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Thesis Title

A New Channel Assignment and Routing Scheme for Competitive and Cooperative Wireless Mesh Network (WMM)

By

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Abstract

With a specific end goal to keep away from transmission's crashes and enhance arrange exhibitions in remote work systems (WMNs), a solid and effective medium get to control (MAC) convention and a decent channel allotment are required. Wireless mesh networks are multi hop networks of wireless routers, where each router node is equipped with multiple radio interfaces and multiple channels are available for communication. There is an increasing interest in using wireless mesh networks as broadband backbone networks to provide ubiquitous network connectivity in enterprises, campuses, and in metropolitan areas. An important design goal for wireless mesh networks is capacity. It is well-known that wireless interference severely limits network capacity in multi-hop settings. One common technique used to improve overall network capacity is use of multiple channels. Essentially, wireless interference can be minimized by using orthogonal (non-interfering) channels for neighboring wireless transmissions. The current IEEE 802.11 standard provides several orthogonal channels to facilitate the above**.** Presence of multiple channels requires us to address the problem of which channel to use for a particular transmission. The method which is used to assign the proper channel to a link is called Channel Assignment. The overall objective of such an assignment strategy is to minimize the overall network interference**.** Since the number of radios on any node can be less than the number of available channels, the channel assignment must obey the constraint that the number of different channels assigned to the links incident on any node is utmost the number of radio interfaces on that node. Routing is the process of finding a path from a source to some arbitrary destination on the network. A routing protocol is needed whenever a packet needs to be transmitted to a destination via number of nodes and numerous routing protocols have been proposed for wireless network. These protocols find a route for packet delivery and deliver the packet to the correct destination. In this paper, a joint Channel assignment and routing protocol are proposed to ensure low interference by assigning the non-overlapping channels to the multiple radios.

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Chapter 1

Introduction

1.1 Wireless Mesh Networks

In order to avoid transmission's collisions and improve network performances wireless mesh networks (WMNs) is a vital technology. It allows multiple channels use in the same network is often presented as a possible way to improve the network capacity. A Mesh Network is defined as being an infrastructure network working with an ad hoc mode. Communications in WMNs are multi-jump and multipoint-to-multipoint, the system is self-organized. What’s more, its exhibitions are influenced by versatility regardless of the possibility that it is low that is the reason outlining an adaptable MAC for WMNs is an issue. This versatility can be tended to by the MAC layer in two ways. The primary route is to upgrade existing MAC conventions or to propose new MAC conventions to increment end-to-end throughput when just single divert is accessible in a system hub. At the point when a few correspondence directs are accessible in the system, a moment route is to permit transmission on different directs in each system hub. Remote work systems (RWs) or Wireless Mesh Network system (WMN) have developed as a promising innovation for the arrangement of last mile broadband Web get to framework in both urban and provincial conditions. Such systems are described as settled spine WMNs where hand-off hubs are for the most part static and are for the most part provided by a changeless power source. With the accessibility of off-the-rack, minimal effort, ware organizing equipment, it is conceivable to fuse various radio interfaces working in various radio channels on a solitary work switch; consequently framing a work arrange. This empowers a potential expansive change in the limit of work systems [1].

Wireless Mesh Network systems are multi-hop systems of remote switches. There is an expanding enthusiasm for utilizing remote work arranges as broadband spine systems to give omnipresent system availability in undertakings, grounds, and in metropolitan regions. An essential outline objective for remote work systems is limit. It is notable that remote obstruction extremely restricts arrange limit in multi-jump settings. One regular method used to enhance general system limit is utilization of numerous channels. Basically, remote obstruction can be limited by utilizing orthogonal (non-meddling) channels for neighboring remote transmissions. The current IEEE 802.11 standard for WLANs to be sure gives a few orthogonal channels to encourage the above. Nearness of different channels expects us to address the issue of which channel to use for a specific transmission; the general target of such a task procedure is to limit the general system impedance [1, 2].

1.2 Channel assignment in WMNs

The activity in WMNs is predominantly coordinated amongst hubs and the Internet yet we trust that too activity exists between hubs themselves. High-transmission capacity applications require adequate system limit so it is trying to make the system giving such limit. So as to move forward WMNs limit a decent administration of the accessible frequencies is fundamental. One of the special attributes of multi-radio work systems or WMNs is the nearness of obstruction among the hubs principally because of the common idea of remote medium and covered channels of neighboring hubs. Along these lines, to successfully alleviate the general system impedance, there is a need to plan a joint directing and channel task conspire though the channel task decides the system topology of a system and steering finds the information ways to course the streams in view of the system topology being controlled by the channel task. Directing and divert task in WMNs has been a dynamic zone of research throughout the previous quite a long while. Different approaches have been proposed for joint channel task what's more, steering in view of insightful systems, for example, multi-operator innovation and hereditary calculations. There is another system for taking care of hard advancement issues called Ant Colony Optimization (ACO) which is a meta-heuristic approach for taking care of such issues. The ACO approach has not been utilized so far for settling joint channel task and directing issue in multi-radio WMNs [3].

Channel assignment in a multi radio WMN condition comprises of doling out channels to the radio interfaces so as to accomplish proficient channel use and limit impedance. The issue of ideally doling out diverts in a discretionary work topology has been demonstrated to be NP-hard in light of its mapping to a chart shading issue. In this way, channel task plots prevalently utilize heuristic systems to allocate diverts to hubs in the system. The execution bottleneck related with divert task in WMNs has been widely considered in the writing. In this segment we display a taxonomical grouping of different Channel allocation plans for work systems. Figure 1.1 presents the scientific classification on which whatever remains of the area is based. In particular, the proposed Channel assignment plans can be isolated into three principle classifications — settled, dynamic, and half breed — depending on the recurrence with which the Channel assignment plot is altered. In a settled plan the Channel assignment is nearly consistent, while in a dynamic plan it is persistently refreshed to enhance execution. A cross breed conspire applies a settled plan for a few interfaces what's more, a dynamic one for others. In the accompanying we examine these three classes and give cases of Channel allocation plans from every classification in our chapter 2 in section 2.3 [5, 6].

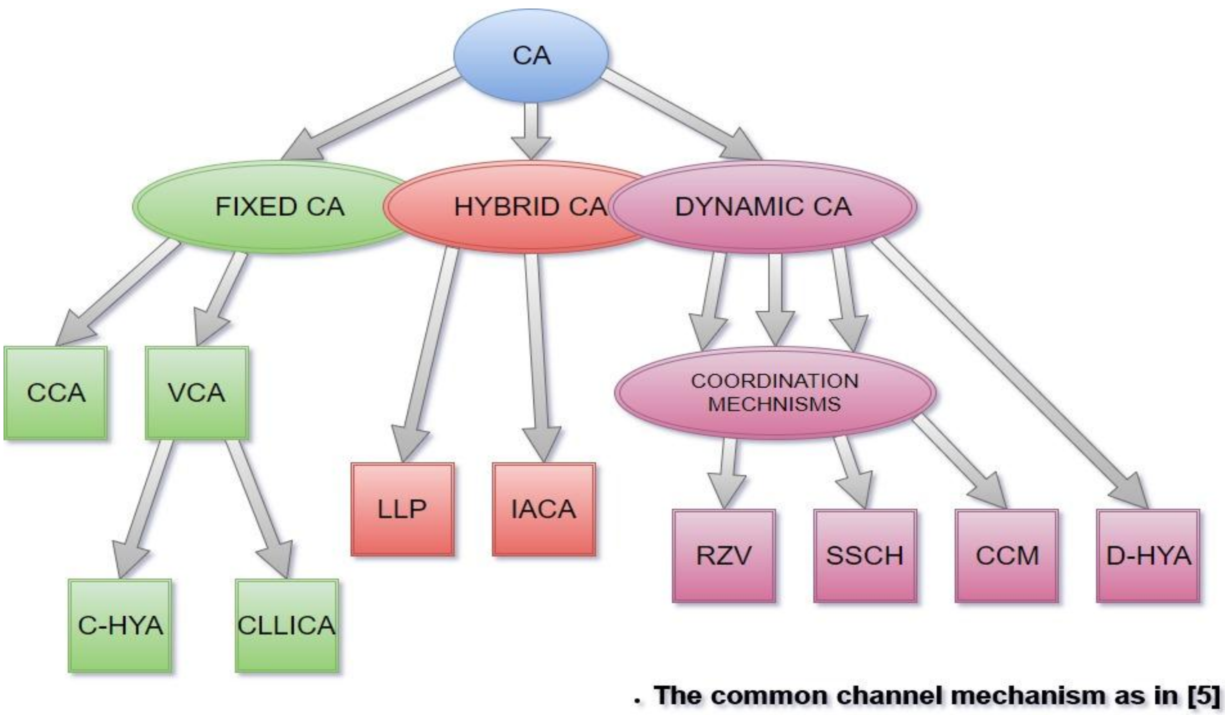


Figure 1.1: Taxonomy of channel assignment schemes in wireless mesh networks.

1.3 Thesis Objective

In this paper we worked on the design and implementation of an efficient channel assignment and architecture for wireless mesh network which has multichannel and multi-radio features. We consider multi-jump remote work systems, where every switch hub is outfitted with different radio interfaces furthermore; numerous channels are accessible for correspondence. We address the issue of relegating channels to correspondence interfaces in the system with the target of limiting generally arrange impedance. Since the quantity of radios on any hub can be not as much as the quantity of accessible channels, the channel task must comply with the imperative that the quantity of various channels relegated to the connections occurrence on any hub is at most the number of radio interfaces on that hub.

This paper also consists of the simulation setup and the performance evaluation of our proposed channel and its routing protocol. In this paper we evaluated our simulation in four different issues and got results for our routing protocol which is QMR-AODV. The evaluation parameters are Routing Overhead, Packet Delivery Ratio, Average Network Delay, and Average Response Time. In this paper we consider multi-channel, multi radios wireless mesh network, where each router is deployed with more than one interface. In wireless mesh network, it is necessary to assign proper channel to each interfaces, which minimize the total network interference. Similarly, a proper routing protocol ensures the right route to send a data from source to destination effectively. Our main objective is to provide a scheme to improve the overall performance of multi-channel multi radios wireless mesh network by improving the pocket delivery ratio, reducing network latency and the routing overhead.

Here, we proposed a joint Channel assignment and routing protocol to ensure low interference by assigning the non-overlapping channels to the multiple radios.

Chapter 2

Working principle of wireless mesh network system

2.1 Introduction

The Multiple-Radio capability, and their assignment to the multiple non-overlapping channels, makes Wireless Mesh Networks (WMNs) as one of the prime candidate to be deployed as the future wireless broadband access technology. The WMNs are characterized by the self-organizing, self-healing, dynamic and distributed architecture, where the backbone routers are relatively static. On the other hand, WMNs are facing the same inherited problems of capacity limitations and interference being in the category of multi-hop wireless networks. First, the multi-hop nature of its routers put an upper bound on the end-to-end data rate achievements. Secondly, the interference phenomenon needs to be seriously considered while developing any protocol for such types of networks. Support for providing the Quality of Service (QoS) to the recent broadband applications like Voice over IP (VoIP), Video Conferencing and Online Games is one of the essential requirements from the access technologies. These QoS in the form of delays and bandwidth must not be compromised and should be guaranteed for the smooth functioning of the network. If channel assignment is one of the deterministic parameter in improving the capacity of the network by minimizing the interference and providing communication parallelism among the multiple radios of the neighboring nodes, routing plays an equally important role by providing the guaranteed end-to-end path selection based on some required metric. Both these issues are interdependent and hence affect each other. In this chapter, a joint routing and channel assignment scheme for the WMNs has been developed, where the channel assignment scheme tries to minimize the interference of the network while ensuring the connectivity. Routing, on the other hand, provides an end-to -end guaranteed path based on the end users delay requirements. A MANET routing protocol, called Ad-hoc On Demand Distance Vector (AODV), has been extended to make it Multi-Radio Multi-Channel (MRMC) compatible and to provide an end-to-end path to the end users ensuring the maximum tolerable delays guarantees. The decision of end-to end route selection between a pair of source-destination nodes is taken based on the end users requirements and the capabilities match of each individual link with those requirements. Experimental results show that the proposed scheme achieves low network latency, high throughput and low routing overheads in the network [1, 2, and 3].

2.2 Wireless Mesh Networks-An overview

Wireless networks have been evolved with time to cope with the ever increasing end users demands in terms of data rate, scalability, reach-ability, mobility and ease of use. There cent advancements in wireless network access technologies have provided a platform of ubiquitous communication for multiple types of data including voice, multimedia and other web-based applications. However, the scale-ability and data rate of wireless networks are constrained due to the wireless nature of medium and the availability of finite spectrum. Wireless Mesh Networks (WMNs), a key technology in the wireless access, have emerged recently to provide on the go connectivity to the end users. WMNs are dynamic multi-hope networks having the capabilities of self-organization and self-configuration. Conceptually, WMNs have been evolved from Mobile Ad-hoc Networks (MANETs) and thus inherit the forwarding and self-configuration capabilities from them. WMNs consist of two main components i.e., Mesh Points (MPs) and Mesh Clients (MCs). While MPs are the wireless routers interconnected to one another in a multi-hop fashion to form what is called the mesh backbone, end users MCs typically consist of the client machines accessing internet through the mesh backbone with wired or wireless medium. Depending upon the location and functionalities of MPs in WMNs, they are further divided into three categories [1, 3, 4].

Those mesh routers which give connectivity to the end users are called Mesh Access Points (MAPs) and are usually located at the user premises. Those mesh routers inside the WMNs backbone which are responsible for forwarding the MCs data to/from the Internet are called Mesh Points (MPs). There are some backbone routers, called Gateways, which provide connectivity between WMNs backhaul and the Internet through wired medium. In the Figure 3-1, a WMN is shown, where some MCs are connected to the MAPs and the traffic is forwarded by the MPs to the Gateways. Gateways in turn play the role of an exit/entrance door for the data traffic from and to the Internet to/from the WMNs. WMNs are a promising technology to provide broadband wireless connectivity in the user premises due to their rich resources and fixed wireless routers, having stable power supplies. The multi-hop capability results in a scalable solution for otherwise limited ranged networks. These networks are highly resilient as failure of some nodes has no effect on the connectivity of end users and overall network at large [2, 3].

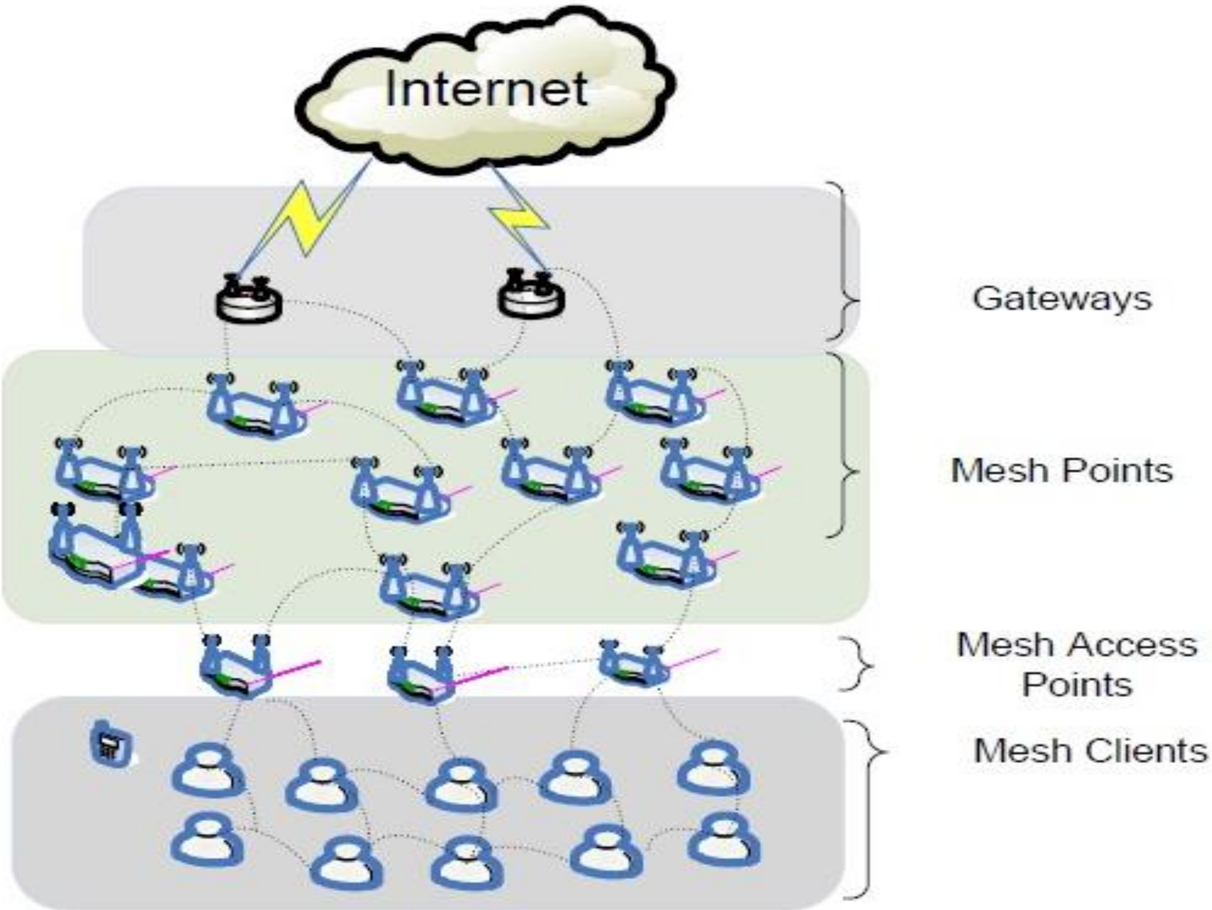


Figure 2.1: A wireless Mesh network system

2.3 Channel Assignment in wireless mesh networks

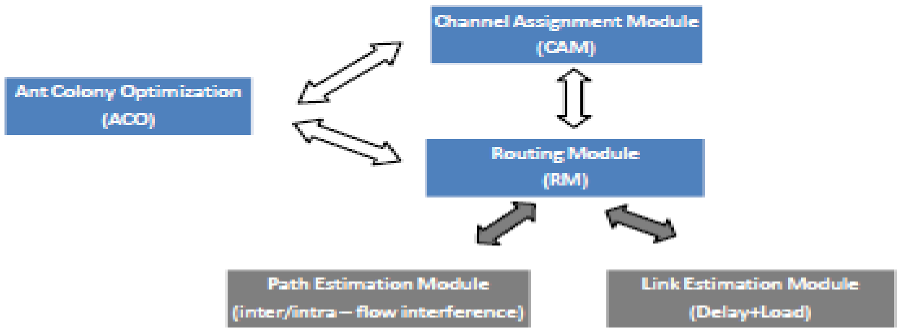
Routing and channel assignment in wireless mesh networks has been an active area of research for the last several years. Various approaches have been proposed for joint channel assignment and routing based on intelligent techniques such as multi-agent technology and genetic algorithms. There are several channel assignment ways.

- Joint Channel Assignment
- Fixed Channel Assignment
- Common Channel Assignment
- Dynamic Channel Assignment
- Varying Channel Assignment
- Centralized Channel Assignment
- A Distributed Channel Assignment

- Hybrid Channel Assignment
- MESTIC

2.3.1 Joint Channel Assignment

This is the design of an efficient channel assignment and routing architecture based on ACO framework for multi-radio WMNs. In order to fully exploit the characteristics of ACO framework and also to make it compatible for WMNs, we implement two custom designed modules namely routing module (RM) and channel assignment module (CAM) routing scheme. We explain the working of our architecture along with the two custom designed modules below [5, 6].



Flowchart 2.1: Joint Channel Assignment and Routing Algorithm.

A. Routing Module:

The routing module is based on a routing protocol called Ant-Mesh. It is specifically designed for multi radio WMNs. This routing module further extends the ACO framework by implementing two estimation modules a link and a path estimation module to effectively utilize the space/channel diversity typically common in multi radio mesh networks. The link estimation module measures the cost of a node's local links in terms of the packet delay taking into account the queuing delay of a node to realistically capture traffic load. The path estimation module is designed to meet the needs and characteristics of WMNs in order to reduce both inter and intra flow interference [4, 5, 6].

B. Channel Assignment Module:

At first, let's assume that the channel assignment is done a priori and the routing protocol does not take into consideration the underlying channel assignment scheme. However, in a multi-radio multi-channel WMN, routing and channel assignment are interdependent because an efficient channel assignment scheme can greatly reduce interference among close by transmissions which helps the routing protocol to distribute the traffic among the nodes as the interference is already determined by the channel assignment scheme. Therefore, we argue that the routing and channel assignment should be jointly optimized to improve the overall network performance in terms of reduced interference which results in efficient load balancing among the nodes in the network. Our proposed architecture is distributed in nature, hence, no centralized control is required to assign the channels and discover the paths, and therefore, no traffic flows information is required a-priori by our algorithm. The channel assignment module (CAM) is implemented by each node and is distributed in nature. A smart ant is generated periodically to find a shortest path from that node to a particular destination. The smart ant stochastically moves from one node to another unless it reaches the destination and upon then, it deterministically tracks back to the source node [7, 6, 9].

While on its way back, the ant packet updates the routing and channel assignment modules on each intermediate node and the source node. Smart ants in our proposed architecture iteratively build a solution to improve the overall network performance. The routing module selects the paths for the flow from source to destination, and thus assigns traffic to each radio and link, while channel assignment module determines the channel that a radio interface should use. Depending upon the load on a particular node and the link quality which is measured and maintained by the link estimation module of the routing module, the channel assignment module is initialized that would send an ant to the network to switch the interfaces/channels on the links along the path from the source to the destination. This will ensure that the channel assignment is dynamically adjusted according to the traffic patterns on each node determined by our routing module [10].

2.3.2 Fixed Channel Assignment

Fixed assignment assigns channels to interfaces either permanently or for long time intervals with respect to the interface switching time. These assignments of channels can be further subdivided into common channel assignment and varying channel assignment.

A. Common Channel Assignment

This is the simplest scheme. In the radio interfaces of each node are all assigned the same set of channels. The main benefit is that the connectivity of the network is the same as that of a single channel approach, while the use of multiple channels increases network throughput. However, the gain may be limited in scenarios where the number of non over lapping channels is much greater than the number of network interface cards (NICs) used per node. Thus, although this scheme presents a simple CA strategy, it fails to account for the various factors affecting channel assignment in a WMN [10, 11].

B. Varying Channel Assignment

In the VCA scheme, interfaces of different nodes may be assigned different sets of channels. However, the assignment of channels may lead to network partitions and topology changes that may increase the length of routes between the mesh nodes. Therefore, in this scheme, assignment needs to be carried out carefully [11, 12].

2.3.3 Dynamic Channel Assignment

Dynamic assignment strategies allow any interface to be assigned any channel, and interfaces can frequently switch from one channel to another. Therefore, when nodes need to communicate with each other, a coordination mechanism has to ensure they are on a common channel. Each node switches channels synchronously in a pseudo- random sequence so that all neighbors meet periodically in the same channel. The benefit of dynamic assignment is the ability to switch an interface to any channel, thereby offering the potential to use many channels with few interfaces. However, the key challenges involve channel switching delays (typically on the order of milliseconds in commodity 802.11 wireless cards), and the need for coordination mechanisms for channel switching between nodes [12, 13].

2.3.4 Centralized Channel Assignment

Based on multichannel wireless mesh network architecture, a centralized channel assignment algorithm for WMNs is, where traffic is mainly directed toward gateway nodes Assuming the traffic load is known, this algorithm assigns channels, thus ensuring the network connectivity and bandwidth limitations of each link. It first estimates the total expected load on each virtual link based on the load imposed by each traffic flow. Then the channel assignment algorithm visits each virtual link in decreasing order of expected traffic loads and greedily assigns it a channel. The algorithm starts with an initial estimation of the expected traffic load and iterates over both channel assignment and routing until the bandwidth allocated to each virtual link matches its expected load. While this scheme presents a method for channel allocation that incorporates connectivity and traffic patterns, the assignment of channels on links may cause a ripple effect whereby already assigned links have to be revisited, thus increasing the time complexity of the scheme [14].

2.3.5 A Distributed Channel Assignment

Is a set of dynamic and distributed channel assignment algorithms, which can react to traffic load changes in order to improve the aggregate throughput and achieve load balancing. Based on the Hyacinth architecture, the algorithm builds on a spanning tree network topology in such a way that each gateway node (the node directly connected to the wired network) is the root of a spanning tree, and every mesh node belongs to one of these trees. The channel assignment problem consists of: Neighbor-to-interface binding: Where the dependence among the nodes is eliminated in order to prevent ripple effects in the network. Interface-to-channel binding: Where the goal is to balance the load among the nodes and relieve interference finally, channels are dynamically assigned to the interfaces based on their traffic information. The tree-topology constraint of the scheme poses a potential hindrance in leveraging multipath routing in mesh networks [14].

The channel assignment problem consists of:

- Neighbor-to-interface binding (i.e. it selects the interface to communicate with every neighbor), where the dependence among the nodes is eliminated in order to prevent ripple effects in the network.

- Interface-to-channel binding (i.e. it selects the channel to assign to every interface), where the goal is to balance the load among the nodes and relieve interference

Finally, channels are dynamically assigned to the interfaces based on their traffic information. The tree-topology constraint of the scheme poses a potential hindrance in leveraging multipath routing in mesh networks.

2.3.6 Hybrid Channel Assignment

Hybrid channel assignment strategies combine both static and dynamic assignment properties by applying a fixed assignment for some interfaces and a dynamic assignment for other interfaces. Hybrid strategies can be further classified based on whether the fixed interfaces use a common channel or varying channel approach. The fixed interfaces can be assigned a dedicated control channel or a data and control channel. While the other interfaces can be switched dynamically among channels, hybrid assignment strategies are attractive because, as with fixed assignment. They allow for simple coordination algorithms, while still retaining the flexibility of dynamic channel assignment. In the next two subsections we describe two hybrid schemes for CA [14, 15].

A. Link Layer Protocols for Interface Assignment

In an innovative link layer interface assignment algorithm (LLP) is proposed that categorizes available interfaces into fixed and switchable interfaces. Fixed interfaces are assigned, for long time intervals, specific fixed channels, which can be different for different nodes. On the other hand, switchable interfaces can be switched over short timescales among non-fixed channels based on the amount of data traffic. By distributing fixed interfaces of different nodes on different channels, all channels can be used, while the switchable interface can be used to maintain connectivity. Two coordination protocols based on hash functions and the exchange of Hello packets are proposed in to decide which channels should be assigned to the fixed interface and manage communication between nodes. In the authors propose a CA scheme based on the second coordination protocol, but this scheme does not take into account the traffic load in assigning the fixed channels [15].

B. Interference-Aware Channel Assignment

The channel assignment problem in wireless mesh networks in the presence of interference from collocated wireless networks is addressed in. The authors propose a dynamic centralized interference-aware algorithm (IACA) aimed at improving the capacity of the WMN backbone and minimizing interference. This algorithm is based on an extension to the conflict graph concept described in, called the multi-radio conflict graph (MCG), where the vertices in the MCG represent edges between mesh radios instead of edges between mesh routers. To compensate for the drawbacks of a dynamic network topology, the proposed solution assigns one radio on each node to operate on a default common channel throughout the network. This strategy ensures a common network connectivity graph, provides alternate fallback routes, and avoids flow disruption by traffic redirection over a default channel. This scheme computes interference and bandwidth estimates based on the number of interfering radios, where an interfering radio is a simultaneously operating radio that is visible to a mesh [15].

2.3.7MesTIC (Recently Channel Assignment Scheme)

The central goal of channel assignment for multi radio mesh networks is to improve the aggregate throughput of the network, taking into account the effects of traffic and interference patterns, as well as maintaining topological connectivity. Based on our observations of the impact of traffic patterns and network connectivity on the performance of a WMN, below we propose an innovative scheme called MesTiC, which stands for mesh-based traffic and interference aware channel assignment. It has the following important features:

- MesTiC is a fixed, rank-based, polynomial time greedy algorithm for centralized channel assignment, which visits every node once, thereby mitigating any ripple effect.
- The rank of each node is computed on the basis of its link traffic characteristics, topological properties, and number of NICs on a node.
- Topological connectivity is ensured by a common default channel deployed on a separate radio on each node, which can also be used for network management.

Fixed schemes alleviate the need for channel switching, especially when switching delays are large as is the case with the current 802.11 hardware. In addition, MesTiC is rank-based, which gives the nodes that are expected to carry heavy loads more flexibility in assigning channels. Finally, the use of a common default channel prevents flow disruption. It should also be mentioned that the proposed scheme has been designed for a mesh network with a single gateway node, but could easily be extended to multiple gateways with minor modifications to the basic scheme [18].

2.4 Comparison:

The table below is a comparison between WLAN, MANET and Wireless Mesh Networking System in various prospects of networking [2, 4].

	WLAN	MANETs	WMNs
Topology	Static	Dynamic	Relatively static
Mobility of routers	Static	Medium to high mobility	Relatively static
Scale	Office or Home	medium area	Large area/Towns
Infrastructure requirements	Yes	No	Yes
Stable power Supply	Yes	No	Yes
Multi-Radio Multi-Channel capability	Normally no	No	Yes
Relaying capability	No	Yes	Yes

Table 2.1: WLAN, MANETs and WMNs comparison.

2.5 Channel Assignment in Wireless Mesh Networks

In typical WLANs and MANETs, based on the IEEE 802.11 a/b/g/n standards, all nodes are equipped with a single radio where nodes compete for a single channel across the whole network or collision domain. Keeping in view the higher user demand in a wireless broadband setup and the multi-hop nature of WMNs, a single radio solution is not feasible for implementation [2, 12, 14].

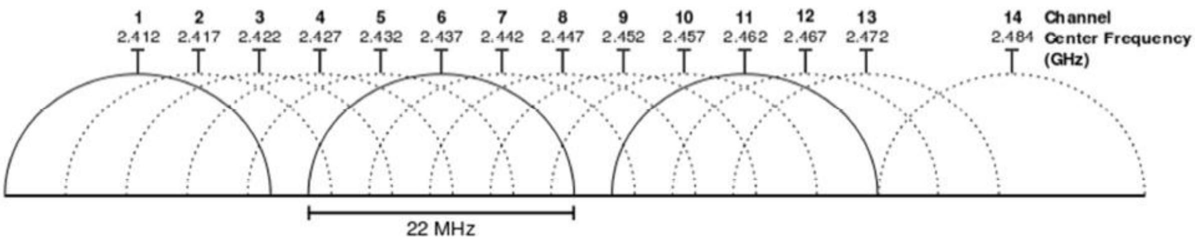


Figure 2.2: Non-overlapping channels in IEEE 802.11 b/g.

A channel is a band of frequency which can be used by a transmitter and receiver when both simultaneously tune their radios to it. The IEEE 802.11a and IEEE 802.11 b/g standards define 12 and 3 non-overlapping channels in the Industrial Scientific and Medical (ISM) band, respectively. These non overlapping channels can be used inside a single collision domain without causing any interference. As shown in the Figure 2-3, a total of 23 channels are available in the 4GHz spectrum for IEEE 802.11b/g out of which only 3 are non-overlapping. Wireless mesh routers can be equipped with multiple radios due to their static nature and the existence of permanent power supplies. Since multiple channels are available in the free ISM 2.4 and 5 GHz bands, multiple radios can be tuned simultaneously to exploit the free non-overlapping channels and hence increase the overall capacity, connectivity and resilience of the wireless mesh backhaul. Due to these characteristics, WMNs is a prime candidate to be implemented as a broadband wireless access network in the user premises. Multi-Radio Multi-Channel (MRMC) capabilities in Wireless Mesh Networks can enormously increase backhaul connectivity, network throughput and fault tolerance as simultaneous transmissions can be achieved through multiple radios tuned to non-overlapping channels with minimum degree of interference. To illustrate the effectiveness of MRMC phenomenon in WMNS, consider the example given in the Figure 2-4. In figure 2-4(a) shows six nodes residing in the same collision (interference) domain and communicating with each other in a set of three sessions. Each node is equipped with a single radio and it is assumed that a single channel is available to all pair of nodes for communication. Two nodes can communicate only if they are in each other's transmission ranges and their radios have been assigned the same channel. As can be seen, communication between nodes (A – B, C – D, E–F) is established by tuning their respective radios to channel C1 in times t1, t2, t3respectively. This is an example of Single-Radio, Single-Channel (SRSC) and is widely applied to 802.11 based MANETs and WLANs. In the Figure 3-4(b), each node is equipped with a single radio, parallel communication session is achieved by tuning each set of radios to multiple orthogonal channels (C1, C2, C3) at time t1 [8, 9].

In this example of Single-Radio, Multiple-Channel (SRMC), theoretical throughput increases by 3 times effectively as compared to SRSC. If each node is equipped with multiple radios, the system throughput and connectivity can be further increased by intelligently tuning their radios to the multiple available channels as shown in the Figure 2-4(c), where nodes D and F are equipped with two interfaces. Given the set of non-overlapping channels C= {C1, C2… C|C|}, tuning the multiple radios of mesh routers to these non-overlapping channels across multiple collision domains is called Multi-Radio, Multi-Channel (MRMC) assignment. There are two approaches for channel assignment, static and dynamic. In static channel assignment schemes, channels are assigned once and forever to the interfaces/radios of the nodes. This type of assignment is simple but it has the cost of non conforming with the dynamics of the network. In a dynamic channel assignment, the channel assignment changes with the change in network dynamics or the user's requirements. This channel assignment has the cost in the form of overhead it generates for managing the channel assignment/re-assignment based on the traffic demands or network conditions [15, 16].

The third type of channel assignment problem studied in the literature is hybrid channel assignment, where some of the interfaces are assigned permanent channels based on their traffic characteristics while other nodes channel assignment is done in a dynamic fashion. This approach reaps the advantages of both static channel assignment and dynamic channel assignment schemes. Channel assignment can also be categorized as centralized and distributed. In centralized approaches, a central node runs the channel assignment algorithm and other nodes are only informed of the resultant channel assignment matrix as to which channel should be used between which pair of nodes in the entire network. While in distributed channel assignment schemes, the channel assignment is performed by all the nodes independently with coordination with other nodes. Centralized channel assignment schemes have the advantages of being simple at the cost of single point of failure. Further, full knowledge of the entire network topology is needed. Distributed channel assignment has the advantages of being efficient but costs more control traffic to the network [15, 16].

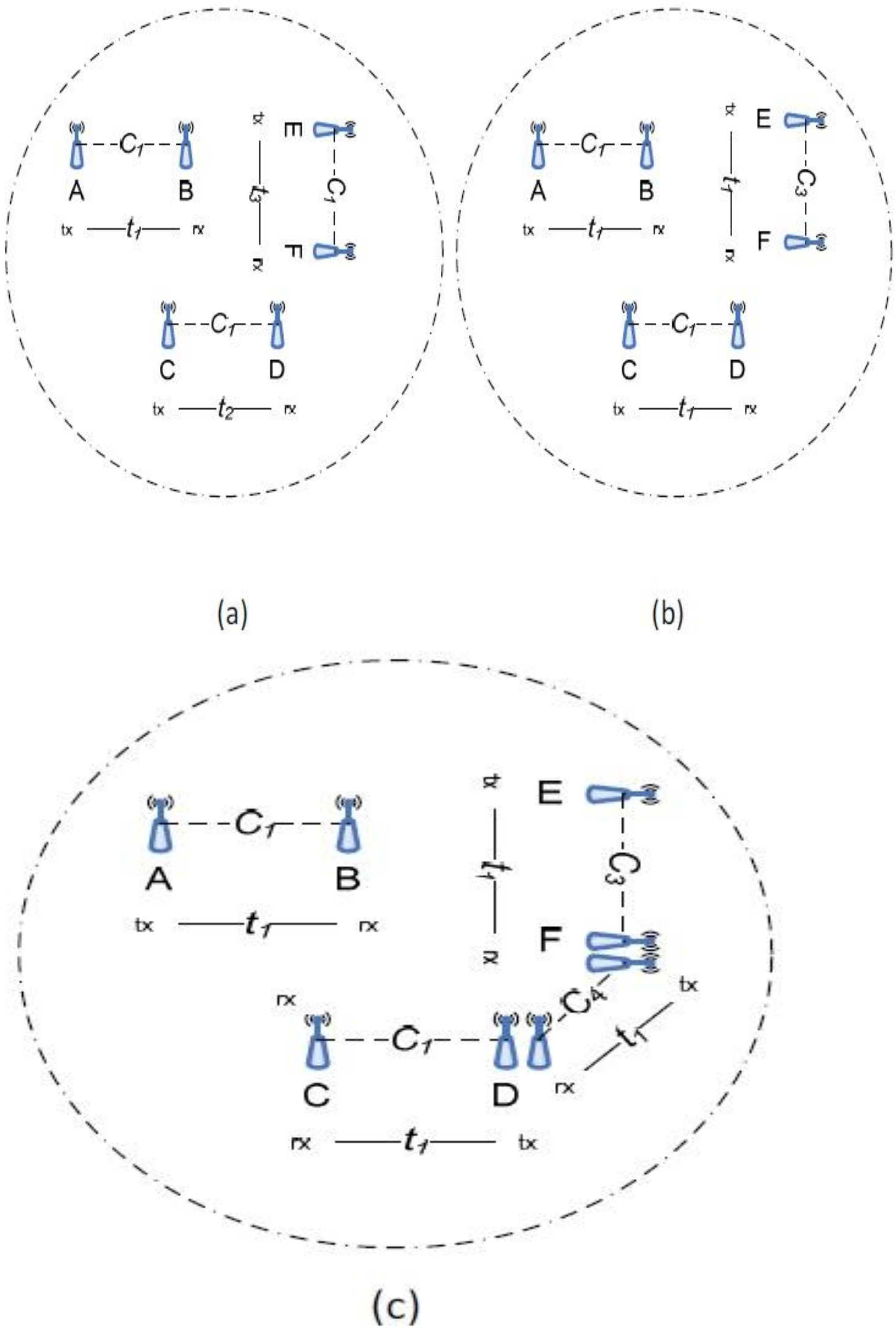


Figure 2.3: (a) SRSC, (b) SRMC, (c) MRMC

2.6 Routing in Wireless Mesh Networks

While channel assignment is one of the fundamental issues of MRMC-WMNs, routing, too, has its impact on the network performance. On one hand, channel assignment scheme in WMNs assigns channels to the node's radios/links, while on the other hand; routing determines the end-to-end path from source to destination and transverses these individual channels assigned to the end-to-end path links. Although routing is fundamentally the Network layer functionality while channel assignment is performed at the Medium Access Control (MAC) layer, both these issues are interdependent. A channel assignment can be affected by the routing due to the ups and downs in the load on specific channels assigned to links, similarly two different channel assignments in the same network can result in different end-to-end paths for the same routing protocol. This interdependency between the two has motivated the research community to solve this problem jointly. Combining routing and channel assignment needs more cross layer information exchange between the two mentioned layers in the case of MRMC WMNs. Broadly; routing protocols can be categorized into two classes, i.e. proactive or table driven and reactive or on-demand [18].

The main difference between these two classes' of protocols is how the routing information is maintained by the individual nodes. Routing determines the end-to-end path from a source node to a destination node. In the case of proactive routing protocols, each node maintains routing tables and periodically updates them. These routing tables on each node contain fresh routes to all other nodes in the network. Thus each node knows the path to all other nodes in the network. The advantage is fast response time at the expense of high routing overhead. In MANETs, Optimized Link State Routing (OLSR) and Destination Sequenced Distance Vector (DSDV) belong to this class of routing protocols. In the case of reactive routing protocols, each node needs not to maintain the routing information. These protocols are called on-demand as the routing path is determined from source to the destination prior to data session, whenever they are needed. AODV and Dynamic Source Routing (DSR) belong to this class of routing protocols [18].

2.7 System Model

An infrastructure based hierarchical WMN is considered where the Mesh Clients, consisting of end users, access the Internet via Mesh Backbone as shown in the Figure 3-1, Section 3.2. There is always some data at the Mesh Clients or at the server connected to the gateways, which have some QoS demands in terms of end-to-end network delays. The application scenarios of WMNs are always in the form of data travelling to or from the Mesh Clients towards the gateways. This means that the QoS provided on an end-to-end path must be bi-directional. For instance, consider the example given in the Figure 3-5, where node A wants to send some data to node B on path Pa-b. Let αa-b be the maximum delay node A's data can tolerate, on-end-to end path Pa-b, where the total path delay is the cumulative delays of individual links. If αa-b>=9 units, the path is feasible for the said application. However, delays on bi-directional links are not the same from both sides. For example, it is possible that node. A data experience one type of delay while sending it to node c; on the opposite c might experience different delay when sending some data to node A on the same link. Generally, for a path Pa-b in the multi-hop network, the end-to-end delay is given by:

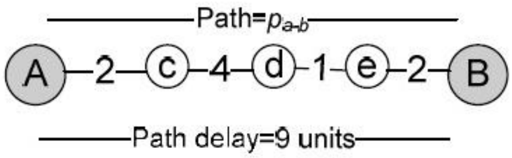


Figure 2.4: End-to-end delay example

Generally, for a path $P_{a\text{-}b}$ in the multi-hop network, the end-to-end delay is given by:

Path_Delay= $\sum_{i=1}^{|l|} l^i_{delay}$......................(2.1)

Where l^i_{delay} is the delay associated with the i^{th} link across the path.

Let S={S1,S2,S3,….., S|S|} be the set of source nodes requesting for some delay sensitive data like a request from the network to find a route to a video conferencing application or a VoIP server. Let D= {D1, D2, D3… D|D|} be the set of destination nodes in the network. In the case of WMNs the (Si, Di) is always the (end user nodes, gateways) or(gateways, end user nodes). Let's each (Si, Di) have some data to send across the WMN backbone through a path PS-D with the some delay constraint. Since WMNs consist of multi hop routers spreading across multiple collision domains and each router is equipped with multiple radios deployed to multiple channels; therefore, there are multiple routes possible for this data to transport from the source to the destination. The routing function is to select such a route across these multiple collision domains so that the delay constraint imposed by the (source, destination) is satisfied.

A channel assignment scheme based on minimum interference is proposed to achieve the above objective. Secondly, a reactive routing protocol is extended for MRMCWMNs which achieves the minimum requirements set by the end users applications. Both routing and channel assignment are inter-dependent as channel assignment scheme affects the routing decisions on each node; and the load due to the already established connections by the routing decisions triggers the channel re-assignment.

2.8 QoS based Channel Assignment and Routing

We consider an 802.11 based WMNs, where each mesh router is equipped with K multiple radios/IEEE 802.11 compatible network interfaces. The topology of the network is considered relatively static and only a few routers are able to move in the whole network. Multiple orthogonal channels, C, (12 or 3) are available to each node as according to the IEEE 8021.11 a/b/g standards. All the routers, afterwards called nodes, have equal transmission capabilities. This means that all the radios of the nodes belong to the same technology i.e. either IEEE 802.11a or IEEE 802.11 b/g. Similarly all the radios have the same transmission and interference ranges as defined in these standards. A node can assign only one radio to a specific channel. This is necessary because assigning the same channel to two different radios of a specific node causes co-channel interference. The aim of the channel assignment scheme is to assign channels from the channel set C to each link connecting two radios of a pair of nodes in the mesh backbone such that the interference is minimized.

2.9 Channel Assignment

We follow the protocol model for developing the proposed channel assignmentand routing scheme. The channel assignment model consists of the following sub-modules,where the interference is minimized using a similar concept as in.

- Initialization and channel assignment
- Channel/link Assessment and Neighbors Monitoring
- Channel Re-Assignment

2.9.1 Initialization and Channel Assignment

This module assigns multiple non-overlapping channels from the set C to the multiple radios set K of the nodes. The aim of channel assignment is to produce a network topology inside the WMNs backbone so that each link gets a channel causing minimum interference and the backbone is highly connected. In this work, it is assumed for simulation purposes that the channel assignment process is initiated at the gateways. Our assumption is based on one of the basic characteristic of WMNs data traffic which travels from MAPs all the way towards the gateways. This assumption is made in all gateways oriented channel assignment protocols. However, the algorithm is flexible enough that the starting point can be any mesh router in the mesh backbone. It is assumed that there is no prior channel assignment inside the backbone and all the radios of all nodes listen to arbitrary channels for broadcast messages. Broadcast messages are special type of messages as defined in IEEE 802.11 standard, where the destination address is set to all 1's.Any nodes N in the WMNs backbone can initiate the channel assignment process by sending a special channel assignment request in the form of CHReq frame. The first field of this frame is set to broadcast address so that all the neighboring nodes listen to it. The second field is the MAC address of source node which initiated the CHReq frame. The third field is the request Type which shows the type of the frame used in the proposed channel assignment protocol. Six types of frames are used in the proposed model. CHReq, CHReply, CHUsage, CHUsageReply, CHAck and Hello each are having its own code in the Channel Type field, as shown in the Figure 2-6. The fourth field of CHReq is 4 bits long showing the number of channels available to the system.

Four bits are sufficient to cover all the non-overlapping channels in the IEEE 802.11 standards. However, the fourth field of the CHUsageReply packet consists of 26bits, where each two bit is used to show the usage of a channel by the replying node. Upon listening the CHReq broadcast, all the neighboring nodes reply with a CHReply frame in a unicast manner, setting those channel fields where this node has assigned its radios before, with the value of 1, if no prior channel is assigned by the replying node; this field is set to zero accordingly. CHReply frame has exactly the same fields as that of CHReq but with the last field having 26 bits as shown in the Figure 3-6. Each 2 consecutive bits in the last filed of CHReq represents the number of channels the replying node maintains in its Neighboring Channel Usage (NCU) table. Upon receiving the CHReply frame, the initiating node N assigns channels to its radios according to the following rules.

1. Assign among those channels which are not already been assigned to one of the initiating node own radios. This is necessary to avoid the co-channel interference on the initiating node.
2. Assign a channel to each interface while applying rule 1 in neighbors prospective. This will ensure to avoid the co-channel interference on the neighboring nodes. For this, initiating node looks at the channels already been assigned by the sending nodes to their interfaces.
3. Initiating node N assigns those channels to the interfaces which cause least interference to it by looking at the Neighbor's Channel Usage (NCU) list.
4. If all channels under consideration cause same level of interference to initiating node N, send a unicast message to each neighboring node requesting for their NCU lists. Assign channels to each specific interface, causing least interference to the specific neighboring node.
5. If neighboring nodes NCUs have a tie, assign channels to each interface arbitrarily keeping rules 1 and 2 in view.

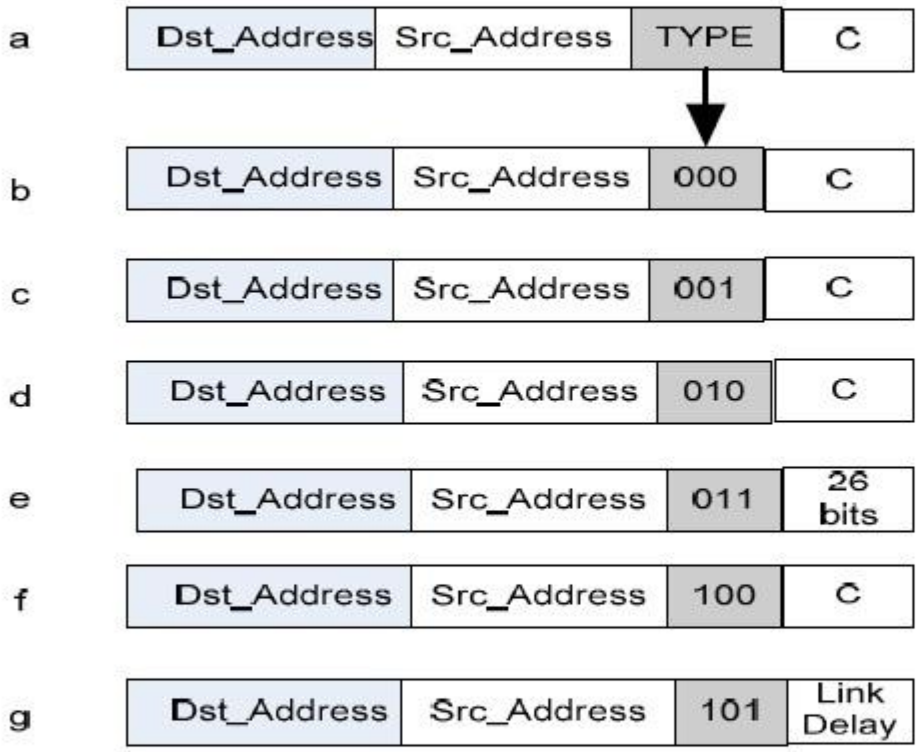


Figure 2.5: (a) Generic MRMC frame type (b) CH_{Rer}(c) CH_{Reply}(d) CH_{Usage} (e) $CH_{UserReply}$(f) CH_{Ack} (g) Hello

An example channel assignment is shown in the Figure 2-7. Five non-overlapping channels are available to the system and node ‘a’ initiates the channel assignment process by broadcasting the CHReq frame to all of it neighbor’s nodes 1, 2, 3 and 4, as shown in the Figure 2-7(a). When these nodes receive the CHReq frame, each unicast the CHReply frame to the initiating node, on the channel on which it has received the CHReq broadcast.

In the Figure 2-7(c), node ‘a’ assigns channels to its neighbors according to rules 1-5. Those nodes upon channel assignment to at least one of their interfaces, repeat the process for their neighbors, as shown in the Figure 2-7(d).

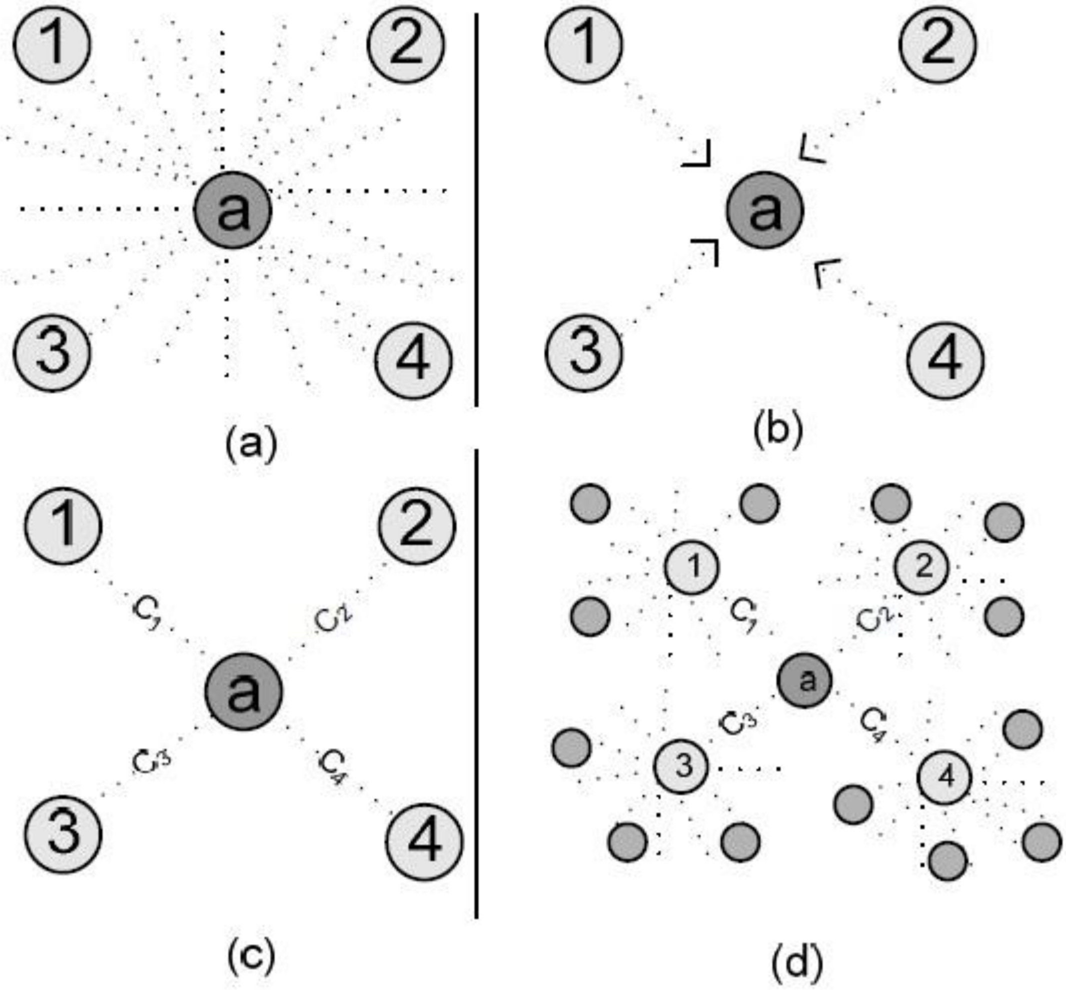


Figure 2.6: An example of Channel assignment

Chapter 3

Construction, Algorithm, Simulations and Graphs

3.1 Channel Assessment and Neighbors Monitoring

When each node assigns channels to all of its radios/interfaces, they switch to the monitoring state. Monitoring state is the state in which each node frequently monitors the channel usage status of all its interfaces. Each node also monitors the status of all its neighbors, whether they are alive or not, through the exchange of Hello messages. The Hello messages, are also used to update the link delay by the nodes they are connected through. This is necessary because the link delay on a bi-directional link is different from both nodes prospective. A greater delay in the Hello message replaces the smaller one on both nodes. Monitoring the link status is needed to calculate the metric for the QoS based routing later on, as discussed in the Section 3.2, where the decision of selecting an end-to-end path is made based on the individual links quality in the path.

Each node, in the monitoring state, maintains and frequently updates a table called the Channel State Table. This table, as shown in the Table 3-1, contains information about the quality of the individual bi-directional links between each pair of nodes sharing a common channel, and has four parameters i.e., Average Queue Length, Average MAC layer back-offs, Transmission rate and Average Lost packets retransmission time. Average Queue Length is the average taken over specific period of time of the MAC layer's queue associated with the interface of a node. This parameter indicates how much a single application layer packet has to wait in the queue of the interface. Average MAC layer back-off is the average value taken over specific times for the number of successful transmitted packet. Transmission time/rate is the number of bits a node's interface can transmit over a medium in per unit time. This value depends on the physical layer modulation techniques and the width of frequency called bandwidth. The Lost packet retransmission is the time it takes for retransmission of lost packets in a given number of packets transmitted over a link.

The QoS parameter for the proposed routing protocol is defined in terms of links delays expected to be experienced by a single application packet, when it is routed over the end-to-end path consisting of individual bi-directional links. The delay sensitive applications like video or audio should have end-to-end delay guarantees from the network. The information provided by the channel monitoring module is available to the network layer as shown in the Figure 3-1. Delay of an end-to-end path in an 802.11 based WMNs depends on many parameters. Since IEEE 802.11 is a shared wireless medium and even in MRMC there is always a chance that a given channel C, assigned to a link connecting two radios, is also assigned to another link in the same transmission or interference ranges. This makes each radio to follow the access mechanism for the wireless medium called Distributed.

If all the channels are of the same rank, it means that all cause the same level of interference to the initiating node N and therefore it sends a CHUsage frame to each neighbor and requests their NCUs. All neighboring nodes reply with a CHUsageReply frame containing theirs NCUs ranks for each channel. The channels are assigned to each interface according to the ranks of each channel in the neighboring node's NCUs. This last step reduces the chances of interference for the neighbor nodes. Once the initiating node N assigns channels to all of its interfaces, it sends the last frame called CHAck to all its neighbors which contain the channel usage of the current node N. All the neighboring nodes update their NCUs for the initiating node N, accordingly. All the neighbors of the initiating node N further repeat the above procedure to assign channels to their remaining interfaces in stages. This process continues till all the nodes in the network have assigned channels to all of their interfaces. The proposed algorithm can be initiated by any node of the WMNs network and multiple nodes can start the same process simultaneously. Once a node N has assigned channels to all its interfaces, it does not listen to further broadcast CHReq frames. The channel re-assignment is triggered in two cases. First, if a neighboring node fails and second, if the set routing threshold is not met by all the interfaces of a specific node. This will be explained further in the Section 3.2.1.

MAC address	$Q_{av_{length}}(bits)$	$\delta_{av}(seconds)$	$Tx_{rate}(\frac{bits}{s})$	α_{av} $(Seconds)$
Inf_0	X	Y	Z	a
Inf_1	X	Y	Z	b
--	--	--	--	c
Inf_n	X	Y	Z	e

Table 3.1: Links Quality State Table on each node

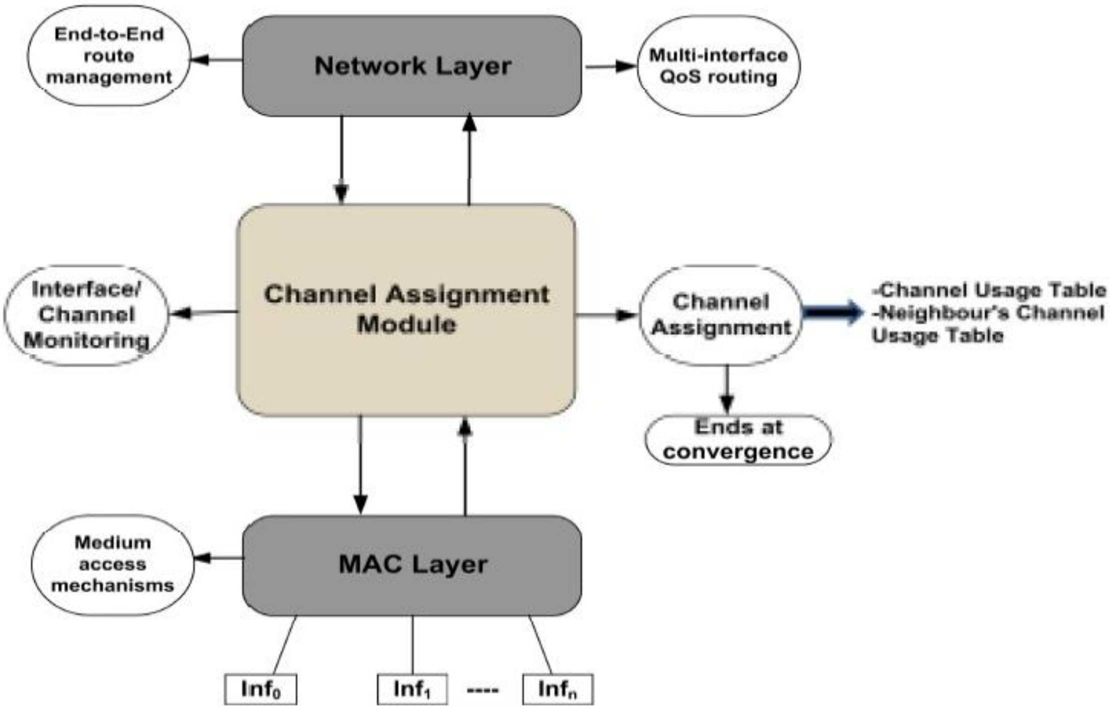


Figure 3.1: Cross layer information for link monitoring and routing decisions

The back-off time in DCF system, in which a transmitting system goes into the idle state, increases exponentially with each lost frames. Even with DCF arbitration for the shared medium, there is always a chance of losing packets on the wireless medium. This parameter is captured in terms of packet loss ratio and is accurately calculated. The lost packet ratio is the number of lost packets x in a given number of transmitted packets y. In IEEE 802.11, those packets are considered lost for which the transmitting MAC does not receive an acknowledgement. Let's a node sends y number of packets on one of its interface, say inf0, in which x packets are lost, the expected retransmission time for one lost packet is calculated as: This delay information is captured in the parameter Equation 2.1and is averaged over time. Similarly, there is a limit on the medium and radio capability to transmit at some bounded rates. Each node calculates this average transmission rate (TUVGWX) for each of its link associated with each of its radio and shows the number of bits transmitted over a link per unit time. Transmission rate value is calculated from the link queue. This whole information is fed to the total delay which is supposed to be experienced by a single packet to be considered for forwarding through a specific interface's link.

$\alpha_{av}= (\frac{x/y}{T_{x\,rate}})$…… (3.1)

$T_{delay}= (\delta_{av}+\zeta_{app} \times T_{per-bit}+\alpha_{av})$…… (3.2)

Where, $T_{per-bit}$ is calculated as follows, $T_{per-bit} = \frac{Q_{av-length}}{T_{x\,rate}}$ …..(3.3)

$\zeta_{app}$is the MAC layer frame size in bits and the variable δ_{av} in the equation (3.2) represents the average back off on the specified interface, where the expected δ_{av} for a single packet is calculated as follows. Let, the backoff incurred over a link during M successful transmitted frames be N, then the expected back off for one packet δ_{av} is calculated as-

$$\delta_{av}=\frac{M}{N} \text{ seconds}$$

The total delay calculation for a single packet is maintained in a separate table associated with each interface of a node. As shown in the figure (3.2), node B is connected to node A through interface 0 (info). Where, channel C_2 is assigned to their shared link. Similarly, it is connected to node C through interface1 (info1) with C1 assigned to their common link. The figure (3.2) also shows the delays calculations for each individual links. This delay information is updated in a bi directional manner through the periodic 'Hello' message exchange. If delay X milliseconds maintained by node B-C link is less than the delay it received from node C for the same link in the periodic Hello message, X will be replaced with the new delay for the same link. All nodes update this delay information for the Bi-directional links in similar way.

Each node keeps the record of channel usage in two separate tables. The first one is of its own interfaces and the channels assigned to each. This table, called the Channel Usage Table, contains the information of each interface of the current node N, channels assigned to each interface and the MAC addresses of other neighboring nodes to which this current node N is connected through these specific interfaces. Table 3-2 shows the Channel Usage Table for a node N where the first column in the table shows the interfaces/radios {inf1, inf2… infn} of the node N. The second column of the Table 3-2 shows the MAC addresses of the neighboring nodes to which it is connected through its interface (infi) in the corresponding previous column. The next column shows which channel is used by the node N for its connection to the corresponding neighboring node.

The second table is called Neighboring Channel Usage (NCU) table. As shown in the Table 3-3, the table shows node N's NCU for all its neighbors and their channels they have assigned to their interfaces. First column shows the node number/MAC address and the corresponding columns show the channel usage of each neighboring node on each channel. The rank of a channel is calculated by the node N as the number of interfaces assigned to C by all its neighbors, accordingly. Information required for rule 1 is available to node N from its own Channel Usage Table. For rule 2, the initiating node gets the information from the NCU to avoid the co-channel interference on the neighboring nodes. The information in NCU is also used to calculate the rank of each channel usage by node N in its neighborhood and it selects a channel according to rule 3 causing least interference to node N.

Node MAC	Neighbors /MAC	Ch_1	Ch_2	Ch_3	... ...	Ch_n
Inf_1	1	1	0	0	.... .	0
Inf_2	2	0	1	0	.... .	0
...	...	...	....	....	...	...
inf_n	x	0	0	0	....	1

Table 3.2: An example channel using table.

Node/MAC	Ch_1	Ch_2	Ch_3	......	Ch_n
1	1	1	0	.....	0
2	0	1	1	.....	0
...	...	....	....	...	...
x	1	0	0	....	1
Channel Rank	2	2	1	...	1

Table 3.3: An example Neighboring Channel Usage (NCU) table at node N for all its neighbors {1, 2, 3…, x}.

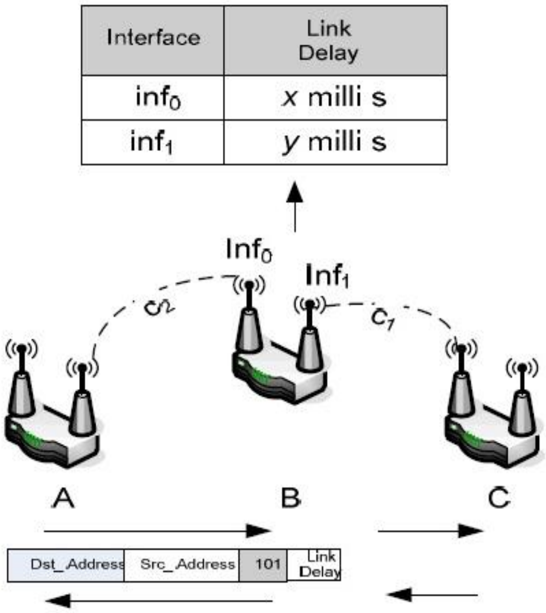


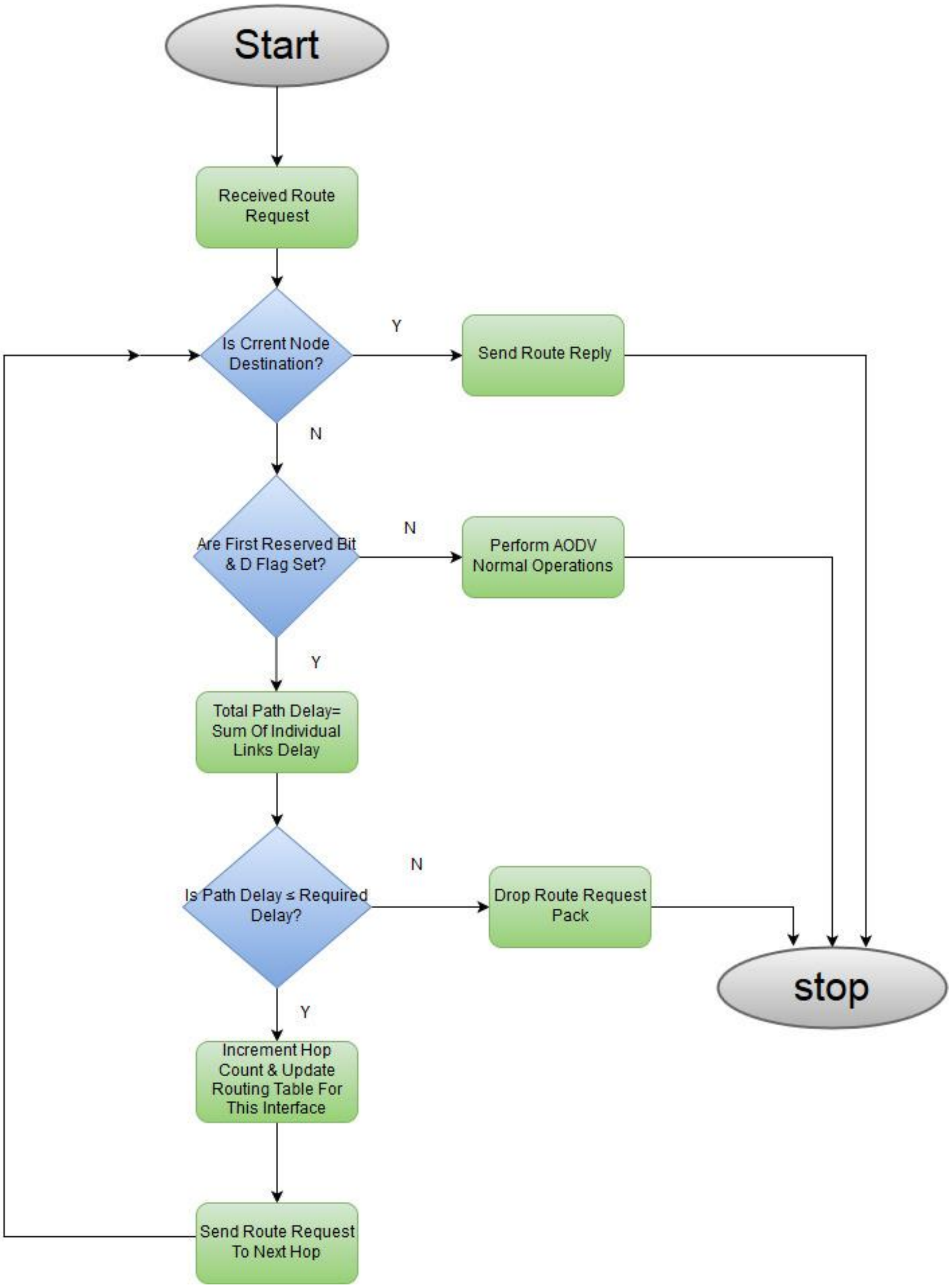
Figure 3.2: "Hello" Message exchange for delay updates and neighbor's monitoring.

3.2 QoS Based Routing

Quality of Service (QoS) is the provisioning of some guarantees by the network to the end users in terms of a set of performance parameters like delay, jitter, and bandwidth and packet loss. Since routing determines the end-to-end path for each source-destination pair in a network, therefore, it is one of the important design factors to be considered in providing these QoS guarantees to the end users. In MANETs, all the standard routing protocols have explicitly ignored this important issue. Since, MANETs are emergency networks and extremely mobile, QoS provision is very difficult task to be achieved on an end-to- end basis. The main factor in deciding the QoS is the routing metric, i.e., the parameter or set of parameters based on which the routing decisions take place. Almost all MANETs routing protocols use minimum hop count as the only metric and the shortest path is considered as the best path. While minimum hop count is a best metric in networks where reach-ability is the only concern, the end users of WMNs put some constraints other than mere reaching to the destination. QoS of the end users is considered as a prime parameter in the proposed joint routing and channel assignment scheme. The MANETs AODV protocol has been used as a base for developing the routing protocol in the proposed solution.

However, AODV has the some shortcomings when used in its original form in the WMNs. First, it is based on network level flooding to forward a route request, thus creating a lot of extra overhead packets. For example, for a network of N nodes and for finding a single path between any source and destination, a total of (N-1) route request packets are flooded in the entire network. Second, there is no defined metric for routes selection in the AODV and thus QoS can't be supported explicitly. Although, AODV prefers the shortest paths, but shortest paths can be worst in providing the QoS as compared to the longest ones in the wireless networks. Third, AODV only supports Single-Radio Single-Channel MAC architecture, while WMNs routers are equipped with Multiple-Radios operating on multiple non-overlapping channels. AODV works as follows. For a pair of Source-Destination (S, D), S broadcasts the requests to its neighbor's for a route to D with RREQ packet. It is on demand in the sense that requests are only sent by the source node, whenever it needs to have connection with the destination for sending some data. All the neighbors of S rebroadcast this route request to their neighbors and the process continues until it reaches either the intended destination or an intermediate node, which have updated route to the destination D, Destination Sequence Number field along with Destination IP address in the RREQ packet is used in the later case. Intermediate nodes avoid duplicate RREQ reception by dropping them if the Originator IP and RREQ ID of the current message is matched with the one maintained by it for the previous RREQ packet. Upon reaching the destination, a unicast RREP packet is sent back to the neighboring node through which it received the first RREQ packet. All next RREQs for the same requests are dropped by the destination. Routes in AODV are maintained through route error (RERR) messages. If a source node moves, it reinitiates the route to the destination. If an intermediate node along the path moves, the neighbor nodes notice this and inform sender node of this failure by sending back the RERR message. A WMNs backbone can be exposed to two types of data as for as its end users are concerned, one which has a bound on some QoS parameters; for example video and audio applications are extremely delay sensitive and if these requirements are not met, it can severely affect users perception and the quality.

The other category of applications which do not need any specific requirements can be considered as best effort as for as the network bandwidth and delay requirements are concerned. Providing of QoS in WMNs is essential as its deployment forecast in the future wireless broadband access technology. Similarly, we divide the applications for the proposed MRMC routing scheme into two categories. One, which has some bounds on the QoS of end-to-end path and others which is best effort and do not need any services from the underlying network in terms of delays and bandwidth e.g., FTP, HTTP and other delay insensitive applications. The AODV extension in the proposed solution is called Quality of Service based Multi-Radio multi-channel capable AODV (QMR-AODV). In the simple AODV and Multi-Radio AODV (AODV-MR) [49, 50], the selected end-to-end path does not ensures the QoS requirements and simply establish routes for the requesting users. In the case of AODV-MR [49, 50], multiple radios are deployed on each node and these radios are tuned to the multiple non-overlapping channels as present in the IEEE 802.11a/b/g standards. When a source, S, needs a route to a destination, D, a RREQ is broadcasted by the source node on all of its interfaces simultaneously. If the RREQ is not a duplicate, each neighboring node of the source ‘S’, upon hearing this broadcast, re-broadcasts the RREQ all of its interfaces. This process of broadcasting continues and disseminates in the whole network until the destination is found. It is important to mention that in the case of AODV-MR, those neighboring nodes which share a common channel hear the broadcast on that channel. Before broadcasting the RREQ, each node maintains the reverse route, which points towards the source node from which this current node has received the RREQ packet. The flooding mechanism, as discussed before, even worsen in AODV-MR as each mesh router now rebroadcasts the RREQ packet on multiple interfaces creating a total of (N-1)x I overhead packets, with an N routers WMNs backbone each having I interfaces. Further, there is no QoS provisioning in both these protocols. Generally, the proposed QMR-AODV works as follows. As shown in the Figure 3-3, when an end user wants to establish a connection with the destination (Gateway), it sends the modified RREQ packet. The modified route request packet has four important fields to be considered by the end users as well as the rely routers. As shown in the Figure 3-3, first the D flag, it is set by the route requesting node which needs this RREQ to be replied by the destination only. Thus, a RREQ with D flag set will never return a path to destination from an intermediate node. This ensures that a path returned by QAODV-MR will always satisfy the end-to-end requirements of user’s applications.



Flowchart 3.1: How the entire algorithm will work.

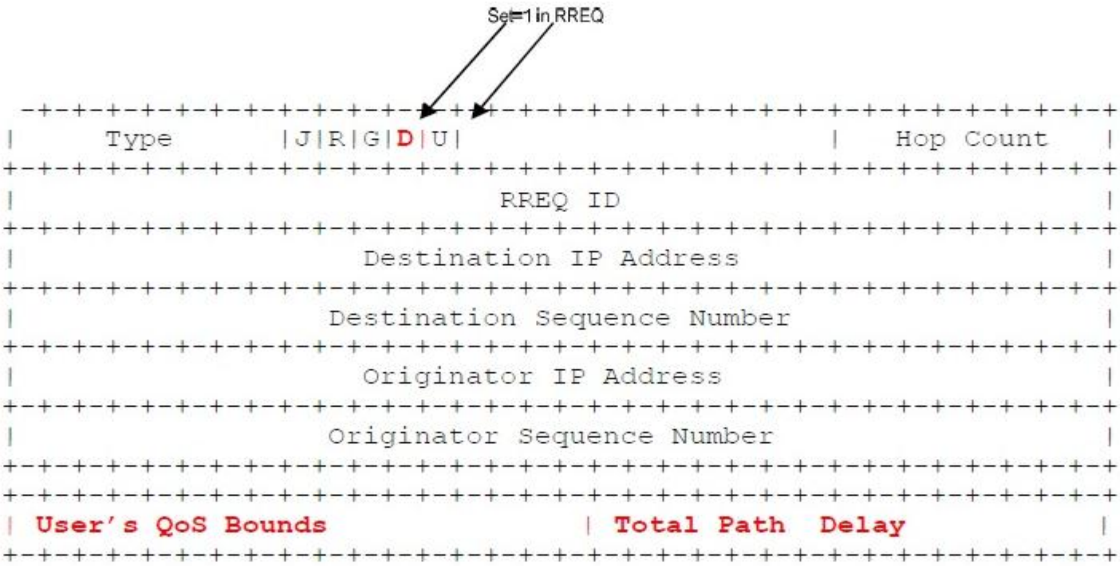


Figure 3.3: Modified RREQ packet format

The first bit in the reserved field is either set or zero. If this bit is set by the requesting end user, it is an indication for the intermediate nodes that some specific QoS is required by the source node. The last field of modified RREQ packet is divided into two halves, the first half shows the maximum delay an application can tolerate (User's QoS Bounds) for each of its individual packet on end-to-end basis. The RREQ packet initiator node, based on the application requirements, sets this field by putting the appropriate value of maximum delay, which can be tolerated by the end users application on the end-to-end path requested. The second half of this field, Total Path Delay, shows the cumulated delay of the path from the initiating node to this current node so far. Upon receiving the RREQ packet, the intermediate node (and the destination node if that is the case) first checks the Destination IP address in the REEQ packet. If a match is found between the Destination IP and the IP address of the current node, the RREQ is for a path request to this node and a RREP is unicasted to the initiating node. If the current receiving node is not the destination, then the intermediate node first checks the D flag and the first reserved bit. If both are zero, the request is considered as a normal AODV RREQ and is forwarded over multiple radios/interfaces of the node, as shown in the flowchart of 3.1.

Algorithm for routing decision on each node

for each node(*n*) on receiving RREQ packet

If RREQ_DEST_IP== NODE_IP //then this node is the destination

Send RREP

else if (**D**=0 and **Reserved**=0)

Forward packet through normal AODV-MR/AODV operations

else // QMR-AODV operations

for ***i***=inf_0 to inf_n

Total_Path_Delay=Total_Path_Delay+ inf_i_delay

If {Total_Path_Delay≤ User's required delay

Hop_Count=Hop_Count+1

Send RREQ to next hop

else

Drop RREQ for inf_i

end if

next i

end if

Figure 3.4: Algorithm for QoS (delay) based on demand routing.

If current node is not the destination, then all the interfaces of this current node are evaluated for providing the required QoS (delay) as requested by the source node as follows. The intermediate node adds up the delay of bi-directional link associated with the current interface as maintained by the channel monitoring module, discussed in the Section 3.2. This updated delay associated with the link/channel assigned to the interface of the node under consideration is added up with last 16 bits field, Total Path Delay, and is compared with the User's QoS demanded delay. As shown in the Figure 3-4, if the User's QoS demanded delay bound is less than the one calculated by the current node for it's a specific interface, the RREQ is dropped for that interface. This means that the current interface's delay added up with the path delay so far cannot guarantee the QoS requirements of the end user application. In this case the RREQ packet is dropped by the node from forwarding at the current interface as shown in the algorithm of the Figure 3-4. Otherwise, Total Path Delay is updated and the RREQ packet is sent to the next hop by this interface. Upon reaching the destination, a RREP packet is unicasted for the first RREQ packet it receive from the one hop neighbor. All other successive RREQs for the same connection are dropped. As shown in the Figure 3-5, the mesh routers B, C, D and H do not forward the RREQ on some of their interfaces simply because the QoS limit set by the end user can't be satisfied. This technique has two fold gains.

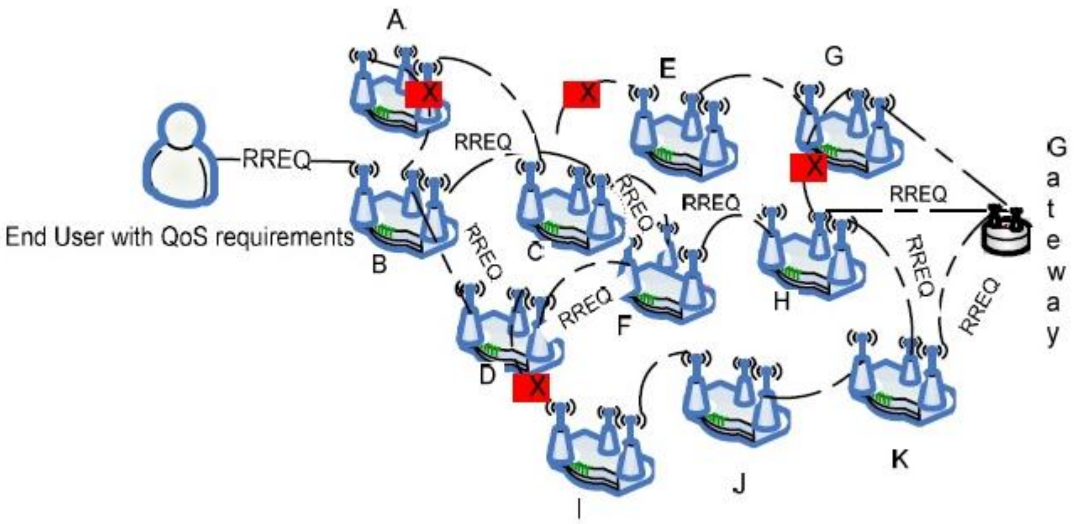


Figure 3.5: RREQ selective forwarding by the WMNs backbone routers.

First, the flooding associated with the AODV-MR is reduced from (N-1) xi to (N-1) in the case if only one interface of all the routers in the path is satisfying the QoS requirements. Another advantage is that by setting the D flag in RREQ packet, only the destination is bound to reply the RREP packet. This, combined with the QoS value comparison on each node's interface ensures the requested quality of the end-to-end path.

3.2.1 Channel Re-Assignment

Nodes can fail inside the network backbone and this failure can affect the performance of network in terms of connectivity and throughput. If a channel assignment scheme is not capable to detect the node's failures, the network nodes can go into isolation. For self-configurable networks like WMNs, node failure should be tackled effectively. In the proposed channel assignment and routing scheme, the channel re-assignment is triggered with three events. First, if a node fails with some or all of its interfaces then this node failure is detected by the Channel Assignment module and channel re-assignment is performed in that locality. Although, WMNs have relatively very static topology and the routers are almost fixed, however, in some cases the routers can be mobile e.g., if the routers are integrated from the Vehicular Network infrastructure inside the WMNs backbone, then mobility can be expected. In this case, a node can move from one location to another one due to mobility. This can impact the topology of the network in terms of connectivity. This information should be captured in an efficient way. Third, there might be some cases that all the interfaces of a certain node are not complying with any of the QoS based RREQ from the end users. This latter case can happen, for example, when the channel assigned to a specific node's link is interfering too much with other links in its range. If a node fails or moves from one location in the backbone to another location, this failure or movement is detected by the neighboring nodes through the periodic Hello messages. Let suppose a node 'a' fails in the example network shown in the Figure 3-6, it means that all of its neighbors will not receive the periodic unicast Hello messages from node 'a'. This will mean two possible events. Either the node in the vicinity has failed or it has moved to a location which is no longer in the transmission range of its previous neighboring nodes. This event triggers the channel re-assignment module.

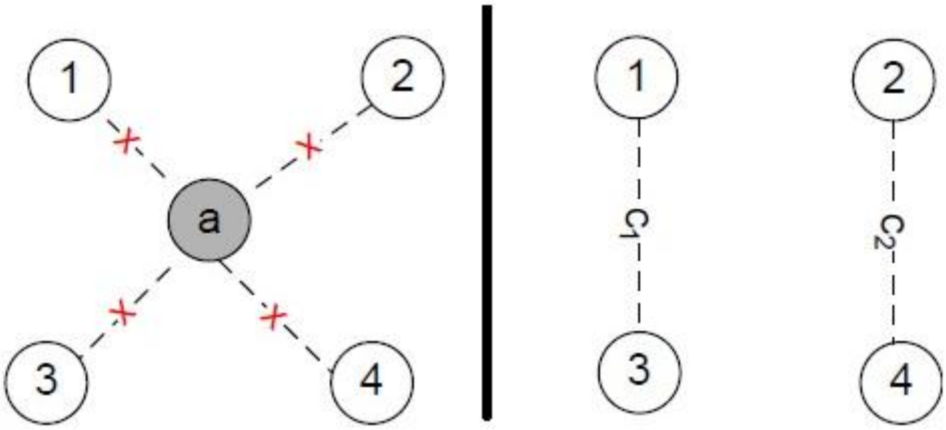


Figure 3.6: Nodes failure and channel reassignment.

Each neighboring node, which had a connection with node ‘a’, will remove the channel assignment information as mentioned in the Tables 3-2 and 3-3 of Section 3.1. In the next phase, the interface on which the neighboring nodes were connected to node ‘a’ are available for channel re-assignment. Each neighboring node of failed node ‘a’ broadcasts the CHReq frame on all the channels. Any neighboring node with an interface unassigned to any channel can reply with the CHReply unicast message. The channel re-assignment is performed in a similar way as mentioned in the Section 2.9.1. Similarly, if a node ‘a’ moves from its current location to some other location inside the network backbone, this event is considered the same as node failure by all its neighbors and channel re-assignment is performed as mentioned for node failure.

However, the re-located node, when no longer receiving the periodic Hello messages from its neighboring nodes, realizes of its movement and starts broadcasting CHReq messages on all of its interfaces. If there is any node in its neighborhood (inside the transmission range) having no channel yet assigned to one of its interface, will reply with the CHReply unicast message. However, it is possible that at the new location there is no node whose interface is available for this new channel re-assignment. The channel re-assignment can also be triggered by the routing request service threshold configured on each node. If a node rejects all the QoS based RREQ's on all of its interfaces for a certain threshold number of times, the channel re-assignment module triggers. This, however, is performed by the affected node by sending the CHReq unicast messages to all of its neighbors. The requesting node, upon receiving the CHReply messages from its neighbors re-assigns channels as according to the channel assignment rules mentioned earlier in the Section 2.9.1.

3.3 Simulation Setup and Performance Evaluation

This section presents the performance evaluation of the proposed channel assignment and QMR-AODV routing protocols. Network Simulator-NS2 version 2.34 was used for development and simulation of the proposed model. Four performance metrics, Routing Overhead, Packet Delivery Ratio, Average Network Latency and Response Time, were observed for a set of two different scenarios. Simulation in each scenario was run 20 times each and the average was plotted in each case to build confidence in the observed results.

Routing Overhead: Routing Overhead refers to the number of routing control packets generated inside the network.

Packet Delivery Ratio (PDR): PDR refers to the ratio of the number of packets which succeeded to reach at the destination to those packets which were generated by the end user's applications. i.e. PDR= Total Received packets/Total generated packets.

Average Network Delay: This parameter refers to the total delay occurred inside the network for the data packets. The latency or delay is measured by calculating the time elapsed between the packet generation at the end user's nodes and when they reach at the destinations.

Average Response Time: Average Response Time is the average of time elapsed between each RREQ and when the source node gets the RREP packet.

3.3.1 Simulation Setup for Delay Sensitive Data

In this scenario, a network of 30 mesh routers was deployed in an area of 1000m x1000m in a grid topology with the following parameters as shown in the Figure 3-7. End users Mesh Clients generate Constant Bit Rate (CBR) UDP traffic with some specific delay constraint for each packet. The performance of the proposed scheme is compared with a Multi-Radio AODV (AODV MR) scheme and comparative analysis is done. All the simulation parameters are given in the Table 3-4.

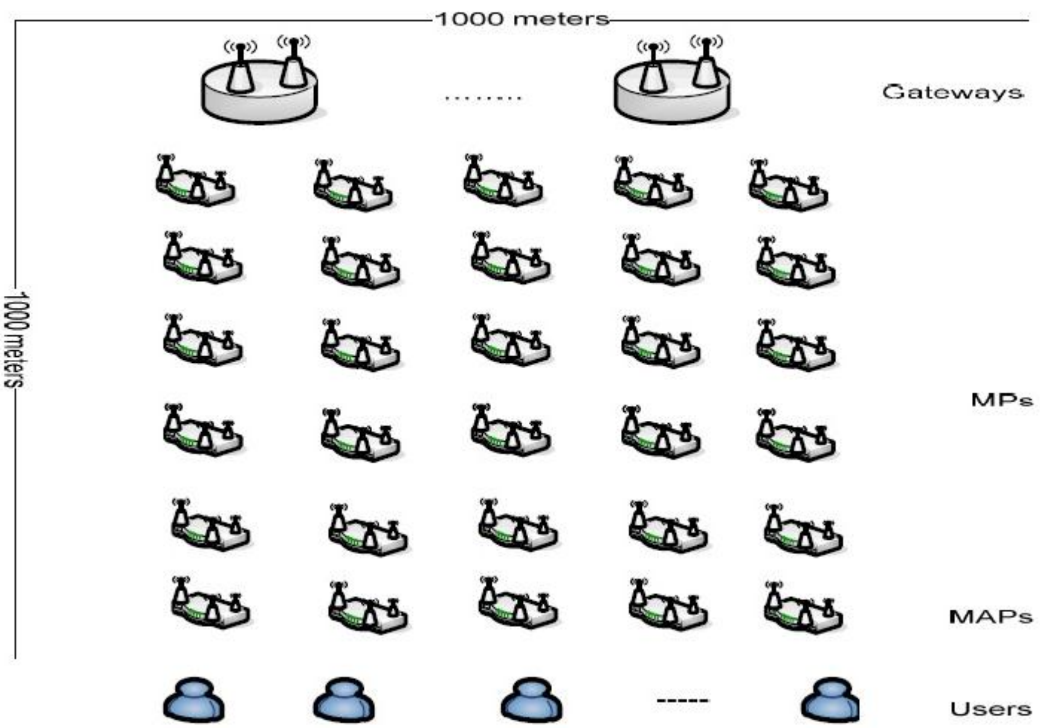


Figure 3.7: Network Deployment.

Simulation Parameters	Assigned Values
Topology	Grid
Number of Mesh Routers	30
Number of Interfaces(inf) on each Mesh Router	3
Number of Mesh Clients	45
Medium Access Control (MAC)	IEEE 802.11a
Number of Channels	8
Propagation	TwoRay Ground reflection
Transmission Range	250 meters
Max Interface Queue length	50
Routing Protocols	AODV-MR, QMR-AODV
Mobility Model	None(Static)
Number of flows	Varies (10 to 60)
Packet Size	1000 bytes
Packet generation rate	128 kbps per flow
Simulation time	600 Seconds
Topology covered area	1000x1000 meters
Data Rate	2MB

Table 3.4: Simulation Setup.

Routing Overhead: As shown in the Figure 3-8, both the AODV-MR and QMR-AODV produce almost the same number of routing overhead packets at the beginning. The reason is that for less number of flows, QMR-AODV functions the same as the AODV-MR due to less load and hence less congestion in the networks. Effectively, all the interfaces of intermediate nodes are conforming to the QoS delays bounds of RREQs of the end users applications. Furthermore, when the number of flows increases from the end users, the network gets congested and QMR-AODV outperforms AODV-MR by producing less amount of routing overhead. This is because; QMR-AODV now forwards the RREQ only on those interfaces of the intermediate nodes which are capable to handle the requested delay. On contrary, with increase in the network load, AODV-MR functions the same by broadcasting each RREQ on all of its interfaces except the one on which it was received. This linear increase in the routing overhead is evident from the Figure 3-8 for number of flows 30 and onwards. The AODVMR produces 24% more routing overhead for 30 flows going up to 36.1% for 60 flows, as compared to QMR-AODV.

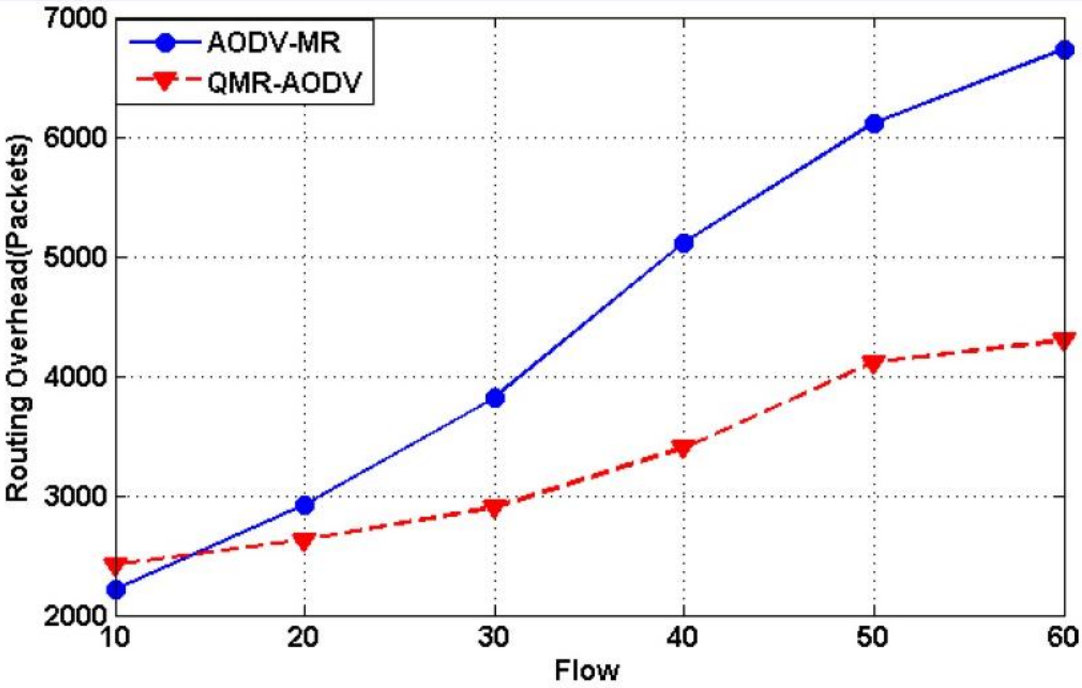


Figure 3.8: Routing Overhead for multiple numbers of flows.

Average Network Delay: The Average Network Delay of QMR-AODV is compared with AODV-MR for different number of end users generated flows. As shown in the Figure 3-9, QMR-AODV performs better by producing less latency in the network for all its data packets. The prime reason is the QMR AODV's route selection mechanism based on the delay condition. While AODV-MR selects any route without QoS guarantees and thus the data is stacked on the congested links inside the network. Secondly, AODV-MR broadcasts RREQ messages on all of its interfaces which creates more congestion inside the network and hence more latency. As depicted by the Figure 3-9, the Average Network Delay increases for AODV-MR abruptly with the increase in the end user generated flows while QMR-AODV's latency increases very steadily. Overall, the average network delay for AODV-MR increases from 40.4% to 55.89%for traffic profiles 10 flows to 60 flows, comparatively:

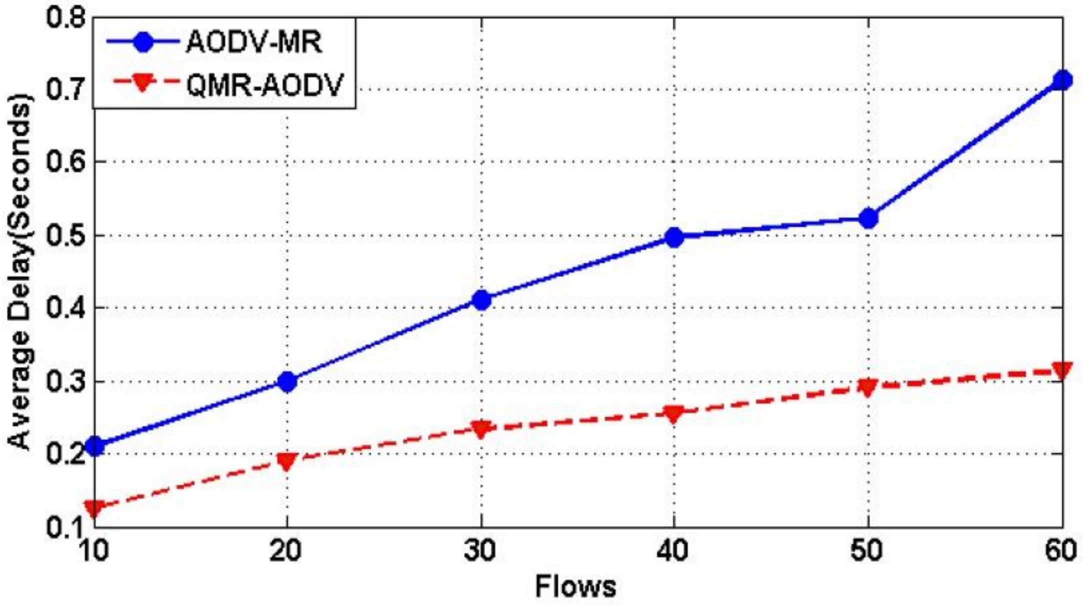


Figure 3.9: Average Network Delay for multiple numbers of flows.

Packet Delivery Ratio (PDR): PDR is an important performance measure of any routing protocol and indicates its significance in terms of achieved throughput on end-to-end paths. As shown in the Figure 3-10, both protocols perform equally at lower generated flows, where their PDR is almost equal to 100 percent. However, when the number of users flow increases, the PDR starts dropping for AODV-MR. AODV-MR produces more routing overhead causing more network congestions and collisions. Secondly, it selects whatever path is available and thus the end node's data is either lost due to queue overflows or due to collisions on the links. On the other hand, QMR-AODV selects paths with the delay guarantees and unicasts the RREQ packets on specific interfaces. This reduces the overhead inside the network leading to less collisions and congestions. Each end node data gets a confirmed service in terms of delays on end-to-end path and thus less data is lost during the communication. Overall, QMRAODV performs better to carry up to 70% more data on extremely congested network as compared to AODV-MR.

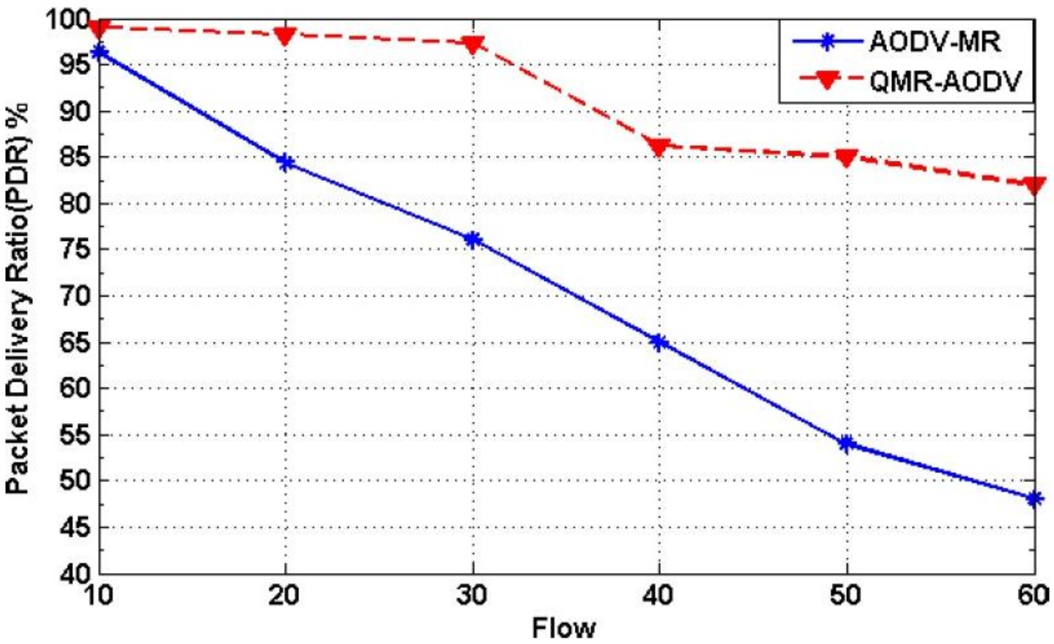


Figure 3.10: Packet Delivery Ratio (%) for multiple number of flows.

Average Response Time: The Average Response Times of both protocols is measured by taking the average of the time elapsed between all RREQs and their returned RREPs at the source nodes, for different number of flows. The Average Response Time is given by:

$R_t = P_t + N_d$ ……… (3.4)

Where, R_t= total average response time

P_t= avg. processing time

Each request and packets takes for its operation for determining the end to end route from source to destination and N_d is the delay associated with the network. As shown in the Figure 3-11, AODV-MR's has a better response time for low as well as high traffic profiles. The reason is that each QMR-AODV's RREQ packet is assessed for delay requirements and the interface compatibility. This takes extra processing time for RREQ to reach at the destination. On the contrary, AODV-MR's RREQ packets are only processed at the intermediate nodes for the routing information and then broadcasted on all the interfaces. This reduces the end to end latency for the RREQ-RREP cycle between the source and destination nodes. Second, AODV-MR's RREQ might return a path for the source node's RREQ from the intermediate nodes and thus extremely decreasing the response time.

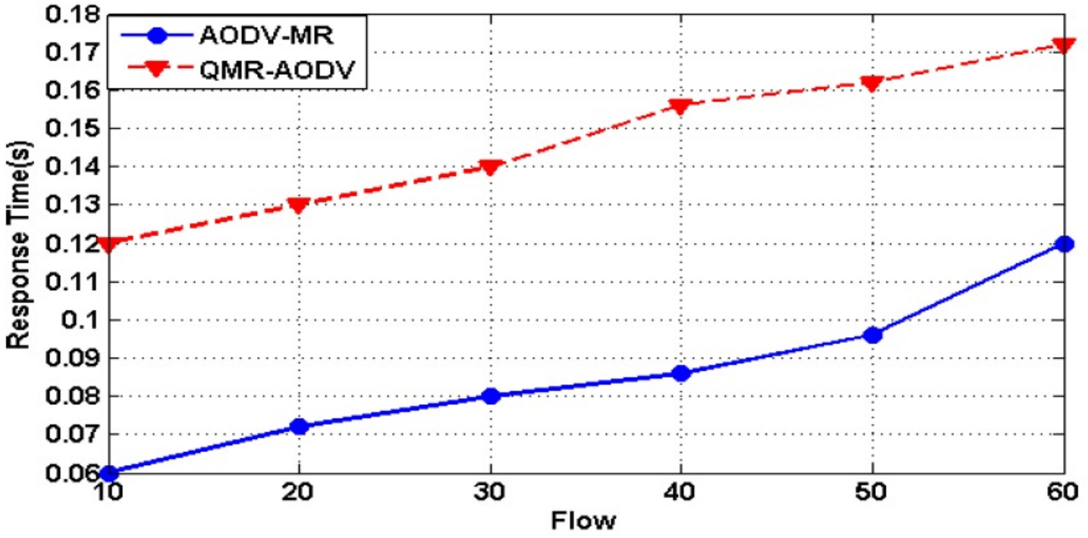


Figure 3.11: Average Response Time of the routing protocols.

3.3.2 Simulation Setup for varying number of radios

In this scenario, the number of radios/interfaces per node was incremented from 2 to 8 in step 1. Each time, the average delay and routing overhead was measured based on an average of 20 simulation runs. Number of flows generated by the end nodes was kept 30. All the remaining parameters were kept as according to the Table 3-5. IEEE 802.11a was used as the underlying MAC. Figure 3-12 shows the effect of varying the number of nodes interfaces on the routing overhead. When the number of radios/interfaces on each node is 2, the Routing overhead is almost equal for both AODV-MR and QMR-AODV. This is because both are using one interface for reception and the other one for transmitting the data.

In this case QMR-AODV only unicasts the RREQ packet to its next hop neighbor when the interface is capable of meeting the delay requirements. AODV-MR broadcasts the RREQ packet as it arrives only on the second interface. Since in a two interfaced nodes, the possibly of collision is minor keeping in view the number of channels available in IEEE 802.11a, and hence both performs equal. However, when the number of radios on each node is increased to 4, an abrupt change in the routing overhead is observed for AODV-MR. This is because the RREQ is now broadcasted on all the interfaces causing more routing overhead.

On the opposite, a very small increase in the QMR-AODV's routing overhead is observed with varying the number of radios per node. The reason is that QMR-AODV's selective forwarding of the RREQ messages to its next hop neighbors which effectively reduces the number of RREQ diffusion in the network. The Figure 3-12 also shows a linear increase in the routing overhead for AODV-MR from 6 to 8 radios case. This means that AODV-MR fails to work efficiently with large number of interfaces per node.

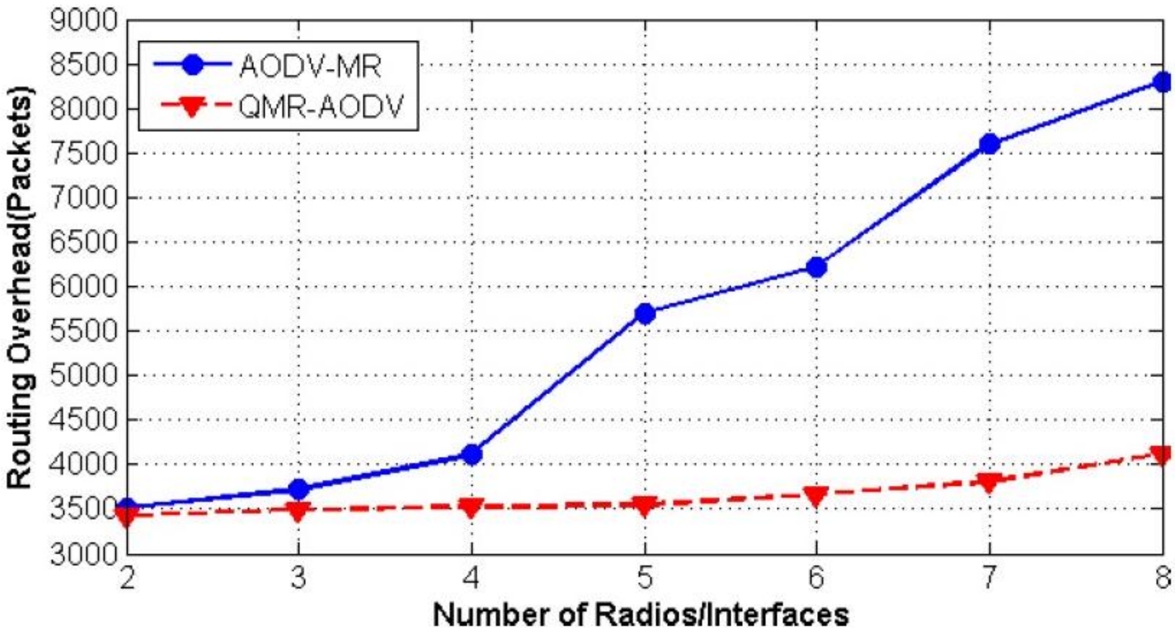


Figure 3.12: Routing Overhead with varying number of network interfaces/Radios.

Figure 3-13, shows the Average Delay experienced by all the packets inside the network comparatively with varying the number of radios per node. The average delay is high for both protocols when the number of interfaces is 2, where AODV-MR does better with less average delay as compared to QMR-AODV. The reason for high delay with less number of radios for both the protocols is that the network is less connected with fewer radios per node. More interfaces per node means more connectivity and more routes to the destination. It also means that with more radios per node, more parallel communication links and load distribution is achieved. With fewer interfaces per node, each link is congested with the high amount of data from the end users, which leads to congestion and network latency.

For 2 interfaces per node, AODV-MR performs better than QMR-AODV because of the possibility of the latter to drop a RREQ from transmitting to the next node based on the non-compliance with the QoS requirements. Thus, those RREQs packets, which never get RREPs, are re-sent by the end source nodes and thus increase the total delay.

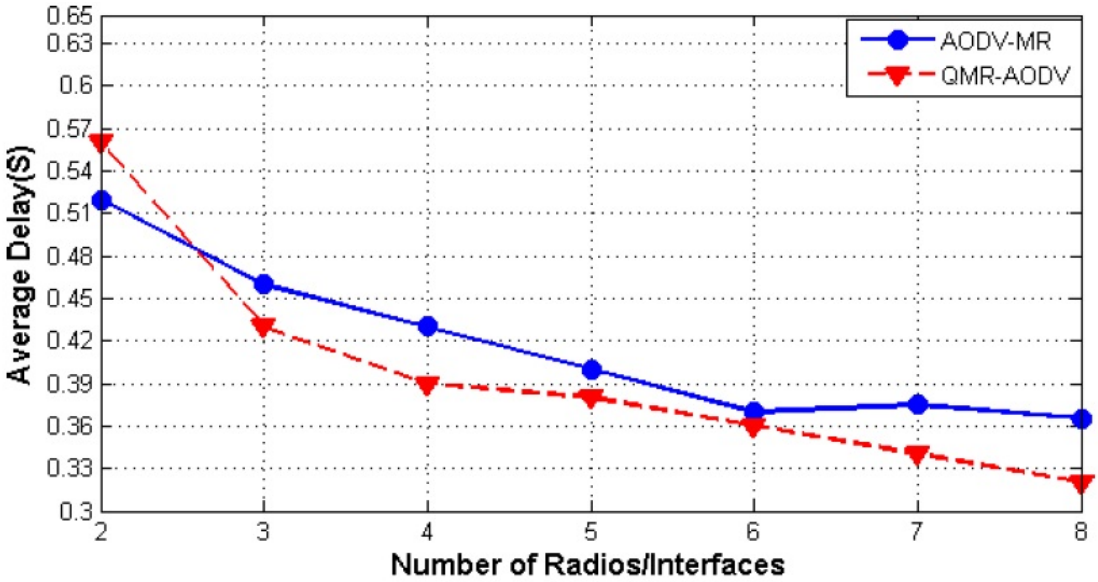


Figure 3.13: Average Delay with varying number of networks interfaces/radios.

However, QMR-AODV outperforms AODV-MR when the number of radios per node increases as can be seen in the Figure 3.13. This is because, increasing the interfaces per node for the same number of users' flows, connectivity increases and hence there are more chances for the RREQ to be sent on those interfaces which can meet the end users required QoS delay requirements. This ensures the data is always routed through best possible paths leading to fewer delays. Second, QMR-AODV comparatively produces less RREQ as mentioned earlier and thus decreasing the chances of congestion in the network.

Chapter 4

Discussion

4.1. Summary

This chapter presents joint channel assignment and routing scheme for Multi-Radio Multi-Channel WMNs. The proposed channel assignment scheme ensures low interference by assigning the non-overlapping channels to the multiple radios with a dynamic and distributed scheme based on channel usage exchange messages. The channel assignment scheme is capable of detecting nodes failures and mobility within the WMNs backbone. The delays associated with the bi-directional links are accurately captured by the channel monitoring module in terms of average queuing delays, back offs, transmission rate and retransmission for the lost packets. This delay information is further used by the QoS based routing scheme as a metric for determining the end-to-end path. The proposed QMR-AODV routing protocol controls the network wide flooding of conventional AODV by selective forwarding the RREQ packets. This helps to decrease the network routing overhead. QMR-+AODV returns a guaranteed end-to-end path according to the applications requirements as each node assesses each of its interface during the RREQ packet forwarding, for complying with the applications required minimum delay bounds. Further, the proposed scheme improves the packet delivery ratio, network latency and effectively reduces the routing overhead.

Chapter 5

Conclusion

5.1. Conclusion

In this paper we have concluded and discussed recently proposed techniques and approaches of channel assignment WMNs backbone where every node consist at least two network interface card. In this report many excellent approaches of channel allocation is discussed. The main objective of this paper is to take the maximum benefit from available channels in Wireless Mesh Networks by using a specific channel assignment and routing protocol. The authors of the other literatures have proved that there techniques and approaches to improve network performance. In this work we have classified a proposed techniques regarding the channel allocation and routing. Inside the extent of this broadened theoretical, we proposed a productive channel task and directing design for multi radio. In this article we have distinguished the key difficulties related with relegating channels to radio interfaces in a multi radio WMN. We exhibited a completely disseminated component that relegates 802.11 channels to multi-radio hubs in remote work systems. Our task component balances out to an attractive channel arrangement that strikes a decent harmony between organize network and channel decent variety. Our outline considers a few requirements show in current 802.11 gadgets, and its dispersed nature guarantees it is adequately light-weight to be executed on large scale work systems. This paper tends to a central plan issue in multi radio remote work systems, to be specific the channel task plot. The calculation we configuration goes for augmenting the arrange limit. The fundamental thought is to recognize the connections that are most basic to conveying activity and after that secure them against the obstruction.

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Appendix

1. Network Simulator-NS2 version 2.34
2. Required codes for the proposed algorith

A.1 Excerpts from simulation implementation

```
# ==================== #
#     CHANNEL MODEL    #
# ==================== #

# CONSTANT
set threshold   7.35638e-14 ;# Setting receiving threshold value for mobile nodes
set thresh_rt   1.72719e-14 ;# Setting receiving threshold value for routers
set t_power_n   7.214e-3    ;# Setting the transmission power for mobile nodes
set t_power_r   0.2818      ;# Setting the transmission power for routers

Phy/WirelessPhy set   freq_       2.4e9       ;# radio frequency
Phy/WirelessPhy set   L_          1.0         ;# system loss factor
Phy/WirelessPhy set   Pt_         $t_power_n  ;# transmission power
Phy/WirelessPhy set   CPThresh_   10.0        ;# capture phenomenon
Phy/WirelessPhy set   RXThresh_   $threshold  ;# reception threshold
Phy/WirelessPhy set   CSThresh_   [expr $threshold * 0.0427] ;# carrier
    sensing threshold

# CONSTANT / CHANGING in set of shadowing scenarios sequence
set prop [new $val(prop)]
$prop set             pathlossExp_   $pExponent  ;# path loss exponent
$prop set             std_db_        $deviation  ;# shadowing deviation
$prop set             seed_          $rand_seed  ;# seed for RNG
$prop set             dist0_         1.0         ;# reference distance
```

Listing A.1: The network interface and propagation settings

```
# Setting the name of a source file with the nodes' mobility
set      mobilityF   ./Load_mobility/mobility_file_     ;#
append   mobilityF   $rand_seed ".tcl"                  ;#
source   $mobilityF                                     ;#
# Setting the name of a source file with the traffic pattern
set      trafficpF   ./Load_traffic/traffic_file_       ;#
append   trafficpF   $rand_seed ".tcl"                  ;#
source   $trafficpF                                     ;#

# Setting the name of an NS trace file
set      ns_trace    ./NS_trace/trace_                  ;#
append   ns_trace    $routing_p "_" $rand_seed ".tr"    ;#
set      traceFile   [open $ns_trace w]                 ;#
```

Listing A.2: Setting the simulation input and output files

3. The proposed Routing protocols
   A. QMR-AODV: It is Base on quality of service interface packet sending protocol. The complete abbreviation is Quality of service based Multi-Radio Adhoc own distance vector routing protocol. It is used for Wireless Mesh Network.
   B. AODV-MR: This routing protocol is for MANET. The complete form is Adhoc own distance vector routing protocol for Multi-Radio MANET system.