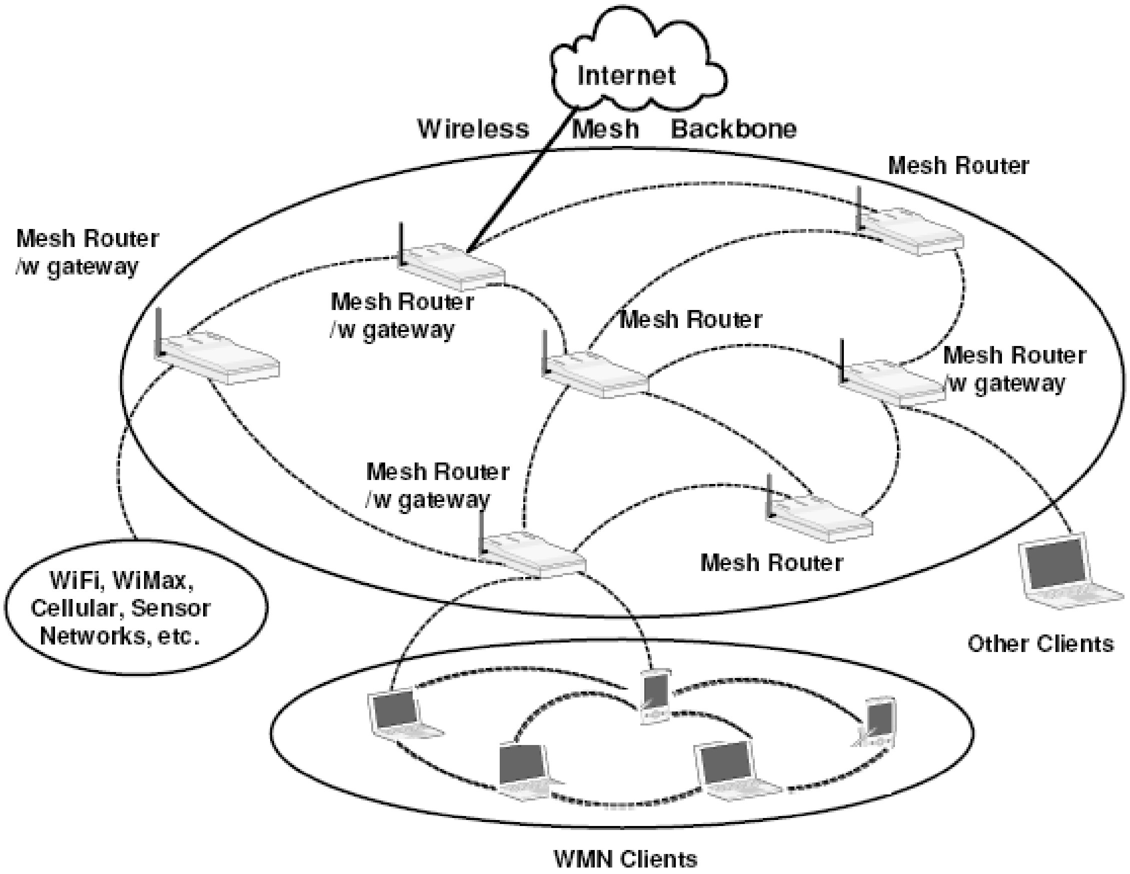


Figure 1.3: Hybrid WMN.

1.2 Design Issues

There are several design issues that need to be addressed regardless of which mesh architecture is being used [6].

First, there are Medium Access Control (MAC) layer design options. Research has shown that when each node is equipped with a single radio, the performance drops as more nodes enter the network. The reason is that mesh networks work in multi-hop environments and by having a single radio each node can either transmit or receive, but not both simultaneously. This was the motivation for multiple channel usage. There are several variations of this idea. One option is to use a single radio with a single transceiver for each node. When there is only one transceiver per node only a single frequency can be used. However different nodes can operate on different frequencies simultaneously. Another one is to have a single radio with multiple RF chips which will allow the node to operate on multiple frequencies. A final option is having multiple independent radios allowing multiple communications at the same time. This option is the most complicated one since there is a need for an additional MAC layer to coordinate the individual radios. However, the implementation of these solutions, require innovative hardware and software solutions, such as reconfigurable radios which are still in their infancy. Nevertheless, they are expected to enter the market in a widespread manner in the forthcoming years.

Scalability is another crucial attribute which affects the performance of the network. The protocol used in each layer should be scalable, meaning that the size of the network should not decrease the performance measurements. For instance, routing protocols should use the most optimal path, transport protocols must not lose connections and MAC protocols should not cause throughput to drop as additional nodes join the network. Failure of any of these can cause degradation of the network.

Moreover, the protocols must be designed with security in mind. There has not been yet a complete work of how security should be handled in WMNs. Initially, the existing ad hoc network security schemes can be reviewed and possibly adapted to work in WMNs. The adaptability must be done carefully to include the specific characteristics of this type of networks.

1.3 Mesh Routing Protocols

Since the mesh networks share many common points with ad hoc networks, the latter are used as a basis for development of efficient mesh routing protocols. There are three main categories of protocols: reactive, proactive and hybrid.

1.3.1 Reactive

Reactive routing protocols are also known as on-demand. As their name states, the sender looks for a way to reach the destination only when data is ready for transmission through a process known as route discovery and it is accomplished through two types of messages. The route request (RREQ) and the route reply (RREP). Route request messages are issued from the sender when transmission of data is ready. If the destination is within range, it recognizes the RREQ, replies back with RREP and then the actual transmission takes place. In case the destination is not within the transmission range of the sender the transmission becomes more complicated. RREQ messages are propagated through the network until the destination is reached. A series of RREP messages can arrive at the sender. Usually, the first RREP is used in the data transmission process. Now, the sender sends the packets through the route that was just discovered. In the example of Figure 1.4, node A is trying to send data to node G. However node A does not know how to reach node G yet. As a result, RREQ messages are issued and propagated through the intermediate nodes until node G receives a RREQ from the source. Then, RREP are sent back as described above. Node A now knows that the correct route to send data to node G is node A → C → D → F → G. Widely used reactive protocols include Ad-hoc on Demand Distance Vector

Protocol (AODV) [23], Dynamic Source Routing (DSR)[16], Temporary Ordered Routing Algorithm (TORA) [19], and so on.

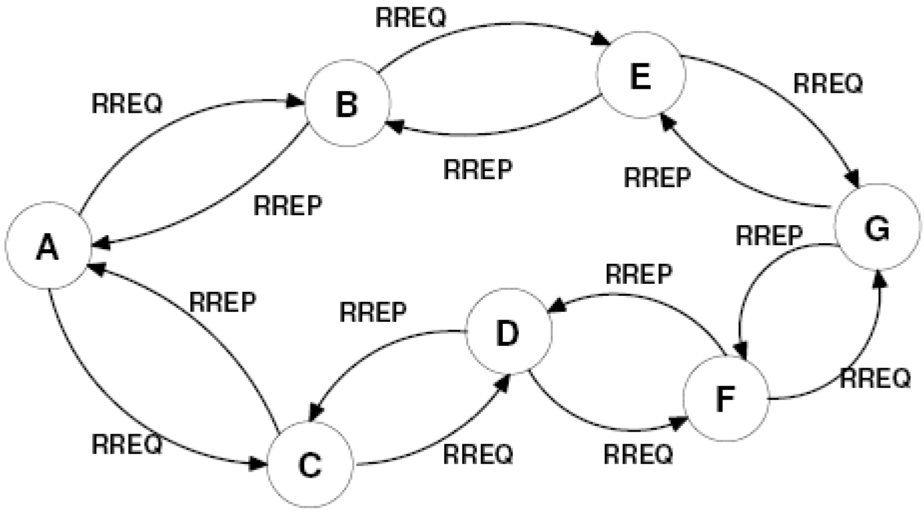


Figure 1.4: Example of a reactive routing protocol.

1.3.2 Proactive

Proactive routing protocols are also known as table-driven. They have routing table including complete routing information about all the nodes in the network. Every node advertises its routing table to its one-hop neighbors in periodic time intervals. Initially, when the network is first set up, there is a convergence time, the time it takes all the nodes to learn how to reach all the other nodes in the network topology. The table-driven routing appears in two variations: (i) source routing, where every node has stored the full path to every possible destination and (ii) next hop routing, where the table holds only the next hop for sending the packet. Optimizer Link State Protocol (OLSR) [15] and Destination Sequenced Distance Vector (DSDV) [21] protocols are just to name a few.

1.3.3 Hybrid

Hybrid routing protocols combine features of both proactive and reactive ones. Usually, the topology is divided into specified regions or zones. Data distribution within a region is table-driven (proactive) and when communication between nodes of different regions needs to take place, it is accomplished through on-demand (reactive) routing protocol. In Figure 1.5, there are two zones, 1 and 2 each having 3 nodes. Routing between nodes A, B and C as well as between nodes D, E and F is proactive. When a node needs to send data to a node of another zone, this process is carried out through the gateway nodes C and D of zones 1 and 2 respectively in a reactive routing manner. Examples of hybrid protocols include Dynamic Zone Topology Routing protocol (DZTR) [3] and Zone Routing Protocol (ZRP) [13].

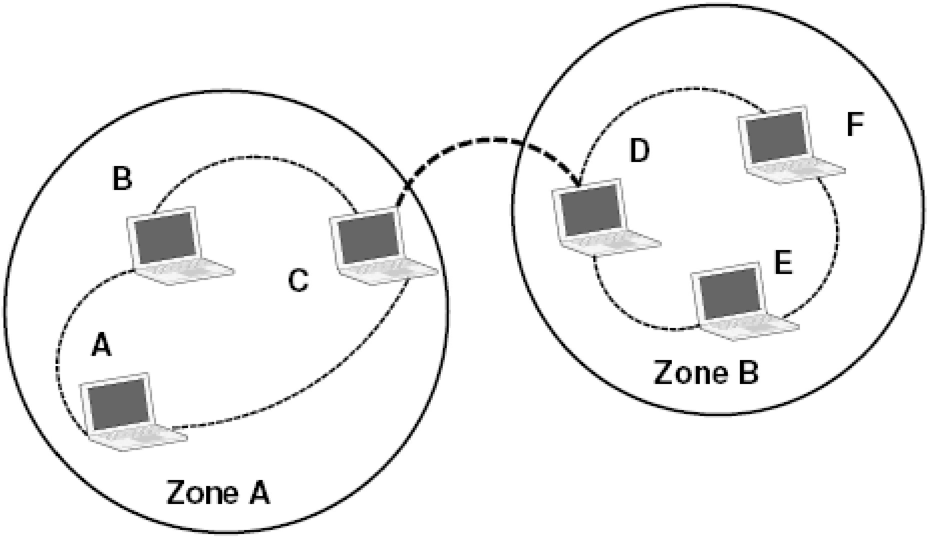


Figure 1.5: Example of a hybrid routing protocol.

Certain modifications need to be made to the protocols mentioned above, in order for the protocol to comply with mesh routing requirements. These changes were focused mainly on the path selection metric. The shortest path is still an option, as in traditional ad-hoc networks, but there were other interesting path selection metrics introduced, such as Expected Transmission Count (ETX) [10] and Expected Transmission Time (ETT) [11].

1.4 Contributions

This thesis designs and simulates a hybrid routing algorithm for a specialized scenario of a mesh network consisting of moving UAVs used by the Air Force to investigate new grounds (Figure 3.1). It combines characteristics of both proactive and reactive routing protocols used currently in ad hoc networks. The protocol is evaluated based on various performance metrics including routing overhead, packet delivery ratio, and latency. A stand alone simulator, based on Java, is used to carry out the simulation study since well-known network simulators such as ns-2 [2] and GloMoSim [1] are not feasible options for wireless mesh networks. Among the different research challenges that mesh networking faces, routing is one of the most crucial to the overall performance of the network.

1.5 Organization

The outline of this thesis is as follows. Chapter 2 describes some of the related literature work in the areas of mesh networking and routing protocols. Chapter 3 presents the proposed hybrid mesh routing protocol in detail. Simulation engine, environment, metrics, and results are given in Chapter 4. Chapter 5 concludes the thesis.

CHAPTER 2 : RELATED WORK

This section presents the existing literature work on routing protocols and mesh networks in general. However, since WMN is a very new technology and has not been standardized yet, part of the related work regarding routing protocols refers to ad hoc networks since they both belong to the same family.

There is a very interesting comparison between ad hoc and mesh networks in [17]. The ease of deployment and the compatibility with other wireless technologies are some of the few reasons why mesh networking has a high potential of overtaking the market in the near future. WMN nodes can communicate both with other clients, forming a client architecture, and with mesh routers. They are also flexible in terms of mobility and their ability to carry multiple radios with multiple frequencies which provides them with great potential to achieve high throughput performance.

[7] is an effort made by an MIT team to provide an area with internet access through a wireless mesh network backbone. The project is widely known as Roofnet. More specifically 37 nodes spread in an area of 4 km^2 in the city of Manchester, MA in an unplanned manner. Various performance parameters of the topology are evaluated such as link throughput relation with node density as well as antenna placement strategies. Regardless of lack of planning, the randomly deployed mesh network offers an average throughput of 627 kbits/sec even though the average route has 3 hops. Such a throughput can be considered more than enough for every day usage and despite the long routes it performs much better than the potential performance of a single-

hop network. Using omni-directional antennas at each node is the key to the high throughput measurements.

There are many papers providing a comparison study between the various MANET routing protocols. In [18], the authors made a comparison of OLSR, DSR and AODV routing protocols with respect to the quality of service. It is concluded that proactive protocols such as OLSR tend to find shorter paths than reactive protocols (AODV) and as a result achieving lower end-to-end delay. However, when OLSR is tested without link layer feedback, it reveals the highest broken link latency which results in high packet loss ratio. It is also observed that reactive protocols buffer packets during route discovery while proactive ones buffer under high mobility conditions.

Dynamic Source Routing (DSR) [16], Zone Routing Protocol (ZRP) [13] and RUNNERS protocols are simulated and evaluated in [9]. Their findings suggest that DSR achieves low message delivery rates but minimized latency in packet delivery while ZRP behaves well in networks of low mobility rate but its performance drops for highly mobile networks. Finally RUNNERS sustained its performance with high mobility rates. After extracting the necessary conclusions about the protocols' behavior, the authors designed two new protocols combining characteristics of the previously tested routing approaches. The new protocols prove to perform reasonably well in networks of in various mobility patterns and speeds.

In [4], all three categories of MANET routing protocols are compared through simulation.

The protocols evaluated were OLSR, AODV and DZTR from the proactive, reactive and hybrid routing protocol classes respectively. The results showed that hybrid protocols are more scalable and when under low mobility AODV performed similarly well.

A new metric, called Expected Transmission Count (ETX), used by multi-hop routing protocols for path selection is presented in [10]. It predicts the total number of transmissions (including retransmissions) until it is delivered to its destination. In order to compute its value, it uses the per link loss ratio in both directions of each wireless link. It was tested in a 29 node testbed and proved to have excellent performance even as the network grows larger and the links become longer.

Based on this idea, a new metric, called Estimated Transmission Time (ETT) was introduced in [11]. This metric not only uses ETX mentioned above, but also considers the bandwidth of each link. All the ETT link weights are combined together resulting in a Weighted Cumulative ETT (WCETT) that describes each path. This metric is the core of the Multi-Radio Link-Quality Source Routing protocol. In contrast with ETX [10], the simulations run on the 23 node testbed show that this metric performs well in multi-channel environments.

The ETT metric is also used in another routing protocol technique which appears in [22]. In order to utilize the diversity of the communication channels in a more efficient fashion, this protocol proposed the opportunistic usage of multiple paths simultaneously. While most multi-path protocols use the first identified path for transmission and in case of failure, they start using the other available paths. In [22], the multiple packets are sent through all the identified routes at the same time. This method was proven to increase significantly the throughput since more data was transmitted through multiple paths and there was full usage of the links' available bandwidth.

Most of the above mentioned routing protocols assume that they will operate under a multi-channel environment on the link layer. Despite the fact that link layer protocols are not the main focus of this thesis, an intelligent solution with multiple network interface cards on each node was presented in [5]. The authors propose a protocol called Multi Radio Unification Protocol (MUP) in which multiple NICs are places on a node. With every NIC tuned into a different, non overlapping, frequency, multiple communication transactions can be accomplished simultaneously. In this manner, the local available spectrum is utilized in an optimal fashion. This protocol is mostly suitable for multi-hop wireless networks such as wireless mesh networks where power consumption is not a limiting factor.

In [14], it is shown the importance of cross layer metrics in the routing process. The authors have deployed a mesh network consisting of a backbone of mesh routers. These routers were built from off-the-shelf hardware and open source software and they were deployed in a lab for traffic tests. The tests show that cross layer metrics keep a high level of performance by increasing the network capacity even as more nodes are added in contrast to some traditional routing metrics used. Through a cross layer metric, the router can use information from the MAC layer regarding quality and reliability of a link and as a result short and reliable paths can be chosen for data distribution.

As mentioned earlier, one of the most common reactive routing protocols is AODV (Ad Hoc On-Demand). In [20], there is an interesting approach in extending the current AODV such that it can operate in multi-radio, multi-hop networks. Since it is clear that multi-radio strategy is the key to the mesh networks' success this paper proves this statement. The authors compare the behavior of AODV using a single radio and then multiple radios (2 and 3). The simulation results were encouraging and show a significant improvement in terms of throughput and delay of multi-radio AODV over its single-radio counterpart, especially under high load, making the protocol a promising candidate for multi-radio WMNs.

CHAPTER 3 : THE PROPOSED MESH ROUTING PROTOCOL

3.1 System Design

The main application of the proposed protocol in this thesis is military. The network should guarantee the ability to rapidly deploy a force to any location in the world and instantly communicate using high data rates. This communication can provide live feeds of audio and video from the individual teams executing engagements for training or live combat to their base stations, which can in turn function as routers/gateways to the internet. Thus, the proposed routing algorithm is intended to provide the network with such capabilities and is evaluated through a scenario which considers a set of unmanned aerial vehicles (UAVs) above a certain terrain. The downstream data is usually larger than the upstream since the ultimate goal for the flying reconnaissance planes is to send information to the base stations which could serve as routers/gateways to the internet. However, there are also communication messages being transmitted between the UAVs which help them coordinate their terrain identification process. There is a variety of the UAVs operating at various speeds, altitudes and paths, as depicted in Figure 3.1.

- Class A: High-altitude, high-speed UAVs are taking reconnaissance data at the altitude of 40,000 feet and speed of around 800km/h.

- Class B: Medium-altitude, medium-speed UAVs are patrolling certain areas at the altitude of 20,000 feet at a speed of around 200-300km/h.

- Class C: Low-altitude, low-speed UAVs which are hovering or moving with slow speed around a relatively static area. Their altitude can be 0-1,000 feet and their speed of 0-100km/h. The ground nodes which can be either slow moving battle tanks or base stations serving as gateways for data processing and internet connection also belong to this class.

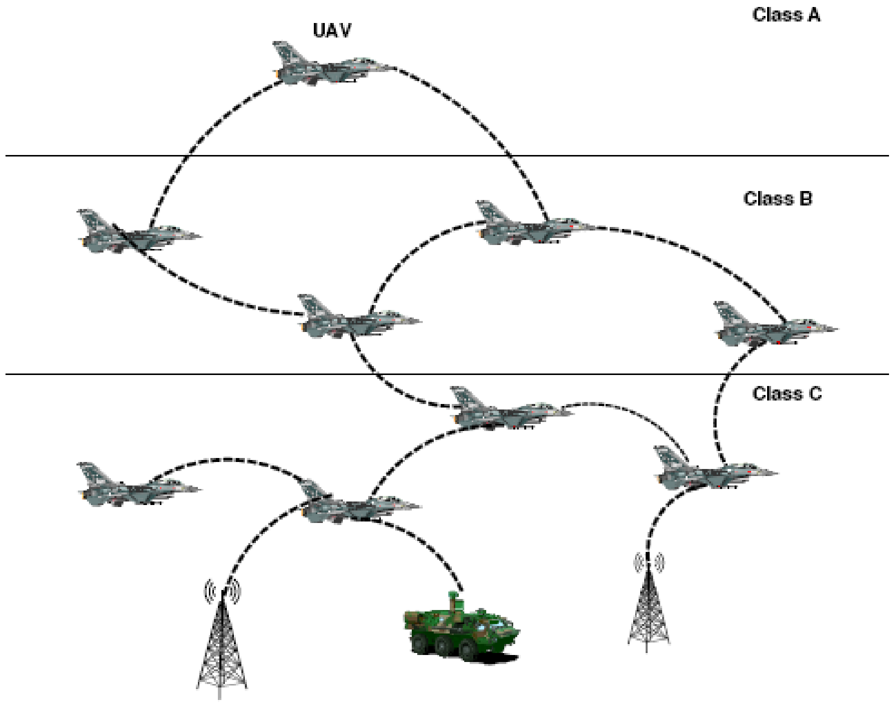


Figure 3.1: Node classification.

3.2 A Typical Scenario

Let us now consider a typical scenario of the system. More specifically, there will be several UAVs deployed and controlled from a base station. A class A reconnaissance airplane identifies a potential point of interest. Initially it will scan the specific area and transmit information about it to any base station. However, due to its high speed it can only observe the target for a limited time and with minimal detail level. Therefore, it can communicate with a lower class airplane and pass the observation task to it and have a better image of the area. This process can also happen the other way around. A lower class node can ask a higher class airplane to get a wider view of a certain area. As a result, we have two types of data to transmit: communication data which coordinates the assigned tasks to the UAVs as well as images or video of the scanned target. Class C planes usually just serve the role of intermediate nodes to the task of data delivery to the ground stations.

3.3 The Protocol Description

The proposed routing protocol uses attributes and characteristics of current ad hoc routing protocols since the situation is very similar. In ad hoc networks, we have two main types of routing protocols as discussed earlier. In our case, the decision made was to use both routing methods taking into consideration the class of each node.

More specifically, class A nodes use reactive while class B and C nodes follow proactive routing protocols as can be seen in Figure 3.2. Reactive routing causes flooding which usually affects the performance of the network negatively. However, the estimation is that since the nodes are moving at a very high speed any table-driven protocol could have a high number of invalid entries resulting in high packet loss ratio. That is why reactive routing is preferred at this level. In addition, class A nodes are not the busiest ones since the highest load is in the two bottom classes of nodes. So, it is obvious that in the upper node class there is a tradeoff between the performance and the data delivery assurance.

In classes B and C, proactive routing is used for routing the packets to their destinations. The reason being that mobility is not extremely high; therefore, a proactive protocol is a suitable choice. Nevertheless, packet overhead is expected to be relatively high due to the periodic table updates. That would be a waste of bandwidth in cases where the nodes are not used frequently. However, class B and C nodes are busy transmitting their own data as well as forwarding other nodes' data. As a result, having extra overhead becomes valuable since it contributes to the assurance of the successful packet delivery.

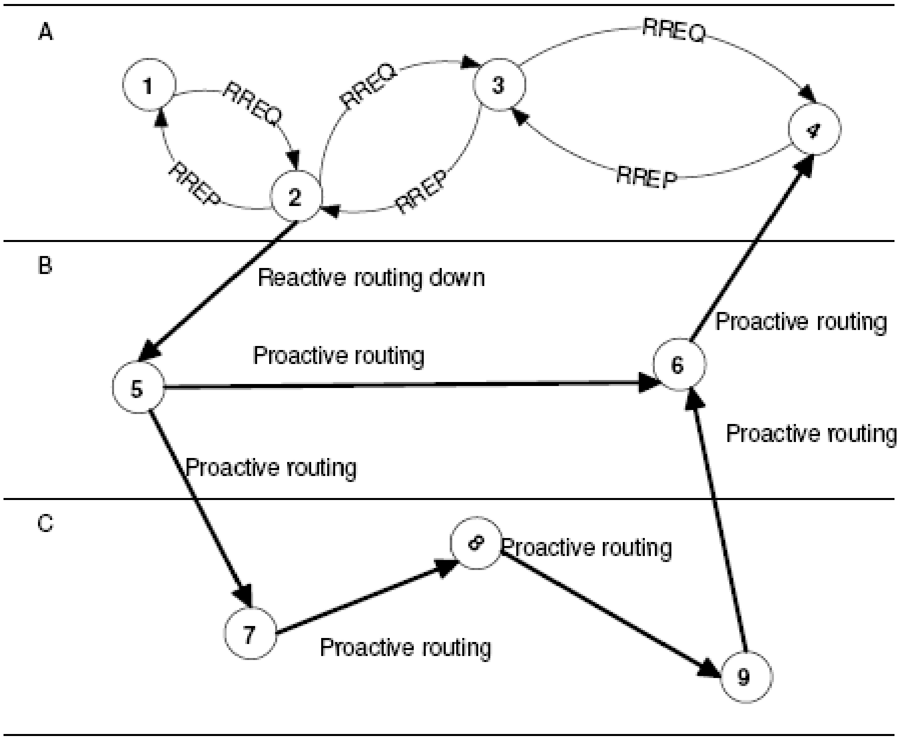


Figure 3.2: Protocol description.

In order to better understand the structure of the logic through which the protocol works, a straightforward pseudocode explanation is provided below.

Algorithm 3.3.1: SIMULATOR($numberOfNodes$)

```
ask user for nodes' coordinates
for i ← 0 to 1000
  do
    comment: Simulate nodes's mobility
    if timer is increment of 10
      then
        move nodes
    comment: Send routing table updates periodically.
    if timer is increment of 20
      then
        update routing tables
    for j ← 1 to number of nodes
      do
        if packet generation = true
          then
            select a random destination
            if source is class A and destination is class B or C
              then
                start route discovery to the closest neighbor of classB
                add to that node's queue the actual destination
            if source and destination are class B or C
              then
                read routing table
                add to the source's queue the next hop
        transmit everything in queue
    comment: Calculate metrics from output trace file.
    calculate latency
    calculate packet overhead
    calculate delivery ratio
```

3.4 An Illustrative Example

Below there is a brief example of how the nodes behave once traffic is generated. Figure 3.3 shows a set of five nodes (two of class A and three of class B) together with the generated traffic. The nodes having a heptagon shape are class A nodes and the rest are class B or C nodes.

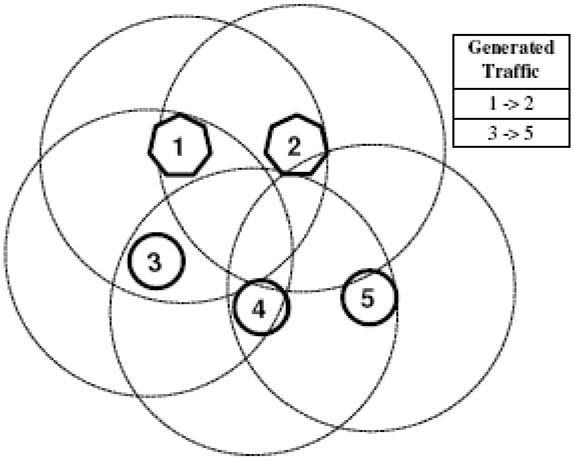


Figure 3.3: The nodes with their transmission ranges.

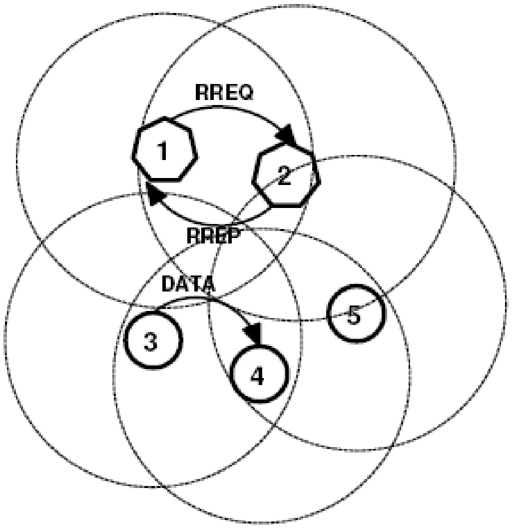


Figure 3.4: An illustrative example, step 1.

During the first step (Figure 3.4), node 1 initiates a route discovery process by issuing a RREQ message with a sequence number of 1000. Node 2 receives the RREQ message. As a result, node 2 replies with a RREP message destined for node 1 with the same sequence number. At the same time, node 3 wants to send a packet to node 5. Node 3’s routing table has information that node 5 is its 2-hop neighbor which means in order to send data to node 5, it needs to forward the data packet to the next hop neighbor, which is node 4. So it sends the packet to node 4 with sequence number 1001.

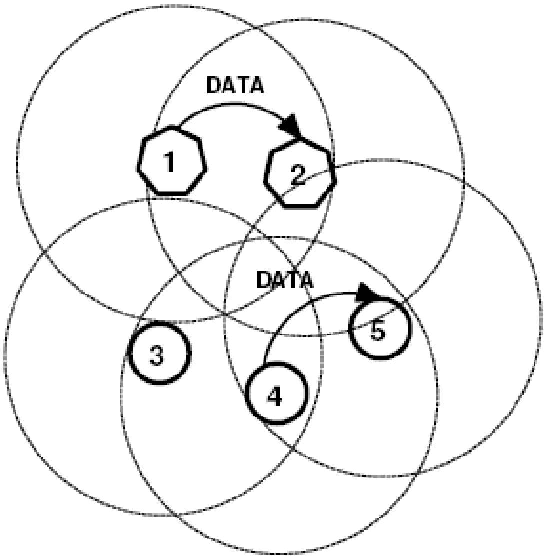


Figure 3.5: An illustrative example, step 2.

In step 2 (Figure 3.5), node 1 has received RREP from node 2 and it is now clear to transmit the actual data packet tagged with a sequence number of 1000. Node 4 has received the packet from node 3, but it has a final destination of node 5. Node 4 checks its routing table and sees that node 5 is within its transmission range (1-hop) and transmits the packet to node 5 with a sequence number of 1001. At this point the transaction having sequence number of 1001 has finished.

During this third step, node 5 has generated a packet to be delivered to node 4. According to its routing table node 4 is within a 1-hop range and it sends the packet directly to node 4. For the illustrated example discussed, the output recorded in the trace file which logs all events that happen within the time of the algorithm run, is presented in Table 3.1.

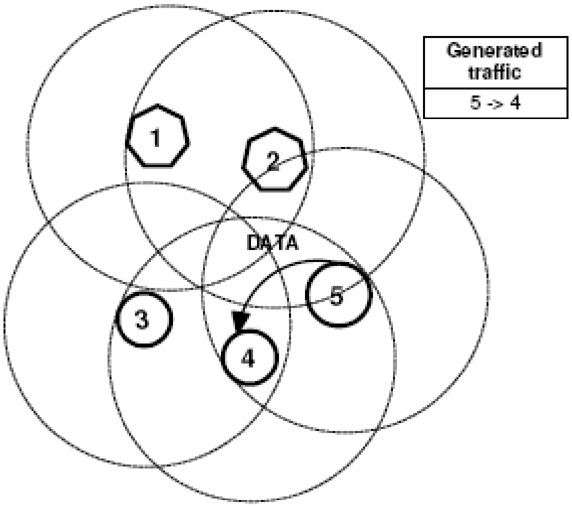


Figure 3.6: An illustrative example, step 3.

Table 3.1: Summary of the events triggered in the example given.

TIME	*MESSAGE TYPE*	*SEQUENCE NUMBER*	*from*	*SOURCE*	*to*	*DESTINATION*
1	RREQ	1000	from	1	to	2
1	RREP	1000	from	2	to	1
1	DATA	1001	from	3	to	4
2	DATA	1000	from	1	to	2
2	DATA	1001	from	4	to	5
3	DATA	1002	from	5	to	4

CHAPTER 4 : SIMULATION STUDY

This section provides detailed presentation of the simulation method, its environment. We also present and interpret the results of the simulations. The algorithm is built from scratch and simulates the movement of UAVs and collects routing data. Our simulation study concentrates on the network layer and collects data about the behavior and performance of the proposed protocol. We assume the existence of an ideal collision-free Medium Access Control (MAC) layer.

4.1 Simulation Environment

The simulator itself is a stand alone program written in Java2 [24]. The environment used to develop the source code is Eclipse [12]. The mechanism generates a random number of events among the nodes and it logs every transmission in an output trace file similar to the one in (Figure 3.1). This file in the end is processed in order to extract the protocol metrics. The input of the algorithm is the total number of nodes participating in the simulation, and their initial coordinates. The altitude the nodes are allowed to fly is assumed to be between 0-400 units (0-40,000ft). If a node is placed within 0-132 units of altitude then it is class C (lower class). In the same manner, nodes between 133-264 are class B and the upper class nodes are from 265-400. Nodes are considered within transmission range of each other if their distance is less than 60 units. In general, there are more nodes flying at lower than at higher altitudes. In our simulation, we kept consistent the proportionality of the nodes in a given class and respected the relation count(A) < count(B) < count(C).

The nodes are following a mobility pattern in which class A nodes move faster, class B move slower than class A and faster than class C and the bottom class nodes are the slowest of all, if not stationary.

As mentioned in the algorithm description, the packet transmission is handled in a different way according to the source's and the destination's node class. Class A nodes transmitting data among themselves is handled through the reactive part of our hybrid protocol. When the source has data to be sent, it issues a RREQ message which is passed through in an expanding loop manner until it reaches the destination. At that moment the destination sends RREP messages which arrive to the initial source through the reverse path of the RREQ message. Following the route discovery phase, the transmission starts through the previously identified path and at a sequence of one hop per time unit. Many on demand (reactive) routing protocols have also a route cache where the temporarily store routing information about various destinations. Usually this information has a short time to live (TTL) period. Only in the case where there is no routing info in the route cache, route discovery process is initialized. This is not the case in this scenario. Class A nodes are moving at such a high speed that even if there is information in the route cache it is highly probable that it is invalid by the time of transmission. This would result in packet loss and perhaps handled by the MAC protocol for a retransmission, a process resulting in additional delay. Thus, we perform route discovery at every transmission. By this method the unnecessary delays are minimized since the route will always be up-to-date at the beginning of the transmission. There is always the probability of packet losses due to the high moving pace of the UAVs, but still this is the best possible way to handle this issue.

Traffic between Class B and Class C nodes is handled through the proactive part of the protocol; routing tables are being used to forward the packets from source to destination.

Table 4.1:Routing table of node 6.

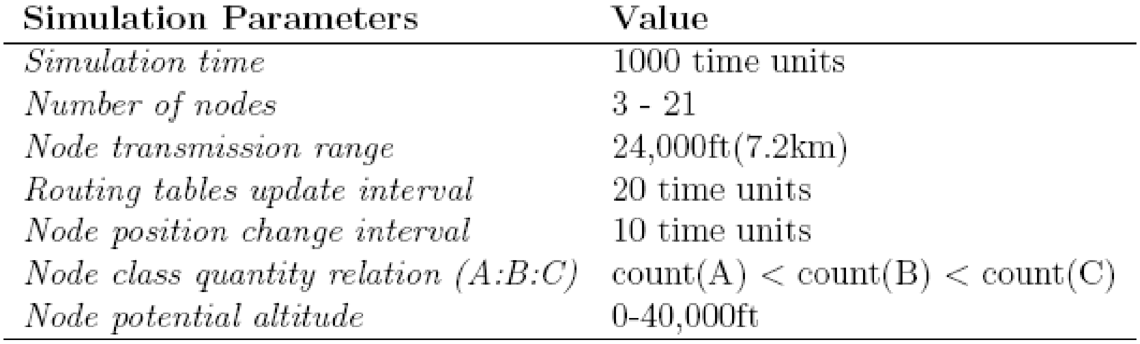
Destination	*Next Hop*	*Hop Count*
1	4	3
2	4	2
3	4	2
4	4	1
5	5	1

For example, let us assume we have a total of 6 nodes in the network. Table 4.1 shows the routing table of node 6. The first column is the destination node and the second column is the next hop that the data should be transmitted to in order to reach the actual destination. For instance, if node 6 has to send a packet to node 1 it should forward the data to node 4, which is the next hop, and node 4 will then forward it appropriately so node 1 can receive it. Nodes of class B and C move at a slower speed which allows routing tables to be used effectively without having a great amount of lost frames.

In order for each node to have the most correct routing tables possible, every node sends its routing table to its neighbors. The path selection metric for the table creation process is the minimum hop count. More specifically, a node has only one entry for each destination. If the destination is not within immediate range then the next hop is chosen based on the shortest path to that specific destination. In the simulator, these routing updates occur every 20 time units. As a result, every 20 time units each node refreshes its routing information. When the network is first deployed there is a certain time that takes for the nodes to learn about the existence of the rest the nodes and store information regarding them in their tables. The measured part of the simulation starts after the “warm-up” period, at a point where the network has fully converged.

In the event that a node A class needs to transmit data to a class B or C node, the hybrid nature of the protocol comes into place. In case the two nodes are within transmission range of each other, then the event takes place just like a reactive transaction. The source initiates route discovery with a RREQ message and the destination, which is in range replies with a RREP and then the one hop transmission occurs. On the other hand, when the two nodes are not in range then class A node, which is the source, issues a RREQ. The closest class B or C node replies and gets the message from the upper class node. At this point is the responsibility of the intermediate class B or C node to deliver the frame to the final destination, using the routing information within its routing table. Thus, the first step was accomplished in a reactive manner and the rest in a proactive. Since collisions are not an issue, multiple events that involve a specific node can happen at the same time. Assuming that the routing protocol uses an ideal (duplex) MAC layer, each node can receive and transmit packets at the same time. A summary of the simulation parameters can be seen in table 4.2

Table 4.2:Simulation parameters.



Simulation Parameters	Value
Simulation time	1000 time units
Number of nodes	3 - 21
Node transmission range	24,000ft(7.2km)
Routing tables update interval	20 time units
Node position change interval	10 time units
Node class quantity relation (A:B:C)	count(A) < count(B) < count(C)
Node potential altitude	0-40,000ft

4.2 Simulation Metrics

We evaluated the protocol's performance, using the following routing metrics [8]:

- % Routing overhead: The routing overhead is the packets used for routing table updates as well as control packets from the reactive part of the protocol (RREQ, RREP). It is calculated using the following formula:

$$\%Overhead = [\frac{Overhead\,packets}{Overhead\,packets + Data\,packets}] \times 100$$

- Packet delivery ratio: It is the ratio of the number of packets successfully delivered over the total packets transmitted in the simulation:

$$Packet\ delivery\ ratio = [\frac{delivered\,packets}{delivered\,packets + lost\,packets}] \times 100$$

- Latency: The time that takes a packet to arrive at the destination. It is measured in time units with a time unit being the amount of time for a packet to reach a one hop destination. All links are considered to have equal cost.

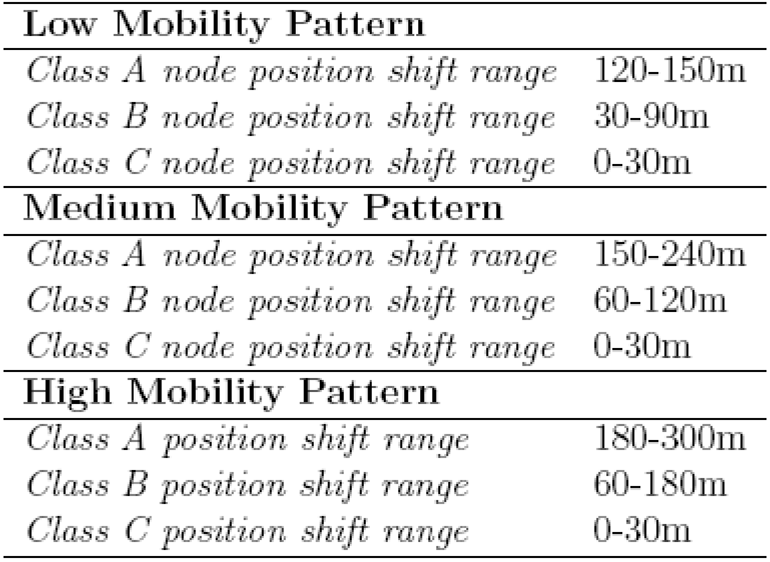
We study the variation of these three metrics in function of the following simulation parameters:

- Number of nodes: The amount of nodes participating in the simulation, ranging from 3 to 21. Regardless of the number of nodes taking part in the simulation, the UAVs are positioned, in such a way that they provide a node density of about 1 node in every 10km^2.

- Node density: The network topology is usually affecting the network performance. Node density, which describes the deployment of the nodes, is the number of nodes encountered in every 10 km^2. The values range from 0.6 to 1.4 nodes per $10km^2$. While evaluating the importance of node density, the number of nodes in the topology is maintained at 12 nodes.

- Node mobility: Mobility is a crucial factor that affects mesh networks. We have chosen three mobility patterns: low, medium and high mobility. In every position change each node shifts its x and y coordinates by a distance within the range specified in table 4.3. Through this method random variations in the speed of the node take place providing more realistic conditions for the simulation.

Table 4.3: A summary of the mobility patterns used.



Low Mobility Pattern	
Class A node position shift range	120-150m
Class B node position shift range	30-90m
Class C node position shift range	0-30m
Medium Mobility Pattern	
Class A node position shift range	150-240m
Class B node position shift range	60-120m
Class C node position shift range	0-30m
High Mobility Pattern	
Class A position shift range	180-300m
Class B position shift range	60-180m
Class C position shift range	0-30m

4.3 Simulation Results

4.3.1 Routing Overhead

In this experiment, we measure the routing overhead in function of the number of nodes. The measurements for the three different levels of mobility are shown in Figure 4.1. We notice that the routing overhead is maintaining a value of around 30%, except for the case with a very low number of nodes (n=3), when it is around 45%. 30% is a relatively high overhead for routing algorithms. In our case it is caused by the frequent refreshes of the routing tables, as well as the relatively short data transmission sequences. We note that there is little variation on the percentage of the routing overhead with the increase of the number of nodes. The amount of packet overhead also appears to be independent from node mobility.

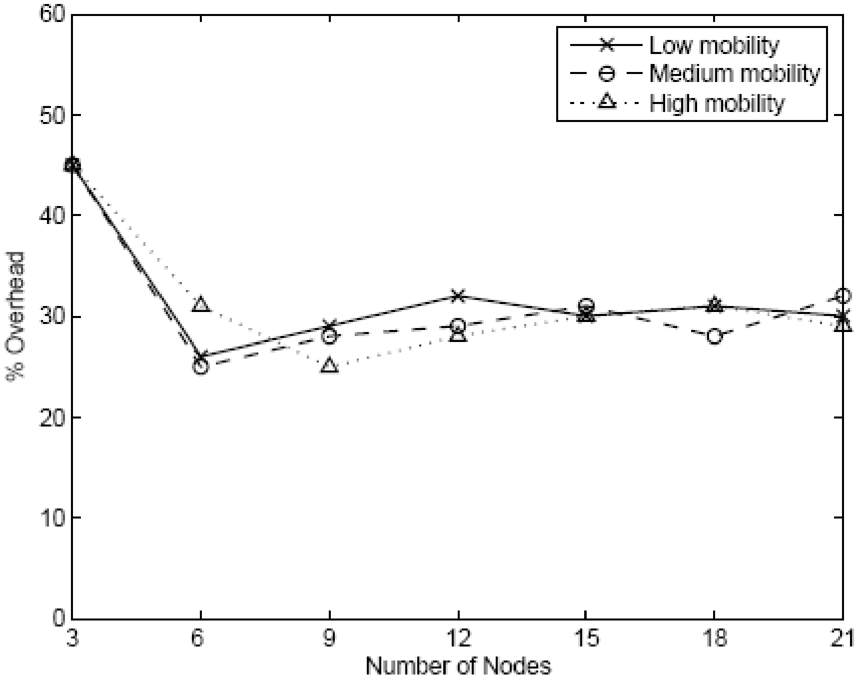


Figure 4.1: Average routing overhead vs. number of nodes for the three classes of mobility.

In the next step, we compared the overhead with respect to the changing node density and how this relation is affected from the different mobility patterns applied each time. As mentioned earlier density is described by the number of nodes in every 10 km^2. The larger the number is, the denser the topology. Figure 4.2 shows the routing overhead in relation to the node density. The resulting values are in the range of 25-33% with an average value of 30%. This proves that routing overhead is not affected by the node density. Similarly to the case, the mobility of the nodes does not alter the relation between packet overhead and node density. Routing updates are broadcasted in periodic intervals regardless of how dense the network is or how fast the UAVs are moving. Of course, they would be affected in case we changed the quantity of nodes in each node class.

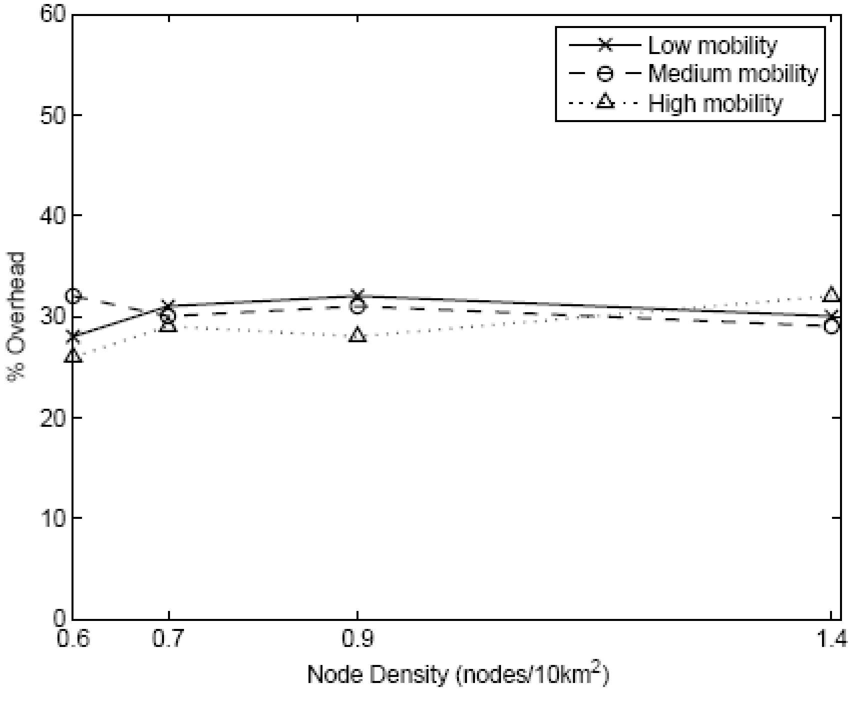


Figure 4.2: Average routing overhead vs. node density for the three classes of mobility.

For example, placing several class A nodes and less class B and C would definitely result in variation of the overhead. However, that is not the case since all simulations followed the same deployment guidelines which give a standard node quantity relation of count(A) < count(B) < count(C) for classes A, B and C respectively.

Overall, it appears that routing overhead has a steadily high value because of the routing table updates and it neither degrades nor improves as various parameters, such as node density and mobility, change. The only parameter that could affect the % routing overhead is the time period that the nodes send table updates to their neighbors as well as the proportionality of nodes within the topology. Since neither of these were changed during the simulations, then it is normal for the overhead to remain almost unchanged.

4.3.2 Packet Delivery Ratio

The packet delivery ratio as a function of the number of nodes for the three levels of mobility is shown in Figure 4.3. As seen in the corresponding graph, packet delivery ratio is generally kept at high levels. When there are only a few nodes in the network, the faster the nodes move, the higher the loss rate will be. If on the other hand the mobility is kept stable, one can conclude that the larger the network is (in terms of number of nodes) the delivery ratio is approaching a percentage of above 90%. Since collisions are not an issue in this study, there are two possible cases in which a packet can be lost: it either has no neighbor nodes in its transmission range or the routing table becomes out of date by the time the packet gets transmitted. Thus, as the network gets larger the probability that there will be at least one node that can forward the packets from any source toward the destination is higher. In other words, there are more UAVs serving as intermediate nodes. Moreover, it looks that the drawback of high overhead brings the advantage of very high packet delivery ratio because routing information within the tables is valid at a great percentage. Class A nodes, which move at a fast rate, have a higher chance of losing packets; however, their traffic load is not very high in relation to the lower nodes. So, the overall packet delivery ratio is only moderately affected by these nodes.

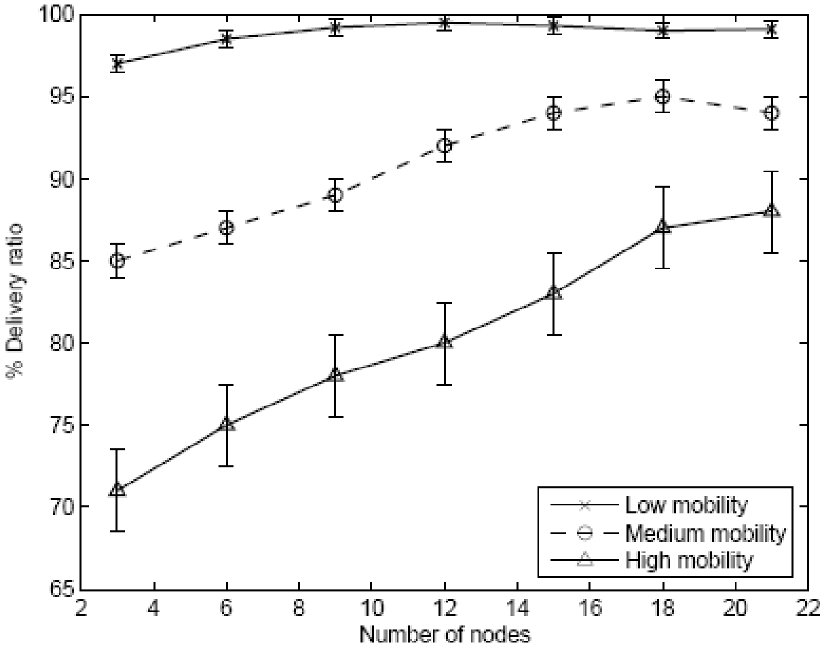


Figure 4.3: Average packet delivery ratio vs. number of nodes for the three classes of mobility.

In the next step, we study the packet delivery ratio as a function of node density for the three classes of mobility (see Figure 4.4). We notice two important trends. First, the packet delivery ratio is increasing with the node density because there are a low number of packets lost due to no nodes being available in the transmission range. Second, we find that in scenarios with low node mobility, the delivery ratio is consistently higher. This is due to the fact that with a lower mobility class, the routing tables have a lower chance of becoming out of date.

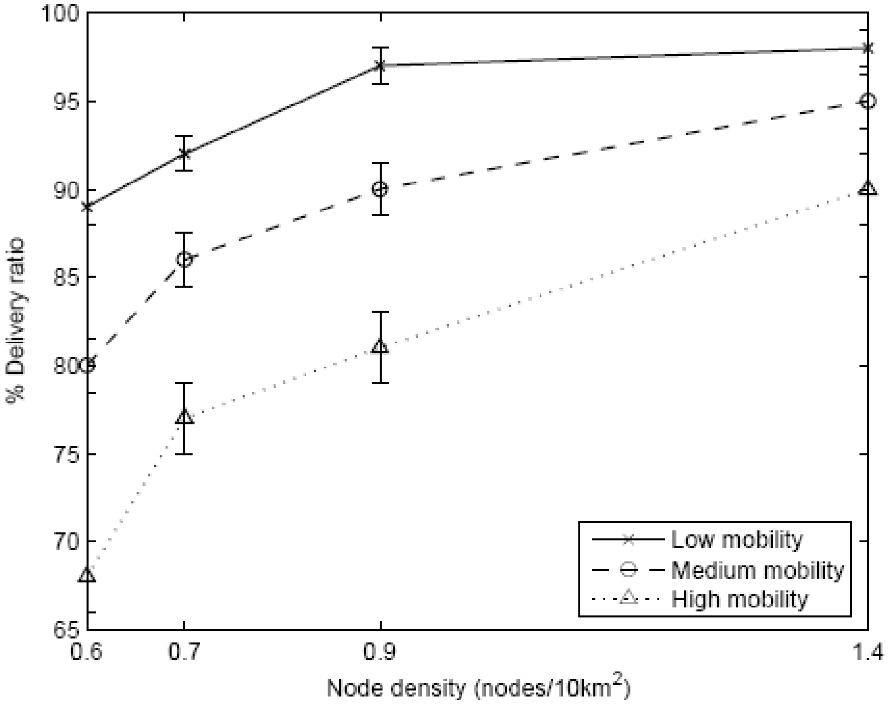


Figure 4.4: Average packet delivery ratio vs. node density (for 12 nodes) for the three classes of mobility.

Summing up, we can conclude that generally packet delivery ratio is maintained at very high levels. It seems that the mesh network is slightly sensitive to node density and highly sensitive to node mobility. A strategic planning of the deployment of the nodes can prevent low density and high mobility existing at the same time and a wise balanced solution among them should be chosen during the network design. Loss rates could become extremely high under certain conditions. However, the fact that the topology behaves and moves as a group proves to be the reason why the network performance is not degrading significantly no matter how the parameters change.

4.3.3 Latency

Through Figure 4.5, which illustrates the latency in relation to the node number in the network, we draw the conclusion that the protocol has high potential of being part of a scalable network. It takes on average from 1.2 - 2.3 time units for a packet to be delivered to the destination. Since a time unit is the time for a packet to be transmitted from one node to another (1-hop), the latency can be interpreted into number of hops. Usually, the more hops it takes for a packet to be delivered, the greater the latency is. A slight increase is noticed as more nodes are added in the mesh network. This is explained by the fact that when more nodes are added the potential distance from any source to any destination gets larger and a longer path will be followed. We also noticed that the average latency is higher for high mobility scenarios. The higher the mobility gets, the probability that any given source is at large distance from any destination, gets higher because the distances are getting larger too. In such a case the most probable scenario is that the packet will need extra hops to arrive at the desired destination.

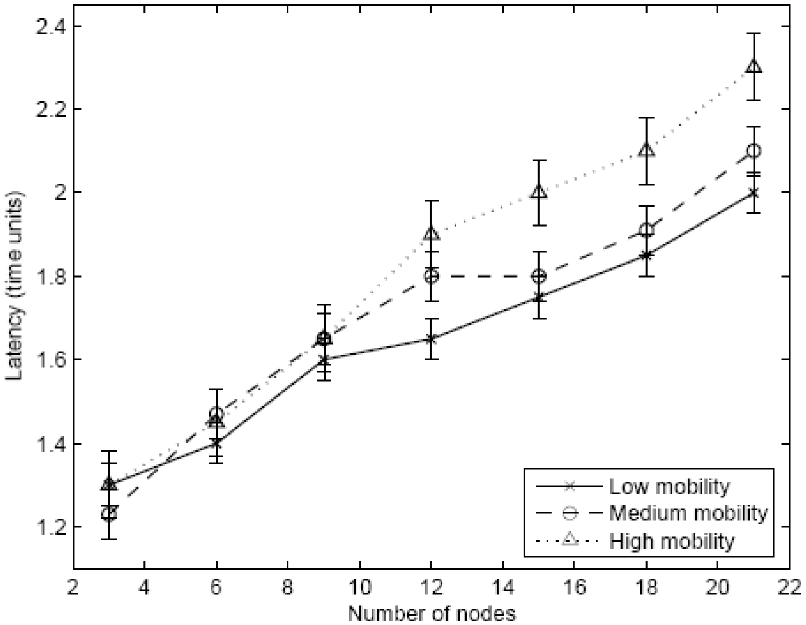


Figure 4.5: Average latency vs. number of nodes for three mobility levels.

In the next step, the latency as a function of node density is examined for scenarios with the three different levels of mobility. Latency is affected by node density. While node density decreases and nodes move away from each other, distances from any source to any destination become larger creating the need for extra hops in the transmission path. The conditions get worse if along with the insertion of more nodes, the mobility is increased. Nevertheless, the reasons are the same: distances between nodes increase causing the latency to escalate (Figure 4.6).

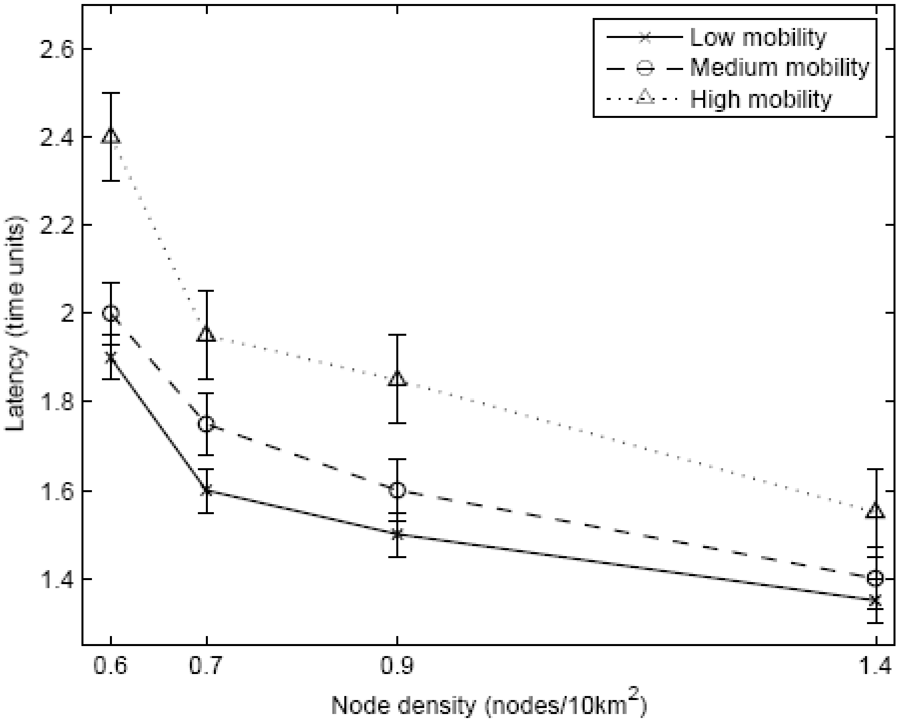


Figure 4.6: Average latency vs. node density (for 12 nodes) for the three classes of mobility.

In the end, it appears that latency is affected both by the size of the network and this relation is in turn affected by the mobility pattern followed by the nodes. There is a tendency for the latency to get higher as more nodes are added or the existing nodes start to move faster.

CHAPTER 5 : CONCLUSION

The purpose of this thesis was to design and simulate a hybrid routing algorithm for military applications in wireless mesh networks. A specific scenario consisting of high speed unmanned air vehicles (UAVs) was considered. High flying nodes use reactive while low flying nodes use proactive routing.

In order to evaluate the performance of the proposed protocol packet overhead, delivery ratio and latency metrics were evaluated with varying number of nodes, node density, and node mobility. The assumption of an ideal Medium Access Control (MAC) was made to avoid packet collision issues.

Most of the metrics collected reveal positive indications about the performance of the network. Delivery ratio and node density appear to be sensitive to node mobility. When the mobility increases the delivery ratio drops unless more nodes are added to provide alternative routes. The shortest path metric for the path selection seems to be adequate since no collision is assumed. However, this protocol suggests it will be bounded with a multi-radio, multi-channel MAC protocol. The proposed routing protocol appears to be reliable because of the high packet delivery ratio which is above 90% most of the time.

Latency might be an issue that could cause scalability problems if the number of nodes and mobility get excessive. The simulations showed that there is a tendency for the latency to increase not only when more nodes enter the network but also when mobility is increased. The data that the Air force needs to transmit to the base stations from the UAVs are streaming video and imaging, which one can say that high throughput is needed at all times, placing latency to be of higher importance than reliability. If the position of the UAVs can be constantly monitored and the number of nodes is kept at reasonable levels, then we can say that this protocol is serving its purpose.

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