

An Integrated Framework for QoS Support in Mobile Ad Hoc Networks

By

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ABSTRACT

An Integrated Framework for QoS Support in Mobile Ad Hoc Networks (MANETs)

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The work of this thesis is presented in two separate parts. The first part focuses on MANETs and the second part focuses on one of its subsets Vehicular Ad-Hoc Networks (VANETs). In the first part, we address the important problem of supporting real-time multimedia streaming applications along with their diverse QoS requirements in MANETs. Specifically, this work proposes and devises an integrated framework for QoS support in MANETs. that is specifically tailored to target specific requirements of multimedia streaming applications in order to meet their stringent QoS requirements.

The ultimate objective of the proposed QoS framework is to meet the end-to-end QoS requirements with the least possible resources while minimizing the average end-to-end delay as well as increasing the network throughput. The proposed framework for QoS support in MANETs encompasses three major functionally interdependent modules including QoS module, QoS Routing module, and QoS cross-layer module that meets the QoS requirements at multiple layers in the protocol stack including the physical (PHY), Medium Access Control (MAC), and the network layers.

The QoS module defines the service architecture of the overall QoS framework. The QoS cross-layer module proposed here ensures that the three layers must work and coordinate together in a

collaborative and complementary fashion in order to satisfy the QoS requirements of the underlying applications. The PHY layer provides the channel-state information, e. g., SNR, while the MAC layer provides mechanisms for resolving medium contention, which ensures reservation at the link level only. The network layer ensures end-to-end resource negotiations, reservation, and reconfiguration. To implement the key module of the proposed QoS framework, a novel QoS-aware multipath routing protocol (QMRP) is developed.

The second part of this thesis addresses one of the main outstanding problems facing VANETs, namely, the broadcast storm problem, as communication in VANET depends heavily on broadcasting a message to all other vehicles in a certain geographical region. Specifically, we propose a dynamic suppression broadcast scheme (DSBS) for VANETs to alleviate the broadcast storm problem by dynamically suppressing the broadcast of a message based on the estimated distance reflected in the SNR value of the received message and the value of the broadcast counter.

Dedication

To my parents
To my ultimate soulmate who imbued hope into me when
I had no hope in myself?

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Nomenclature

ACK: Acknowledgment

AP: Access Point

AODV: Ad-hoc on demand distance vector

AOMDV: Ad-hoc On-demand Multipath Distance Vector

BER: Bit Error Rate

BPSK: Binary Phase Shift Keying

CBR: Constant Bit Rate

CHAMP: Caching and Multipath

CLASS: Cross Layer Signaling Short Cut

CLD: Cross Layer Design

CSI: Channel State Information

CTS: Clear-to-Send

DCF: Distributed Coordination Function

DSDV: Destination Sequenced Distance Vector

DSR: Dynamic Source Routing

ECN: Explicit Congestion Notification

FEC: Forward Error Correction

FIFO: First In First Out

FQMM: Flexible QoS model for MANETs

IETF: Internet Engineering Task Force

MAC: Media Access Control

MANET: Mobile Ad Hoc Network

OLSR: Optimized Link State Routing

OSI: Open Systems Interconnection

PHY: Physical Layer

PLR: Packet Loss Ratio

QAM: Quadrature Amplitude Modulation

QMRP: QoS-aware Multipath Routing Protocol

QoS: Quality of Service

QPSK: Quadrature Phase Shift Keying

RERR: Route Error

RREP: Route Reply

RREQ: Route Request

RTS: Request to Send

SMLDR: Shortest Multipath Routing Using Labeled Distanced

SMR: Split Multipath Routing

SNR: Signal to Noise Ratio

SWAN: Stateless Wireless Ad-hoc Network

TDMA: Time Division Multiple Access

TTL: Time To Live

VBR: Variable Bit Rate

VANET: Vehicular Ad Hoc Network

WSN: Wireless Sensor Networks

ZRP: Zone Routing Protocol

1 INTRODUCTION

1.1 Background

A Mobile Ad Hoc Network (MANET) is a collection of autonomous mobile nodes connected by wireless links that can dynamically form a network to exchange information without using any pre-existing fixed network infrastructure. Nodes in MANETs [1] operate on low power battery devices and intercommunicate through single-hop and multi-hop paths. These nodes can function either as hosts or as routers. Host nodes function as a source to generate traffic flows and/or as a destination in the network. Router nodes act as intermediate bridges to forward traffic directed to other mobile nodes. In a MANET, nodes are free to move randomly and can organize themselves in arbitrary fashion, resulting in frequent and unpredictable changes in the network topology. Such networks have gained popularity because they can be rapidly deployed anywhere and anytime without the existence of fixed infrastructure and/or base stations and system administrators. The ease of deployment of MANETs make it attractive for many applications such as rescue and recovery in disaster areas, education and research expeditions in remote areas and emergency mobile medical units [2].

One of the key elements in providing QoS assurance to applications over MANETs is to establish and maintain routes based on a certain criterion such that there is high degree of assurance to provide soft QoS especially for multimedia applications due to the fast growing of these applications over MANETs, therefore such networks must be not only providing ubiquitous coverage, but also with a very good quality and performance; for more details on soft QoS see [3].

For the past two decades, research in the area of wireless ad hoc networks has been growing rapidly due to the cost reduction in mobile radio equipment (e.g. 802.11 and Bluetooth). Two main networks categorized under wireless ad hoc networks; MANETs and one of its subsets Vehicular Ad-Hoc Networks (VANETs) and Wireless Sensor Networks (WSN). VANET is a collection of autonomous moving cars connected by wireless links that can dynamically form a network to exchange information without using any pre-existing fixed network infrastructure. Moving cars in VANETs function as wireless router or node, allowing cars approximately 100-300 meters of each other to connect and, in turn, create an ad hoc network. As cars fall out of the signal range and drop out of the network, other cars can join in, connecting vehicles to one another so that a mobile internet is created. This thesis focuses on MANETs and VANETs.

MANET's initial applications have targeted military battlefield and disaster recovery. However, with the rapid evolution in multimedia technology, MANETs have been widely used in various commercial application areas including sports stadiums and Personal Area Networks (PANs). Since then, Quality of Service (QoS) support in MANETs has emerged as an area of crucial interest. Supporting multimedia streaming applications, e.g., audio and video, is an essential requirement for group interoperation in both MANET's military and commercial applications. Consequently, QoS provisioning in MANETs is of utmost importance. However, due to the unique characteristics of MANETs, supporting real-time multimedia streaming applications, along with their stringent QoS requirements such as bandwidth, delay, and jitter (delay variations), in these networks is a challenging task and remains an open research problem. In fact, providing QoS support in MANETs is more challenging than both conventional wireless and wire line networks.

Mobile nodes cause broken links as they move from one place to another. These broken links may be detected by the MAC layer protocol or by the absence of broadcasts (for a given predefined interval) from neighboring nodes. Figures 1 and 2 show the effect of mobility and/ or link break on the topology of a small ad hoc network when node I moves to another location, which is the norm rather than the exception in such networks. The initial state and topology of this ad hoc network is shown in Figure 1. When node I moves the entire topology has changed by breaking some existing links such as (A-I) and (C-I) due to the limited transmission range and creating new links such as (D-I) and (I-F) which becomes within communication range.

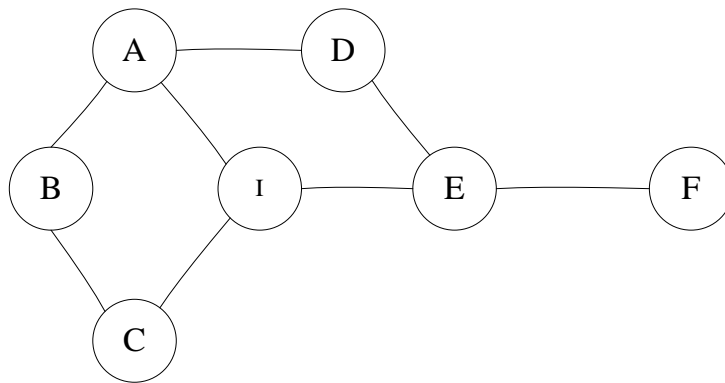


Figure 1.1 Mobile Ad hoc Network Before Node I Moves

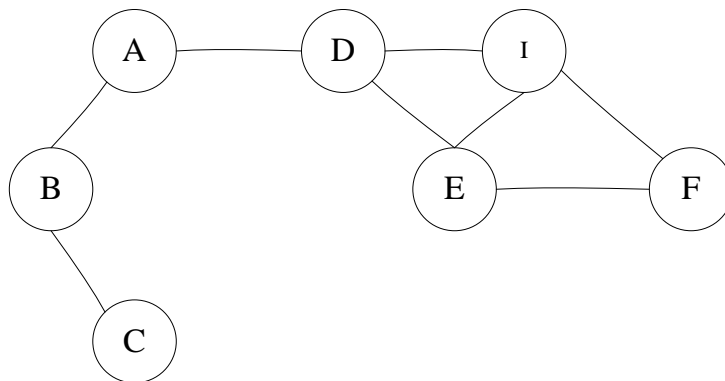


Figure 1.2 Mobile Ad hoc Network After Node I Moves

Topology changes can occur even in low or complete absence of mobility due to variation in the wireless medium as a result of attenuation, interference, multipath effects, shadowing and fading. Due to the unpredictable location and mobility of mobile nodes (MNs) in MANETs, classical routing protocols used on wired networks are not suitable for MANETs. MANET's routing protocols are generally classified as reactive protocols and proactive protocols. In reactive protocols, all MNs acquire and maintain routes on demand, while all MNs in proactive protocols maintain routes to all destinations all the time. Dynamic Source Routing (DSR) and Ad hoc On-demand Distance Vector (AODV) are typical examples of reactive protocols. Optimized Link State Routing Protocol (OLSR) and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) are typical examples of proactive protocols.

1.2 Thesis Motivation

Supporting QoS in MANETs is a complex and challenging task mainly because MANETs have certain unique characteristics that pose a number of technical challenges when provisioning QoS. These include but are not limited to: 1) frequent/constant changes in network topology due to unpredictable node mobility. Thus, the dynamically varying nature of MANET topology makes it exceedingly hard to acquire complete and precise knowledge of the network state. In addition, constant updates of link state information are required to make optimal QoS-aware routing decisions, which results in substantial control and signaling overhead; 2) limited available radio resources; 3) contention for shared wireless channel access; 4) limited battery power of mobile devices; 5) limited wireless transmission range of MANET nodes, so routing depends on intermediate nodes relaying information to distant nodes (multi-hop communication); 6) hidden terminal problems; and 7) the absence of a central coordination authority in MANETs.

A key for supporting QoS in MANETs is to find a route to the desired destination that meets the connection's QoS requirements and, most importantly, can survive for the duration of the session. QoS routing protocols search for routes with sufficient resources in order to meet the QoS requirements of a given connection. Depending on the class of service to be supported, QoS metrics may include bandwidth, end-to-end delay, delay variation (jitter), energy, probability of packet loss, and so on. QoS support in MANETs has received considerable attention where numerous research efforts have targeted QoS routing protocols as the key aspect for providing QoS support in MANETs.

A multipath approach has much attention in research community [4]. Multipath aim is to find more than one path between source-destination pair to maintain QoS assurance for the life time of a connection to address the seamless switching of paths from user's point view. Multipath increases network resilience (i.e., reliability through fault tolerance), QoS assurance [5] load balancing which decreases congestion and bottlenecks also it increases aggregate bandwidth, reduces End-to-End (ETE) delay, delay variation and Packet Loss Ratio (PLR). Additional benefits of multipath routing include reduction of computation time that CPUs require, high call admission ratio in voice applications [3] [6]

Most of the QoS routing protocols reported in the literature are extensions to the conventional well known MANET's multi-hop routing protocols such as Ad Hoc on Demand Distance Vector protocol (AODV) [7], Dynamic Source Routing protocol (DSR) [8], and Temporally Ordered Routing Protocol (TORA) [9]. These routing protocols establish and maintain routes on a best-effort basis. QoS routing protocols are mainly based on extending these original routing protocols, specifically AODV, via adding new QoS metrics, e. g., maximum delay extension and minimum bandwidth extension to the routing table structure at each node. Thus, it is essential

that routing protocols incorporate QoS metrics in route finding and maintenance to support end-to-end QoS.

Many of QoS routing protocols have considered only bandwidth as the key QoS parameter where the main objective is to find shortest path satisfying the bandwidth requirement. This is because bandwidth is the most critical parameter in most MANET applications. Though most of these QoS routing protocols meet some of the QoS constraints under certain assumptions, a comprehensive QoS framework that takes into account most of MANET's unique characteristics and challenges is needed.

1.3 Thesis Statement and Contributions

The work of this thesis is presented in two separate parts. The first part focuses on MANETs and the second part focuses on one of its subsets Vehicular Ad-Hoc Networks (VANETs). In the first part, we address the important problem of supporting real-time multimedia streaming applications along with their diverse QoS requirements in MANETs. Specifically, this work proposes and devises an integrated framework for QoS support in MANETs that is specifically tailored to target specific requirements of multimedia streaming applications in order to meet their stringent QoS requirements.

The ultimate objective of the proposed QoS framework is to meet the end-to-end QoS requirements with the least possible resources while minimizing the average end-to-end delay as well as increasing the network throughput. The proposed framework for QoS support in MANETs encompasses three major functionally interdependent modules including QoS module, QoS Routing module, and QoS cross-layer module that meets the QoS requirements at multiple layers in the protocol stack including the physical (PHY), Medium Access Control (MAC), and the network layers.

The QoS module defines the service architecture of the overall QoS framework. The QoS cross-layer module ensures that the three layers must work and coordinate together in a collaborative and complementary fashion in order to satisfy the QoS requirements of the underlying applications. QoS routing is the process of providing end-to-end loop free paths to ensure that the required QoS parameters are met. The QoS routing protocol should find the path that consume minimum resources. The PHY layer provides the channel-state information, e. g., SNR, while the MAC layer provides mechanisms for resolving medium contention as well as bandwidth reservation and real time traffic support, which ensures reservation at the link level only. The network layer ensures end-to-end resource negotiations, reservation, and reconfiguration.

To implement the key module (QoS routing) of the proposed QoS framework, a novel QoS-aware multipath routing protocol (QMRP), which takes into account the specific characteristics of MANETs, is developed. The salient features of the proposed QoS-aware multipath routing protocol are:

1. Multiple loop-free node-disjoint paths between each source-destination pair are established where each node participates in only one path between the source-destination pair. Even if the primary selected route between a source-destination pair may initially meets the QoS requirements for a given connection, this route may not be able to meet the same requirements for the entire session due to the dynamically variant nature of MANETs. Thus, selecting concurrently alternate QoS-aware routes along with the primary route is an integral component of the proposed framework for QoS support in MANETs.
2. Each selected route (path) incorporates QoS metrics to support end-to-end QoS via utilizing a cross-layer approach that meets the QoS requirements at multiple layers in the protocol stack. This is achieved by capturing the pertinent wireless channel conditions as well as the available

bandwidth and delay constraint from the PHY and MAC layers and feeding them back into the routing layer (network layer) which in turn establishes the end-to-end QoS-aware path(s) based on the QoS constraints.

The second part of this thesis addresses one of the main outstanding problems facing VANETs, namely, the broadcast storm problem, as communication in VANET depends heavily on broadcasting a message to all other vehicles in a certain geographical region. Specifically, we propose a dynamic suppression broadcast scheme (DSBS) for VANETs to alleviate the broadcast storm problem by dynamically suppressing the broadcast of a message based on the estimated distance reflected in the SNR value of the received message and the value of the broadcast counter.

The results presented in this thesis are obtained through extensive computer simulations and modeling using OPNET and substantial system simulator development, which is carried out during the course of this work. This includes modeling considerations as well as software design and testing.

1.4 Organization of Thesis

The rest of the dissertation is organized as follows. Chapter 2 covers literature review routing; classification of routing protocols based on the discovery mechanism is presented, disjointness and multipath issues are discussed. Based on the routing problem in ad hoc networks, Chapter 3 presents the proposed framework for QoS Support in MANETs using cross layer approach. Simulation environment and parameters are presented in Chapter 4 as well as results and discussion. Chapter 5 explores the broadcast storm problem in VANET and how to alleviate it by introducing a new dynamic suppression broadcast scheme. Conclusions and future work are presented in Chapter 6.

2 ROUTING IN MANET

MANETs can be deployed instantaneously without the need for preexisting infrastructure, where nodes communicate directly without any centralized control unit as oppose to wired networks or fixed wireless networks that communicate through the Access Point (AP). To be able to understand the challenges in designing a routing protocol for MANETs, it is critical to understand some of the characteristics of such networks. MANETs characterized by (i) wireless medium is error prone and unreliable as a result of interference, shadowing and multipath fading which means the channel is unpredictable, (ii) node mobility; since nodes move randomly and independently causing links to be destroyed and created frequently and so topology is very dynamic; this results in the lack of knowledge of nodes of the network state, (iii) limited node's resources; since mobile nodes are battery powered in most of applications of MANETs it means that such nodes have less computational power and limited memory capacity [10] [11].

2.1 QoS Routing Protocols Ad Hoc Networks

Due to the unpredictable location and mobility of mobile nodes (MNs) in MANETs, classical routing protocols used on wired networks are not suitable for MANETs. MANET's routing protocols are generally classified as reactive protocols and proactive protocols. In reactive protocols, all MNs acquire and maintain routes on demand, while all MNs in proactive protocols maintain routes to all destinations all the time. Dynamic Source Routing (DSR) and Ad hoc On-demand Distance Vector (AODV) are typical examples of reactive protocols. Optimized Link State Routing Protocol (OLSR) and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) are typical examples of proactive protocols.

QoS provisioning is the overall coordination and cooperation of all layers in the OSI model; where each layer is responsible for maintaining certain factors and measurements. The PHY layer is responsible of the transmission quality (e.g. adjust transmission power to deal with high bit errors), where the link layer deals with the Variable Bit Rate (VBR), the routing layer takes care of the dynamics of mobile nodes and change in bandwidth and delay while transport layer considers Packet Loss Ratio (PLR) finally, the application layer focuses on the disconnections and reconnections [12]. This work focuses on QoS routing.

At the routing layer QoS goal in MANETs is to find reliable and stable routes that provide the required QoS by the application in a multi-hop dynamic environment. The main QoS constraints based on the application's requirements could be classified into (i) bandwidth, (ii) end to end delay, (iii) delay variation and (iv) packet loss ratio. The authors in [13] present combinations of many multiple constraints; however, it also has been shown as mentioned previously that multiple constraints are NP-complete [14]. Due to the frequent link break and creation because of node mobility in MANETs, to assure QoS the network must be "combinatorically stable" [15] meaning changing in network topology must be less than the time it takes to topology updates to propagate. The most recent survey available on the QoS routing solutions for MANETs could be found in [10] [11].

Recent years have shown increased interest in routing protocols that utilize cross layer in MANETs [16] [17] [18]. The authors [19] proposed an adaptive QoS routing protocol by cross layer cooperation based on the current network conditions QoS requirements assured by adaptively using multipath routing and Forward Error Correction (FEC). In [20] the authors

presented cross layer energy-aware multipath routing protocol (EMRP), which exchanges information between PHY, MAC and routing layer to utilize the network resources.

Most of previous discussed protocols use minimum hop count as a criterion in finding and establishing paths between source-destination pairs. However, authors in [21] have shown that minimum hop count routes without considering link quality could degrade the network performance since they might include wireless links that are bad or congested along the path causing the overall throughput of the network to degrade and cause even more delays than longer paths that consist of good links.

2.2 Single Path vs. Multipath Routing

Single path routing refers to finding one path between source-destination pair when a source needs to communicate with a certain destination and the source has no path in its routing table to that destination. Most single path routing protocols start the search for a path to a destination by initiating a route discovery process through the broadcast of a route request (RREQ) message to target the intended destination and wait for a route reply (RREP) message from the destination, when an intermediate node receives a RREQ message and it's the first time it sees this RREQ, the node sets up a reverse path to the source by updating its routing table and adding the previous node as the next node of the reverse path and rebroadcast the RREQ message, if the node has a path to the destination it updates its routing table and generates a RREP packet back to the source, if the node have seen this RREQ previously, it discards the packet since it has already processed such packet. When the destination receives the RREQ it generates a RREP packet via the reverse path that was established through the RREQ. Once the source receives the RREP it starts injecting its traffic to the destination.

Route maintenance in single path routing protocols is simply by generating a route error message (RERR) when it detects a link and/or node failure, this message propagates to all nodes along the path that has a route through that link/node. Each path has expiration timer to eliminate stale paths if they are not used within certain time frame. The most widely known single path routing protocols for MANETs are the Ad hoc on demand distance vector (AODV) [1] [7] and the Dynamic source routing (DSR) [8]. Single paths routing protocols has its limitations and weaknesses, when a node/link fails during transmission session between source-destination pair, the source needs to initiates a new route discovery leading to longer delays and dropped packets as well as increase overall control packets and adding more to the congestion in the network.

On the other hand, multipath refers to the establishment of more than one path between source-destination pair to maintain QoS assurance for the life time of a connection; this approach is very practical and is needed in a dynamic environment like MANETs due to unreliable wireless link, so when a link and/or node fails there is an alternate path to continue transmitting traffic, this increases packet delivery ratio as well as network fault tolerance also it minimizes end to end delay and reduces packet loss ratio. Because of the dynamic nature of Ad hoc networks due to mobility and nodes joining and leaving the network, limited transmission range and limited source power of the nodes, multi-path routing is needed to increase network resilience (i.e., reliability through fault tolerance) and load balancing, which can decrease congestion and bottlenecks, increase aggregate bandwidth, reduce end to end delay, delay variation and packet loss ratio [22] [23] [24] [64]. It was found in [24] that the performance of multipath outperforms multiple descriptions techniques.

Additionally multipath serve as a mechanism to distribute the load through the available paths by many ways; either by using the path until it fails, by using the available paths alternatively or by using all available paths simultaneously.

MANETs must support multimedia and time sensitive applications as these are growing in an exponential behavior, to support such applications MANETs need to provide the QoS required by the user, to do so multipath is employed to compensate for limitations in MANETs [25]. Nonetheless, multipath routing protocols have more overhead per each route discovery process since it finds more than one path in each route discovery process.

2.3 Disjointness

Multi-path routing protocols could establish node disjoint or link disjoint routes through the network. Node disjoint paths have no node or link in common provide higher degree of fault tolerance than link disjoint paths, since node failure in link disjoint can cause many links to fail while node failure in node disjoint will cause only one link to fail; links fail independently. However, node disjoint routes are stricter, therefore, less abundant than link disjoint routes and harder to find [22] [23].

Nonetheless, if the aim is to accomplish load balancing then node disjoint paths are more effective also node disjoint can increase the life time of the whole network by avoiding draining the resources of a node that is located in strategic location as node I in Figure 2.5.

Suppose that node S needs a path to destination D, as can be seen S has two link disjoint paths to D; S-A-I-E-D and S-B-I-F-D but one node disjoint path to D since I is common node between the two paths. Since I is part of two link disjoint paths this can cause node I to reach exhaustion point and causes I to use its resources in a very short period of time which might cause node I to fail and hence all paths through I fail increasing the number of dropped packets and causing

longer delays which may also lead to network partitioning this is similar when a node participating in more than one path move out of range due to mobility, hence the choice was to choose node disjoint multipath routing protocol.

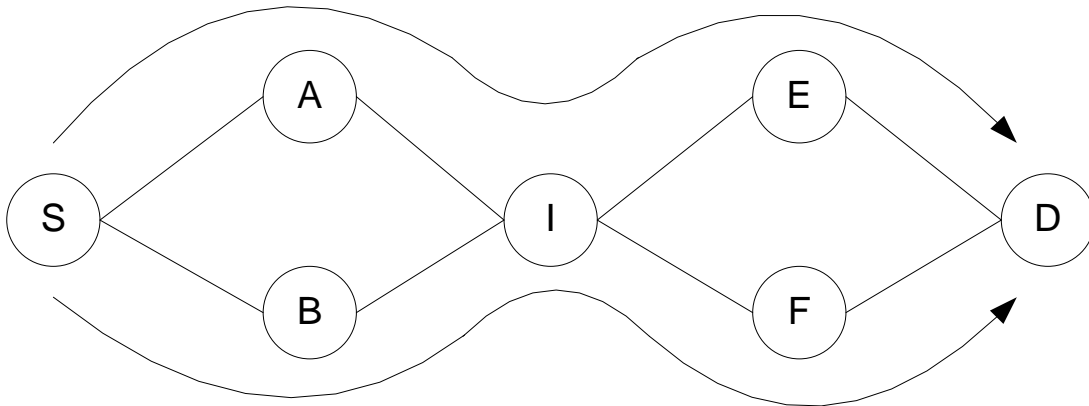


Figure 2.1 Node vs. Link Disjointness

It is worth pointing out that disjointness in this work is different from disjointness in graph theory; disjointness here means between source-destination pair and so all available paths between such pair are disjoint, however, different source-destination pairs may have common links in case of link disjoint paths and common nodes in case of node disjoint paths, this is the same as most disjoint multipath routing protocol in literature [26] [27] [28]

2.4 Table Driven: Proactive Routing Protocols

Table driven or proactive routing protocols; are protocols that allow nodes in the network to have a complete knowledge of the entire network topology at all times, where each node has a path to any other nodes in the network regardless if there is a need for such path or not. Proactive protocols minimize the route discovery time; however, networks that adopt such protocols will suffer from high routing overhead and decrease network capacity especially in the case of large

size networks. Two major algorithms are commonly used in proactive protocols; link state and distance vector.

Link State Protocols:

Each node maintains up to date knowledge of network topology through flooding the network with control packets that carry the state of the link in terms of cost to all one hop a way neighboring nodes [29]. Each node in the network broadcast a packet of the link state that has the node identifier (ID), a sequence number, time to live (TTL) for the packet and one hop away neighbors with the cost to each of them. The mechanism of such protocols consists of two phases; flooding; where link state broadcasted and creation of paths based on the information from the flooding phase, usually the second phase is based on shortest path algorithm [29] [30]. One of the most used link state protocols in research is Optimized Link State Routing (OLSR) [31].

Distance Vector Protocols:

Each node in distance vector based routing protocols knows the distance to its one hop a way neighbor [29] [30]. Each node in the network creates a list of distances to all one hop neighbors and broadcast it, if the node is more than one hop a way it assigns infinity to that neighbor. One of the drawbacks of such protocols is the slow convergence of paths in the network. However, distance protocols are less complex than link state and have lower bandwidth requirements [29]. The most common distance vector protocol is the Destination Sequenced Vector routing (DSDV) [32].

2.5 On Demand: Reactive Routing Protocols

On the contrary of proactive routing protocols, reactive protocols don't keep track of network topology at all times. Nodes know the topology on demand or as needed. Reactive protocols

have two main phases; the route discovery and the route maintenance phases. A source node that has no route to another node (i.e. destination) and wishes to communicate with, initiates a route discovery phase by flooding the network through the broadcasting of a RREQ packet towards the destination. A node builds its routing table during this phase, when an intermediate node receives a RREQ packet and it is not the destination node and has no routing information about the destination; it rebroadcasts the packet to neighboring nodes. When the RREQ packet reaches the destination, the node generates a RREP packet back to the source through the previously path traversed by the RREQ packet. During the maintenance phase routes status are maintained through a RERR packet when a link/node failure is detected and by means of acknowledgements; if a node doesn't send an acknowledgement for a packet that it has received, during a certain time window a route error is sent back to the source which results in invalidating the path and using an alternate path in case of multipath or initiating a route discovery process in case of a single path. One of the most researched on demand protocols is the AODV, which is discussed in more details as it is the core protocol to the work presented in this document.

AODV:

AODV is one of the most studied on demand reactive routing protocols [7] [33]. Sequence number plays an important role in AODV and serves as a time stamp. Each node maintains a monotonically increasing sequence number, every time a node generates a routing message it increments its sequence number. The node also keeps the highest known sequence number for each destination in its routing table. The highest sequence number means a fresher up to date route.

When a source node *S* needs to communicate with a destination node *D* in the network and *S* does not have a route to *D*, it initiates a route discovery process that starts by broadcasting a RREQ packet tagged with a sequence number to achieve limited flooding of the RREQ. Every node that receives the RREQ checks its routing table to see if it has a route to *D*. If it does, it sends a RREP back to *S*; otherwise it rebroadcasts the RREQ incrementing the hop count by one. This way, when a node receives several RREQ through multiple routes, it discards RREQs that result in a higher hop count. Intermediate nodes between *S* and *D* create an entry for the neighbor ID in its routing table from which the RREQ was received. The destination *D* responds to the first RREQ it receives by unicasting a RREP, intermediate nodes forward the RREP back to the source according to their routing table.

Every node maintains an entry in its routing table that updates the route expiry time. Every route is considered valid for a certain time after which the route entry is deleted from the routing table. Whenever a route is used to forward data packets the route expiry time is updated to the current time plus the Active Route Timeout. When a route expires the node deletes the entry for the route and invalidates it. When a link to the next hop is broken the node generates a RERR message to all nodes listed as active neighbors to the node in its routing table and invalidates all routes through the link [34] [35] the node increments the sequence number and sets up the hop count to ∞ making AODV loop free at all times, for more details see [7] [36].

2.6 Hybrid Routing Protocols

To deal with the dynamic nature of MANETs and minimize routing overhead as well as reducing delay, hybrid routing protocols that have mixed characteristics from both reactive and proactive protocols were devised [37]. These protocols use the reactive mechanism with nearby nodes and proactive mechanism with distant nodes by dividing the network into regions or zones. Hybrid

protocols decrease number of control messages during route discovery process [38]. Hybrid routing protocols have many advantages; it shows performance improvement, however, nodes requires more knowledge of the network topology. One of the earliest routing protocols that adopted such scheme is the Zone Routing Protocol (ZRP) [39].

2.7 Multipath Routing Protocols

Multipath routing protocols is a natural choice for handling MANET's environment, where the wireless link is unreliable to improve route resilience [40]. Nodes in multipath based routing protocols are able to establish and maintain more than one path between source-destination pair increasing the aggregate bandwidth, packet delivery ratio, minimizing end to end delay and balancing the load throughout the network. Multipath routing started back in the 1990s when radio networks used the idea of alternate path; when the neighboring node fails to forward packets [41] [42]. Multipath is essential for QoS. Reactive routing protocols are more desirable for multipath due to efficient healing from path failure. Many multipath protocols have been proposed in literature based on the single path AODV protocol. As a modified multipath version of AODV, the authors in [43] proposed Ad hoc on demand Multipath Distance Vector (AOMDV). AOMDV establishes link-disjoint and loop-free paths based on the minimum hop count similar to AODV criteria. Link-disjointness is achieved by a special flooding mechanism, while loop-freedom is ensured by using the notion of advertised hop count value at node N for destination D; this value represents the maximum hop count at N available for D. As a result, alternative paths at node N for D are accepted only if they have a lower hop count than the advertised hop count.

In [44] the authors proposed AODV-Multipath (AODVM), which finds multiple node disjoint paths with no limit on the number of paths. Duplicate Route RREQ for the same source-

destination pair is not discarded instead recorded in the RREQ table, the destination consequently replies to all RREQs. When intermediate node overhears broadcasting of a RREP message from neighboring node, it deletes the corresponding entry of the transmitting node from its RREQ table. When an intermediate node receives a RREP which it cannot forward any further it generates route discovery error message to the node from which it received the RREP; this node will try to look up an alternate path from its table to the source. Even though, the protocol finds many paths but it incurs high overhead and has a low packet delivery ratio in high mobility scenarios.

The Shortest Multipath Routing Using Labeled Distanced (SMLDR) uses the shortest path regardless of the link quality [45]. SMLDR introduces a metric called limiting distance; that is the minimum distance to the destination known at each node.

AODV Backup Route (AODV-BR) proposed in [46], this is an extension of AODV with a backup route in case of the primary route failure without considering the link quality also it has been shown that the protocol does not perform well in heavy load conditions.

QoS AODV (QS-AODV), which considers delay joint with hop count as a criterion for choosing the route proposed in [47]. Nonetheless, the protocol does not consider the dynamics of MANET; such as topology changes due to mobility and/or link /node failure that will lead to changes in the estimated delay. The authors in [48] proposed Caching and Multipath (CHAMP) routing protocol. CHAMP uses the joint packet caching and shortest multipath routing to minimize packet loss ratio due to route failure.

2.8 Summary

This chapter laid the necessary background about many topics related to the work proposed in this document. The chapter talked about routing problem in ad hoc networks; classification based on the knowledge of network topology presented, also a brief review of advantages and disadvantages of single path versus multipath approach were discussed; in addition the meaning of disjointness in routing and types of disjointness such as link and node disjointness along with which type suits the purpose of the routing protocol, if the goal is load balancing then node disjoint is the correct choice while if the goal is to improve fault tolerance then, link disjoint is the choice. Last, several multipath routing protocols proposed in literature were presented, multipath protocols based on the single path AODV protocol are of special interest since the work proposed in this document is a modification of AODV.

3 AN INTEGRATED FRAMEWORK FOR QoS SUPPORT IN MANETs

The proposed frame work consists of three interdependent modules including QoS module, QoS cross-layer module and routing module that meets the QoS requirements at multiple layers in the protocol stack including the physical (PHY), Medium Access Control (MAC), and the network layers.

3.1 QoS Architecture Module

The QoS module defines the service architecture of the overall QoS framework. This work focuses on real time applications that require a certain QoS level. The QoS module supports the services on a per connection /flow basis. The main QoS metrics used by the module are end to end delay, packet delivery fraction and route discovery frequency.

QoS-aware architecture; to fulfill this requirement is to be able to find path with sufficient resources and including links in the paths that are stable and reliable to meet QoS constraints.

The main quality impairment for delay sensitive application voice is delay. ITU-T G.114 recommends [49] the one way transmission time between 0-150 ms delay is acceptable for voice.

The time when a frame is generated at the source until it reaches the destination is the end-to-end delay. ETE delay consists of packetization, queuing, propagation, transmission, and play out delay. Play out delay is the time a packet spends in the buffer at the destination for smooth play out as in Figure 1.3 [50].

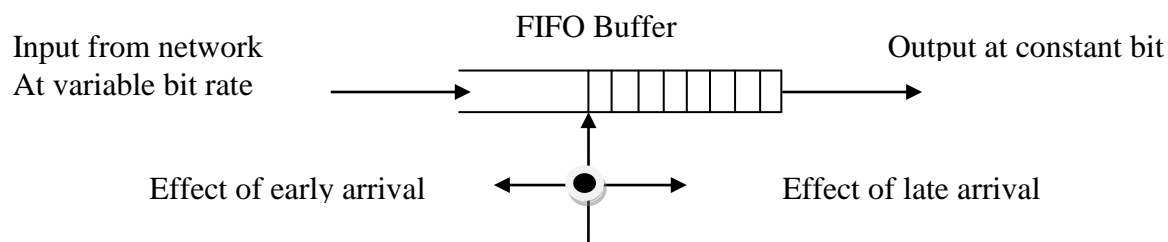


Figure 3.1 Play out Buffer

Bit Error Rate (BER) as a function of Signal to Noise Ratio (SNR) which is a function of distance that translates into modulation reflects the link quality and stability. Figure 1.4 [51] shows BER vs. SNR for five digital modulation schemes: binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and quadrature amplitude modulation (QAM) with different number of bits per symbol

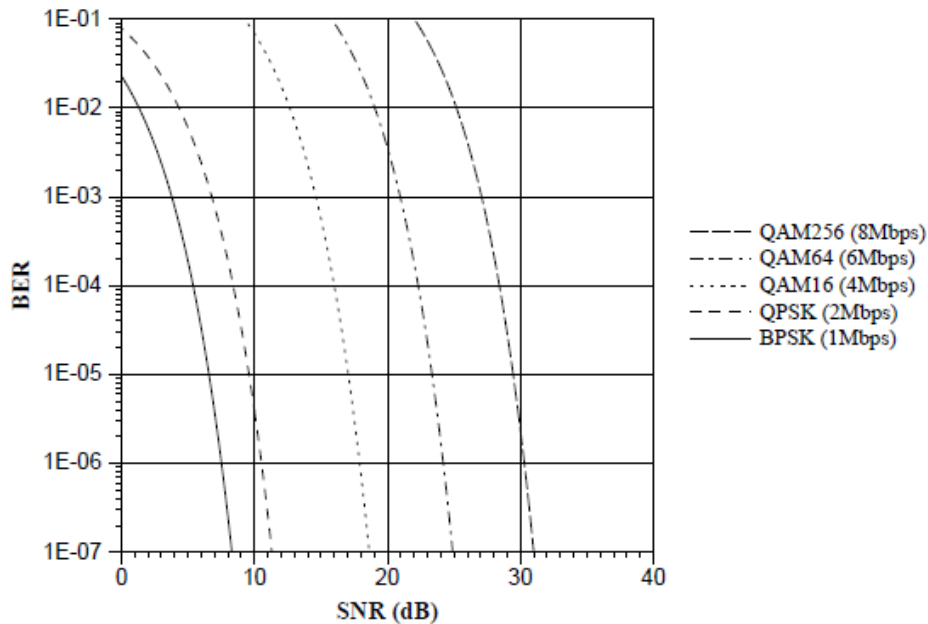


Figure 3.2 BER vs. SNR

QoS in MANETs is an active area in research community since it is more challenging than in wired networks as previously explained. A QoS requirement for an application is to be able to guarantee certain requirements such as delay, delay variation, packet loss ratio and bandwidth for a specific connection. QoS must be fulfilled end to end as well as hop wise communication along the path, this cannot be achieved unless there is cooperation across different layers in the protocol stack.

3.2 Cross Layer Module

Cross Layer Design (CLD) was born due to the limited capabilities of the traditional layered architecture to cope with the distinctive nature of wireless communications. CLD refers to the communications and channel information exchange between none adjacent layers in the Open System Interconnection (OSI) [52] model to exploit the efficiency of wireless communications and improve the performance of wireless networks that suffer from many limitations due to the nature of the wireless medium [16] [53], which means it is a new methodology to design protocols.

To accomplish a better performance gain, interaction and exploitation of dependence between different layers in the OSI model [16], CLD is a must as compared to traditional layered approach [54] [55] [56] [57] [58] [59]. Moreover, for MANETs to have the same robustness and resilience in cellular networks dealing with the dynamic, unpredictable conditions and high error rate of the wireless channel cross layer design through the adaptation to this nature [60] [61] is necessary. Most CLD solutions are by passing some parameters (Channel State Information CSI) from lower layers (i.e. PHY and MAC) to upper layers such as transport and routing layers and vice versa. Protocols that use CSI throughout different layers in the OSI layered architecture in order to enhance their performance by adaptively adjusting their behavior according to the channel state; this enables different layers to have a global knowledge and awareness of the whole network resources availability as well as the constraints of the wireless network.

Cross layer design has its pros and cons; on one hand it violates the traditional layered OSI model compromising the independence of different layers in the model. On the other hand,

nevertheless, cross-layer design addresses issues arising from the nature of the wireless medium which cannot be addressed otherwise; such issues include the broadcast nature of the wireless networks; the channel response time variations.

Many schemes that used cross layer approach have shown performance gain over the traditional layered model as in [54] [55] [56] [54]. In [16] taxonomy for cross layer design based on the violations in the OSI model have been proposed, four different schemes for cross layer design have been identified; (i) integration of adjacent layers, (ii) formation of new interfaces between layers, (iii) merging without new interfaces, (iv) across layers vertical calibration.

The proposed approach includes the PHY, Medium Access Control (MAC) and network layers, where channel state CSI is exchanged between different layers while maintaining the structure protocol stack. Cross layer design is necessary for the protocol design in MANETs; this is due to the dynamic nature of MANETs, to fulfill the requirements of applications in terms of QoS and to deal with the power limitations and security issues arise from the nature of the wireless medium. The previous reasons mandate the cooperation across the OSI layers in order to provide an optimized solution to solve the aforementioned problems.

Physical and MAC cross layer interaction for example signal to noise ratio affects the contention at the MAC level so, in this work the interaction between the two layers is adopted in order to reduce the effect of this problem. Physical and routing layers interaction; many routing protocol choose the link based on minimum hop-count and without considering the link quality. Minimum hop-count is not an optimal solution as it has been concluded in [62].

MAC and routing layers interaction: Routing protocol may affect the MAC protocol and the opposite is true, for example the contention at the MAC level where more than one node tries to seize the channel, this affects the routing decision at the routing layer in case the contention takes

too long the routing layer might initiate a new discovery process and invoke the routing table updates.

The QoS cross-layer module proposed here ensures that the three layers must work and coordinate together in a collaborative and complementary fashion in order to satisfy the QoS requirements of the underlying applications. The PHY layer provides the channel-state information, e. g., SNR, while the MAC layer provides mechanisms for resolving medium contention as well as real time traffic support, which ensures reservation at the link level only. The network layer ensures end-to-end resource negotiations, reservation, and reconfiguration.

The proposed QoS cross-layer module is general and works with any application as well as any routing protocol that supports multipath as shown in Figure 3.1. The proposed QMRP extracts the Signal to Noise Ratio (SNR) from the physical layer (PHY) and passes it to the MAC layer where the later compute the actual transmission rate out from the node and the queue size where delay computation occurs by passing these values to the routing layer to find the path with the lowest delay between source-destination pair to assure QoS based on link quality.

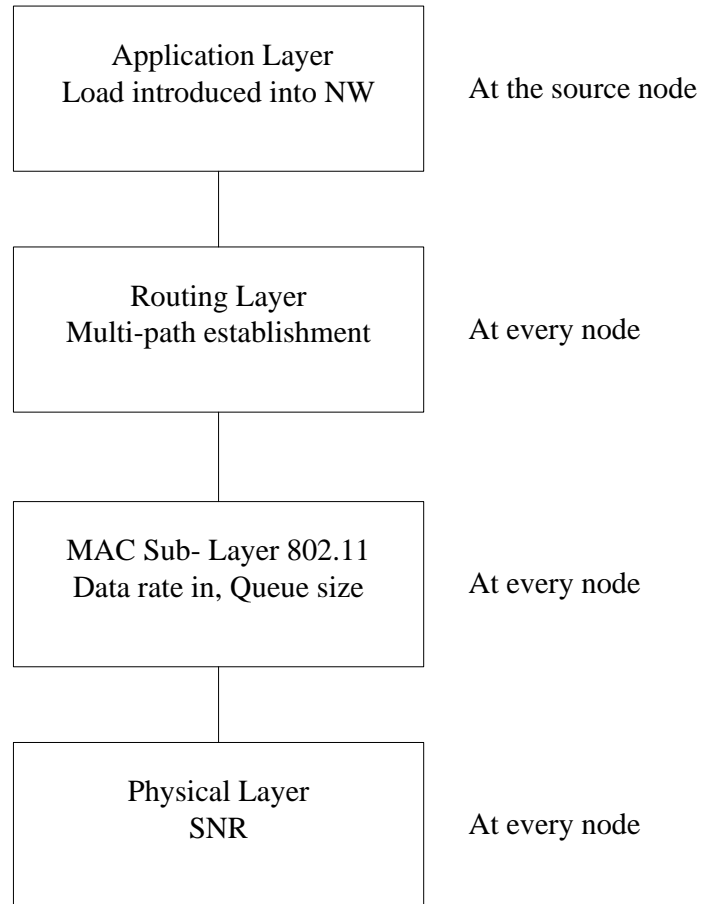


Figure 3.3 Cross Layer Module: System Architecture

3.3 QoS-Aware Multipath Routing Protocol (QoS Routing Module)

This section describes the dynamics and details of QoS-Aware Multipath Routing protocol (QMRP) which computes multiple node-disjoint paths based on the feedback from the physical and MAC layers. QMRP improves AODV significantly by modifying the phases of route discovery, route selection and route maintenance. In this work route broadcasting refers to RREQ/RREP. Figure 3.2 shows the dynamics of the protocol.

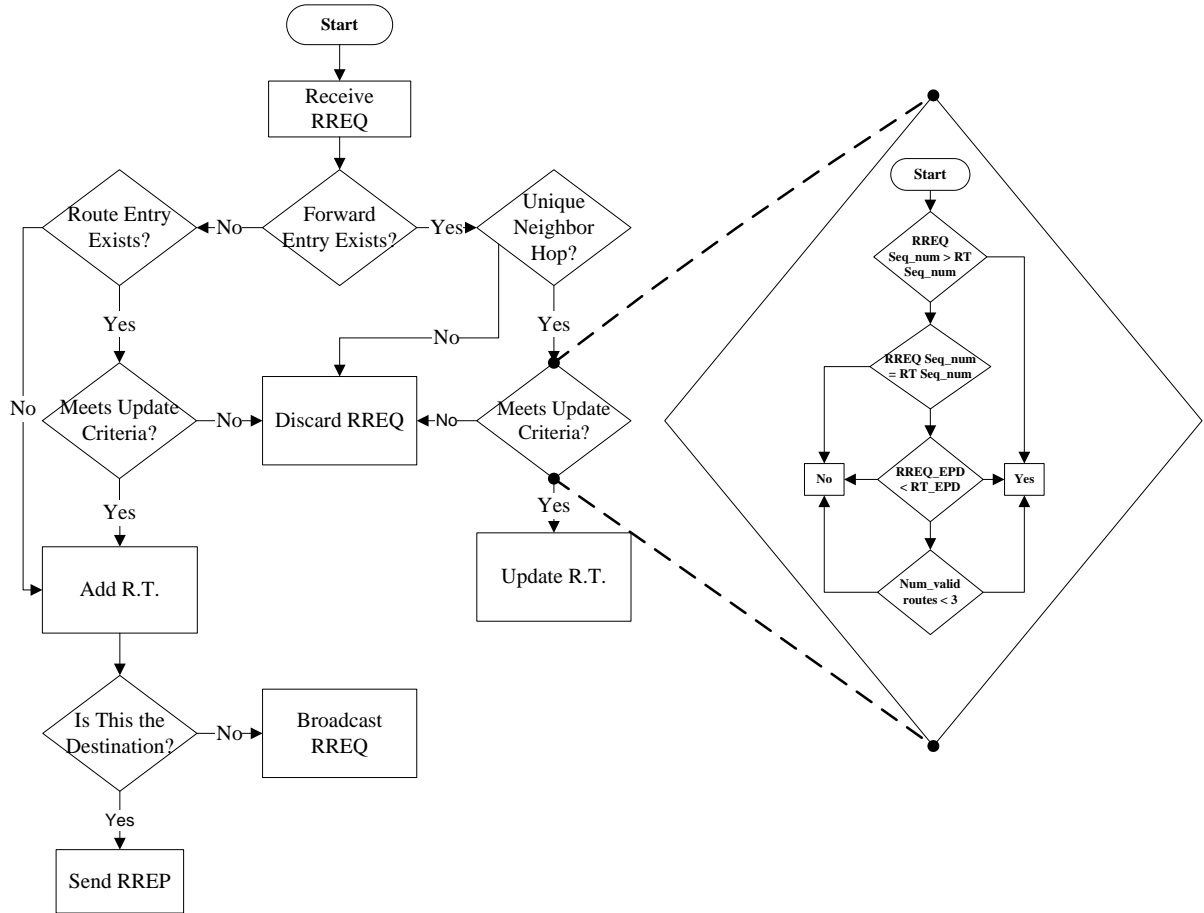


Figure 3.4 Dynamics of QMRP

The QMRP protocol establishes multiple node-disjoint paths that will experience the lowest delay. Most delay-aware routing protocols in literature use the current delay or history to estimate end-to-end delay as a metric. However, this is not an accurate measure of the delay that is going to be experienced by the route-requesting node since this node will increase the total network load. Once the network load increases, ETE delay that was obtained through route broadcasting is no longer accurate. Introducing the projected increase in load into the computation of delay a more accurate delay value will be obtained once the node starts injecting its traffic into the network. The protocol phases are explained below.

3.3.1 Route Discovery

The route discovery process of QMRP starts when node S needs to communicate with another node D and S does not already have a path to D, S broadcasts a RREQ tagged with a sequence number to achieve limited flooding of the Route RREQ. In AODV every node that receives the RREQ rebroadcasts the RREQ incrementing the hop count by one. When a node receives several copies of the same RREQ, it uses only the first copy to form the reverse path; all duplicates that arrive later are discarded. Nonetheless, since the aim is to find multiple paths these duplicates of route broadcasting could be utilized to establish multiple paths, however, only those route broadcasting that guarantee loop freedom and node disjointness will be used to establish reverse paths.

QMRP introduces two additional fields to the route broadcasting packet the Expected Path Delay (EPD) field; which is the cumulative delay up to and including the node itself and a load field; which is the new load that will be added to the network by a node requesting a path to a destination. EPD is initialized to zero while the load initialized to the new amount of traffic that will be added into the network by the source requesting a path to a destination.

To guarantee loop freedom, (i) QMRP preserve the following update rule; keep paths for the highest known destination sequence number. When a route broadcasting packet received by a node with higher sequence number all paths correspond to lower sequence number will be invalidated. (ii) QMRP guarantees loop freedom by utilizing a neighbor hop list; a list of one hop away neighboring node of the source node that initiates a route discovery process by generating a RREQ requesting a path to a destination that is the first hop traversed by a RREQ. (iii) Maintaining the invariant that all nodes can only broadcast one copy of a RREQ per unique neighbor hop. A maximum of three route broadcasting with unique neighbor hop is allowed.

Obtaining the neighbor hop list is as follows if an intermediate node, I, receives a RREQ and the hop count is zero, the node checks the source of the RREQ and the node from which it received the RREQ if they match it increments the hop count and adds itself into the neighbor hop field of the RREQ and add an entry for the node from which it receives the RREQ. Every subsequent node on the path maintains a list of neighbors called neighbor hop list associated with every RREQ message received. When a RREQ is received the neighbor hop field of the RREQ is checked against the neighbor hop list before adding an entry for the path into the node's routing table. Additionally, before rebroadcasting the RREQ, intermediate node of S, I, increments the hop count of the RREQ and updates EPD field with its computed delay as in equation (1).

When a node receives duplicates of the RREQ with unique neighbor hop it records the information from these packets in a RREQ table which contains the following fields, source_id, dest_id, neighborhop_list which contains neighbor Id, EPD, last hop, Exp_timer. Where the source_id is the source that generates the RREQ, dest_id is the destination to which the RREQ is intended, neighborhop_list is the neighbor hop list, EPD for each neighbor in the list, last hop is the last hop on the path and Exp_timer is the expiration timer.

To explain how QMRP guarantees loop freedom using the neighbor hop list Figure 3.3 shows the source node S wants to communicate with destination node D, S broadcasts a RREQ packet to its neighboring node within transmission range, in this case nodes A and B will receive the RREQ. Each of A and B will add itself in the neighbor hop field in the RREQ and rebroadcast the RREQ, node I receives both RREQ from A and B and accepts both of them since they arrive via different neighbor hop of the source node S, now node C receives the RREQ from node B with neighbor hop field B and broadcast it, node I receives it and checks the neighbor hop field which

is B in this case against its neighbor hop list, however, node I has already received a RREQ with the same neighbor hop B so it discards the packet and don't broadcast it any further.

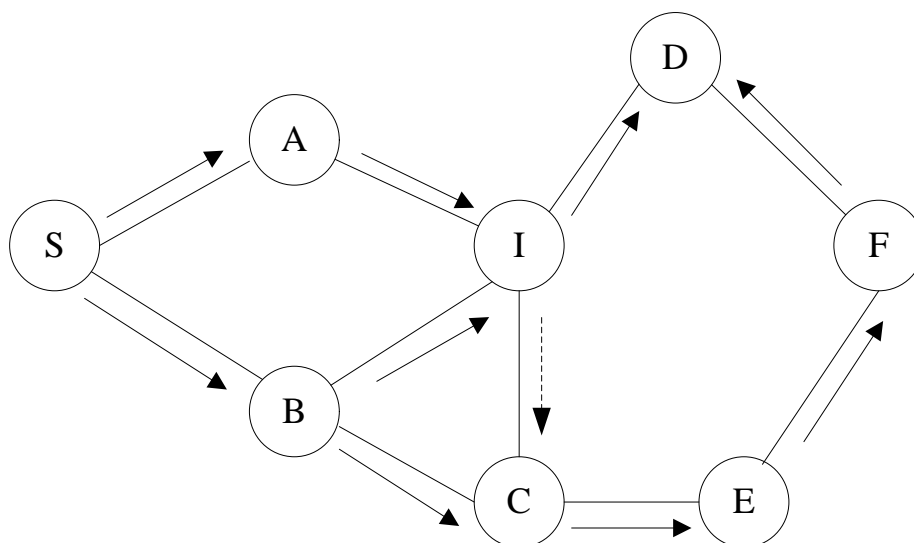


Figure 3.5 Neighbor Hop List

In order to update the node's routing table, an entry is only added or updated if route broadcasting satisfies any one of the following criteria: (i) No route entry exists for the originator of the route broadcasting. (ii) Sequence Number of the route broadcasting packet is greater than the sequence number of the existing route entry. (iii) Sequence numbers are equal and the EPD of the route broadcasting is less than the EPD of the existing route entry and number of valid RREQs is less than three.

Route Reply

If a node receives a RREQ and it is the destination of the RREQ, the node adds/updates the entry in its routing table and generates a RREP. The RREP is unicasted back to the source node and the EPD field of the RREP is initialized to zero. Subsequent nodes that receive the RREP maintain their routing table according to the conditions specified, increment the EPD field of the

RREP with their computed delay up to and including the node itself, and then forward the RREP to the next hop towards the source node that was found through the reverse path during route discovery process based on the minimum EPD; so the node checks its RREQ table and forward the RREP to the next hop with the lowest EPD.

When the destination receives subsequent RREQs from different last hops it generates a RREP to each distinct last hop and per unique neighbor hop. Additionally, all intermediate nodes can only forward one copy of the RREP per source and per destination sequence number; this is to guarantee node disjointness of the paths. If no reverse path is available, the RREP is discarded; this is also in case the node is already participating in an active path for the same source-destination pair. When the source receives all RREPs back from the destination; a maximum of three paths in this study, it uses the path with the lowest EPD value and saves the other two as a backup paths in case the primary path fails for any reason. However, the first discovered path is used immediately.

The EPD includes various parameters from the MAC; data rate received, current queue size, and SNR from the PHY layer that is reflected in the actual transmission out rate. The equation for computing the EPD is give by (3.1).

$$EPD = \sum_{i=0}^n \left[\bar{D}_i + \frac{\Delta t * (DR_i + l - Actual_Tx_{out(i)})}{Actual_Tx_{out(i)}} \right] \quad \text{Equation 3.1}$$

Where \bar{D}_i is the average queuing delay at a node and is given by (3.2)

$$\bar{D}_i = \alpha * \bar{D}_{j-1} + (1 - \alpha) * \bar{D}_j \quad \text{Equation 3.2}$$

Where α is the queue occupancy and is given by (3.3)

$$\alpha = \frac{queue_size - queue_length}{queue_size} \quad \text{Equation 3.3}$$

i : a node along the path

$queue_size$: is the size of the queue at node i

$queue_length$: is the length of the queue at node i

j : is the current period;

DR_i : data rate calculated based on all traffic received at node i , this parameter is passed from the MAC.

Δt : time difference between the current time and an arbitrary time after the new load has been introduced into the network, this can vary according to how long routes are expected to remain active based on mobility and active route timeout value, for simplicity purposes Δt is assumed to be 2 seconds.

l : is the proposed new traffic load that is added by the source initiating a route discovery process into the network.

$Max_Tx_{out(i)}$: represents the maximum data rate that a node can transmit at and given is by:

$$Max_Tx_{out} = Data_Tx_Rate * \beta * (1 - BER) \quad \text{Equation 3.4}$$

In this study we are taking the $Actual_Tx_out$ actual transmission out from a node that is extracted from the MAC layer, which is based on the above equation (3.4).

$Data_Tx_Rate$: rate at which a node is able to transmit/receive

β : network efficiency factor, which is typically between 0.7-0.8.

BER: Bit Error Rate.

3.3.2 Route Maintenance

Route maintenance in QMRP is an extension to that of AODV and is achieved by the means of generating a Route ERRor (RERR) packet. When an intermediate node, I, discovers link/node failure; due to mobility, undetected hello packet, etc..., it generates a RERR packet. The RERR packet propagates towards all nodes that have a path through the failed link and invalidates all available paths in all nodes along the way that have a path through the failed link. When the RERR packet reaches the source and the source still in need for a path to the destination it switches to the second available path in the path list at the source node. If all paths are invalid and the source still in need for a path to the same destination the source starts a new route discovery process as explained previously in A.

Each path has an ID that is a combination of the neighbor hop of the source as well as the last hop on the path which is the previous hop to the destination. At periodic interval every $\frac{\Delta t}{2}$ the source unicasts an update path packet (UPP) to check the status of the path with EPD value initialized to zero towards the destination, when the destination receives the update path packet it initializes the EPD to zero and send it back to the source when the source node receives the update packet it checks the EPD field against the other EPD for alternate paths in its routing table. The preemptive handoff basically takes place when the path EPD value increases and the routing table has a lower EPD for another path it switches to the path with lower EPD; this is in order to maintain QoS for the life time of a connection and always use the best available path in terms of EPD as the primary path for data transmission Also, QMRP uses a salvaging mechanism where packets transmitted over failed path are retransmitted over back up paths.

3.3.3 Packet Forwarding

In this work packets are forwarded along the path with the lowest EPD as in equation (3.1), once the source receives the first RREP from the destination it starts sending packets and after it receives the subsequent RREPs it checks the value of EPD and forward packets over the lowest EPD path, this way the most reliable path is always used, also using the update packet for the status of the path assures that the path with the lowest EPD is always in use.

This strategy is different from many routing protocols that use the primary path until it fails then switches to the secondary back up path until it fails and so on. However, there are other approaches exist for forwarding packets in other routing protocols. One of these is to use all available paths simultaneously where packets are sent along all available paths, this improves utilization of network resources and decreases end to end delay. This approach is beneficial for load balancing, but an issue of packets reordering arises from sending traffic along all available paths.

Another approach is by sending traffic in parallel through available paths. In [63] an overhead is added to each packet then splitting the coded packet into smaller blocks and transmitting the blocks along different paths.

3.4 Summary

In this Chapter, the architecture which works with any single or multipath protocol and the dynamics of the proposed protocol QMRP has been presented. All phases of the protocol are explained; from the initiation of route discovery process by broadcasting a RREQ packet when a source node needs to communicate and establish a path to a certain destination in the network in order to transmit data to the moment that the destination node receives the last packet in the data session, going through all different phases in between; establishing reverse route, receiving the RREP, establishing multiple paths, forwarding data and maintaining the routes by using an update packet to keep in use the best path available in terms of EPD; which incorporates many factors from different layers to provide QoS for time-sensitive applications.

4 PERFORMANCE EVALUATION OF QMRP

4.1 Simulation Environment and Parameters

OPNET [64] simulation package is used to analyze the performance of the proposed QMRP protocol and compare it with the AODV. The random way point mobility [65] model is used as the mobility model. Constant Bit Rate (CBR) where generated by all nodes of size 512 bytes each plus headers of different layers (UDP/IP/MAC). All different traffic connections set up between source-destination pairs are at random. The rest of the simulation environment parameters are summarized in the Table 4.1.

Table 4.1 Simulation Parameters for QMRP

Parameter	Value
Transmission Range	250 m
Simulation Time	500s
Simulation Area	1200 m x 600 m
Number of nodes	50
Number of Transmitting nodes	Varies between 5-40
Traffic Type	CBR
Packets Generation Rate	3 packets/sec
Mobility Model	Random Waypoint
Speed	Varies between 5-25 (m/s)
Pause time	0 s
Channel rate	2 Mbps
Packet Reception Power Threshold	-95 dBm
Wireless channel model	Error free, bidirectional

4.2 Performance Metrics

The following four key metrics considered to evaluate the performance of the protocols.

- 1) Average ETE delay: is the difference in time between the reception of a packet by the destination and the moment it was generated by the source; it includes all possible delays encountered by a packet.
- 2) Packet Delivery Fraction: is the amount of traffic received successfully at the destination as a fraction of the traffic generated by the source node.
- 3) Route Discovery Frequency: number of all RREQ packets generated per sec by all sources
- 4) Normalized Routing Load: is the number of control packets (RREQ, RREP, RERR, update path) transmitted per data packet delivered at the destination, each hop wise transmission is counted as a new transmission.

4.3 Results and Discussion

1- Varying mobility: (experiment I)

The first set of experiments Figures (4.1-4.4) show the four key performance metrics as a function of mobility; speed m/s. Traffic is 20 connections through the network and the speed varies between 0 static to 25 m/s, the rest of parameters are given in table I. Each reading across all scenarios and experiments is the average of 10 runs. Figure 4.1 depicts average ETE delay. QMRP has about 30% improvement over AODV in average ETE delay at high speed; this is due to the fact that AODV path selection criteria is based on minimum number of hops between source-destination pair regardless of the nodes status along the path. On the other hand paths in QMRP are established based on the EPD. QMRP avoids congested nodes by choosing paths based on minimum EPD instead. QMRP considers delay encountered at each node into the

computation of the EPD when establishing paths between a source–destination pair. The EPD includes not only the current delay, but also the expected delay due to the new load introduced by the source node into the network as well as queuing delay the most contributive factor in ETE delay. Due to mobility frequent link breaks occur in an environment such as MANET which causes AODV's need to initiate additional route discovery process/es to continue transmission. During the search for a new route packets are being delayed and/or dropped.

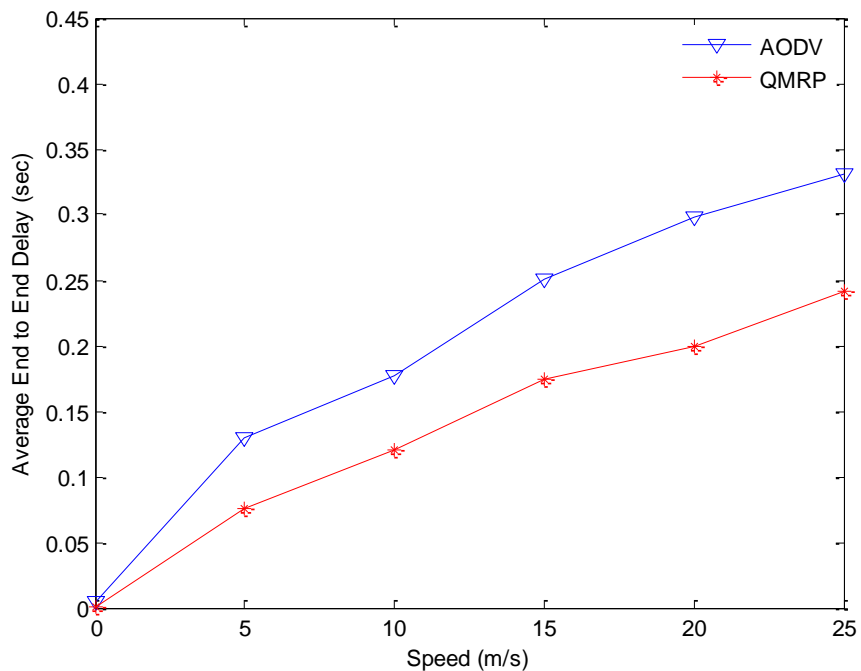


Figure 4.1 Average End to End Delay (varying mobility)

Figure 4.2 shows packet delivery ratio; the difference between the single path AODV and QMRP is about 27% increase in successfully transmitted packets this is due to the fact that QMRP is a multipath protocol and takes into consideration the channel reliability through the SNR from the PHY layer and queuing delays at each node along the path as per to equation (3.1).

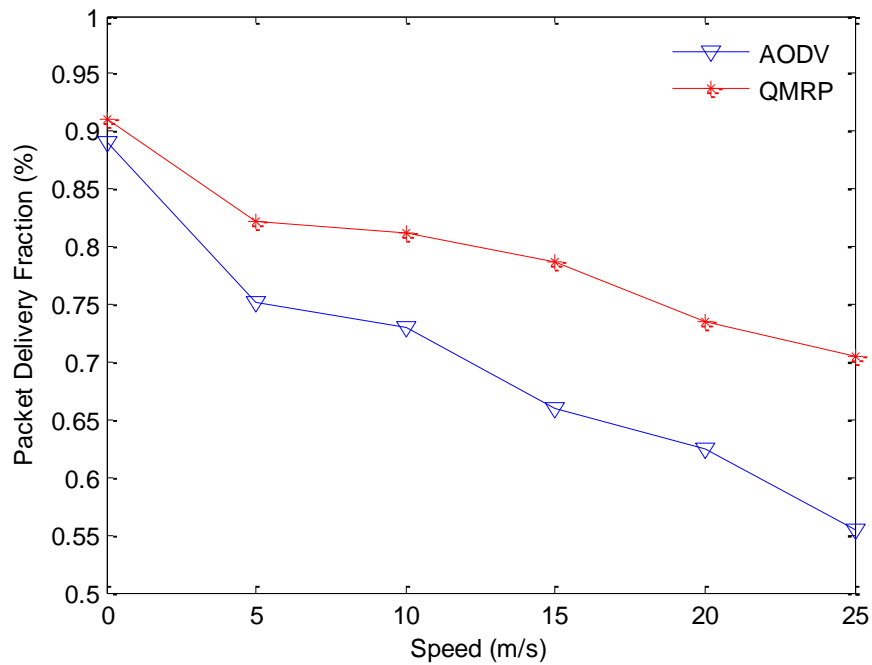


Figure 4.2 Packet Delivery Fraction (varying mobility)

Most of the proposed routing protocols such as AODV don't consider channel conditions, load balancing causing heavily loaded nodes along the path between source-destination. As a result heavily loaded nodes with longer queues will cause longer delays. Also this may cause congested nodes to exhaust their power energy quickly causing failure of sessions, more dropped packets and may lead to network partition. QMRP decreases the number of dropped packets due to the fact that the protocol allows self load balancing by avoiding bottle necks along the path when establishing multiple paths based on many factors included in equation (3.1). Therefore, packet losses are due to mobility as well as node/link failure as mentioned previously.

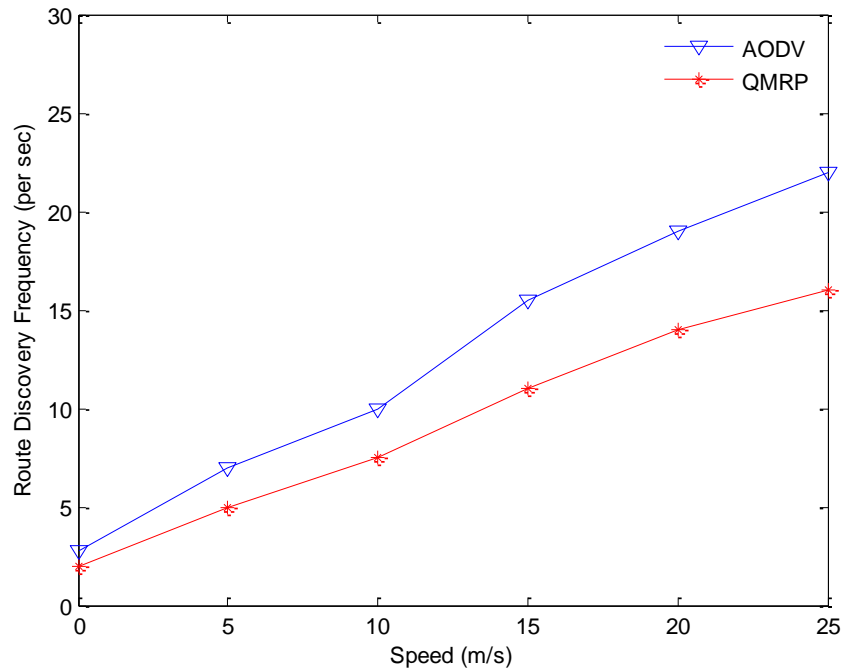


Figure 4.3 Route Discovery Frequency (varying mobility)

As can be seen in Figure 4.3 QMRP has around 30% less than AODV in terms of route discovery frequency. This is due to the nature of the single path AODV vs. multipath in QMRP as well as node disjointness that guarantees nodes/links fail independently. In addition path selection criterion in AODV can increase heavily loaded nodes along minimum hop count path which will also increase the probability of node failure and link breaks accordingly. Also, as mobility increases that will cause links to fail which means AODV has to initiate a new route discovery process during this search for an alternative path, packets are being queued; delayed and/ or dropped.

Figure 4.4 shows the normalized routing load, even though QMRP has less route discovery frequency than AODV, QMRP has more overhead per route discovery process due to more forward of control packets. However this overhead is relatively low.

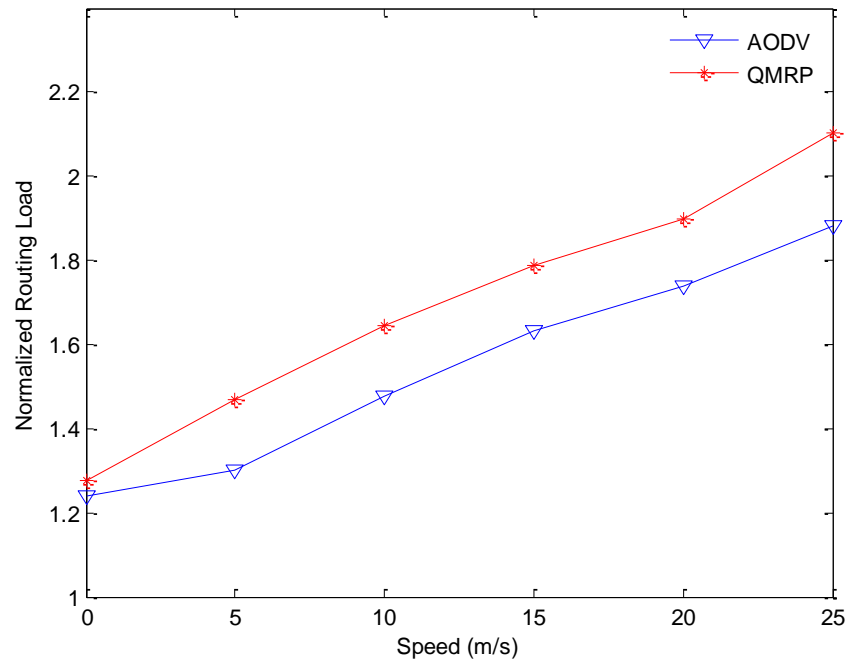


Figure 4.4 Normalized Routing Load (varying mobility)

2- Varying number of connections: (experiment II)

In this set of experiments Figures (4.5-4.8) the number of connections is varied between 0-40 connections and fixing the speed at 5 m/s and the load is fixed at about 245 kbps. increasing number of connections will test the routing protocol under tense conditions. The rest of parameters remain the same as in experiment I.

As the number of connections increases also does the average ETE delay for both protocols as in Figure 4.5, however, QMRP has the lower delay; this is due to the use of EPD in choosing the route. as in equation (3.1) shows it has parameters from the PHY and MAC layers, so the path selection criterion chooses more stable and reliable links, this means packets along more reliable paths encounters less ETE delay. In addition QMRP does self load balancing strategy by avoiding congested nodes with longer queues.

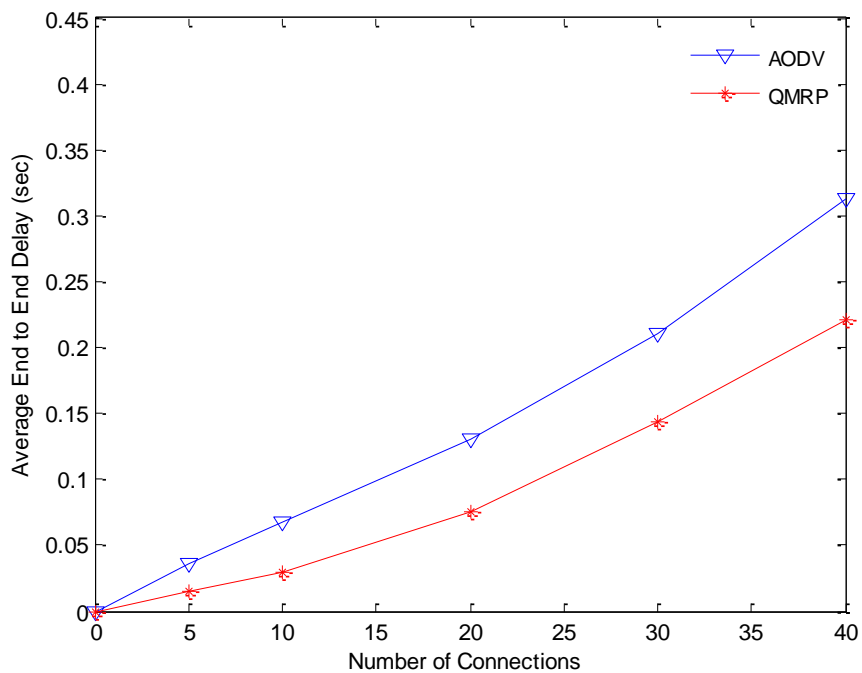


Figure 4.5 Average End to End Delay (varying connections)

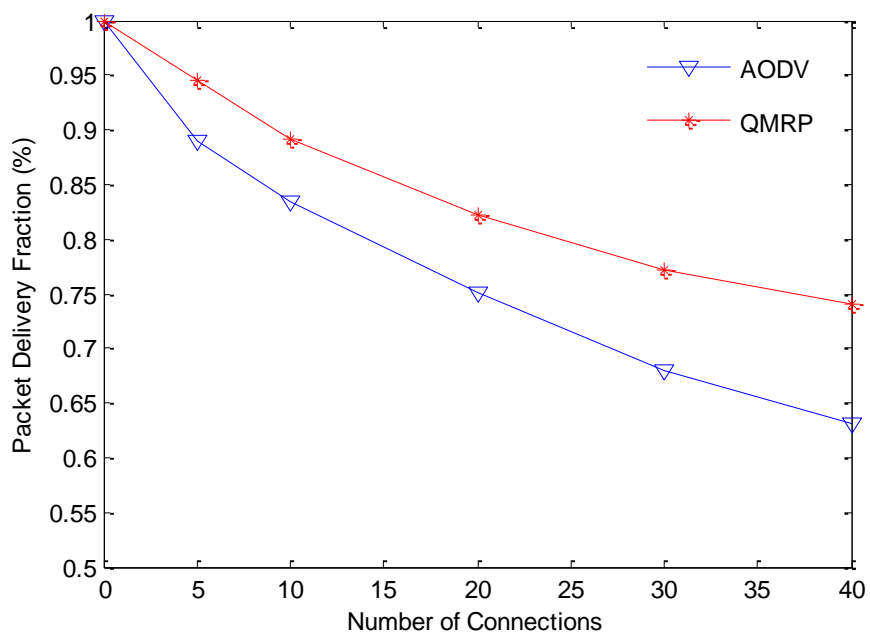


Figure 4.6 Packet Delivery Fraction (varying connections)

Packet delivery fraction shown in Figure 4.6 has the same behavior; as number of connections increases packet loss increases again with QMRP more packet delivered successfully, this is because QMRP has more reliable and stable paths so the probability of dropping packets decreases as compare to AODV. In the case of AODV which is based on minimum number of hops per route without considering the node's queue status and channel conditions causing congested nodes along the path which translates into longer delays and more dropped packets.

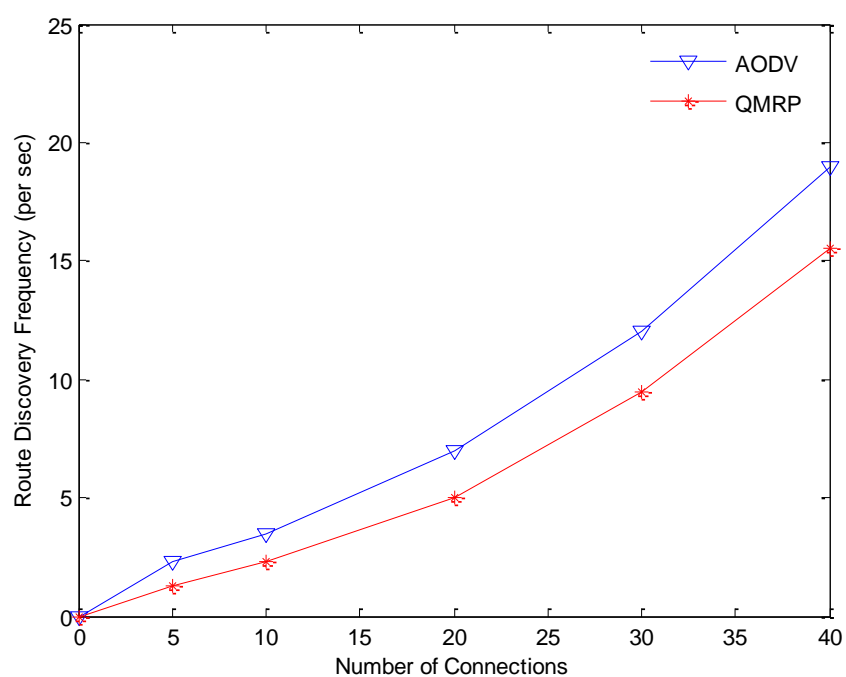


Figure 4.7 Route Discovery Frequency (varying connections)

Figure 4.7 shows that after 20 connections the difference increases significantly between AODV and QMRP in terms of route discovery frequency as a result of node failure and/or link break which means for the single path AODV a new route discovery process.

Even though multipath routing protocols less route discovery processes, still it has more routing overhead over all as compare to single path routing protocol such as AODV which is illustrated in Figure 4.8 QMRP has more routing overhead per each route discovery process, yet this

difference is insignificant; less than 10% only when number of connections is more than 30 connections.

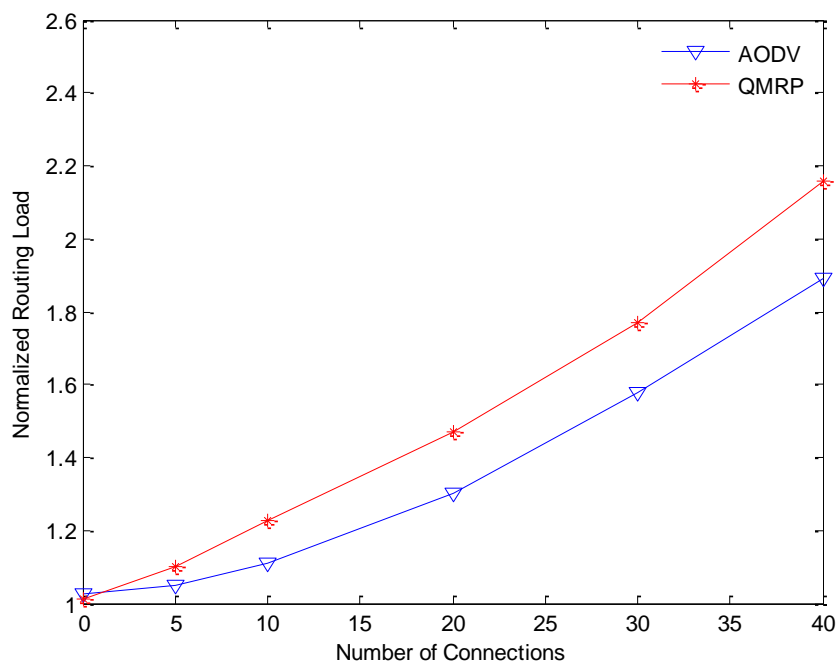


Figure 4.8 Normalized Routing Load (varying connections)

3- Varying Offered Load: (experiment III)

In this set of experiments the effect of offered load; packet generation rate on the performance of QMRP versus AODV is investigated. The speed of nodes in this experiment is fixed at 5 m/sec. and number of connections is 20, thus the only variable is the packet generation rate, the packet size in the previous two experiments I and II was fixed to 512 bytes, here the packet generation rate is varied between 0.75-3.75 packets/sec for each connection. Figures (4.9-4.12) shows the performance of both protocols in terms of the four metrics used in this study. As can be seen in Figures 9-12 as the offered load; packet generation rate increases performance of both protocols degrade. QMRP is better in terms of end to end delay, route discovery frequency and packet

delivery fraction as oppose to AODV, however, AODV performs better in terms of normalized routing load as discussed previously this is mainly due to the overhead involved in each route discovery process since the protocol finds more than one path in each process.

It's worth mentioning here that the performance degrades at low packet generation rate due to the fact that previously discovered paths between source-destination pair fail and/or expires by the time the source want to send traffic to the destination, this can be seen in Figures 4.11, 4.12 more routing overhead involved as well as more route discovery processes initiated at low packet low offered load.

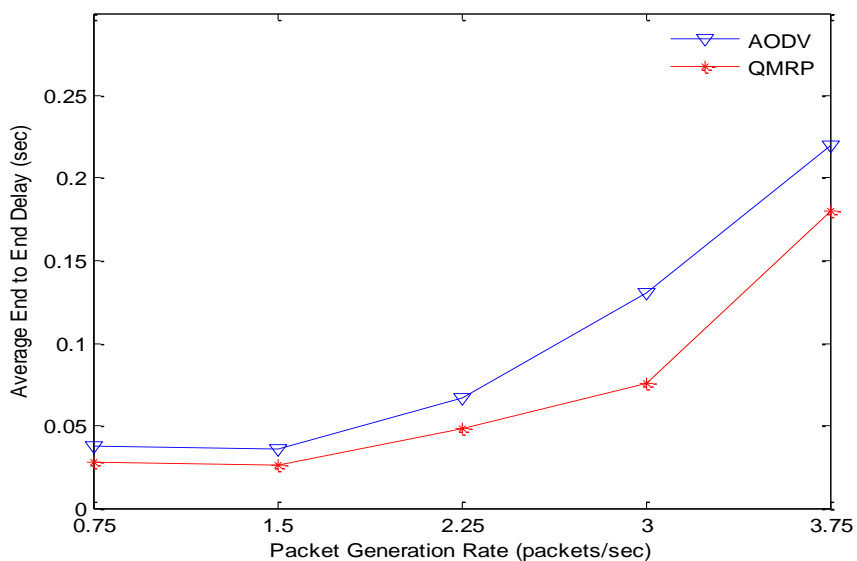


Figure 4.9 Average End to End Delay (varying load)

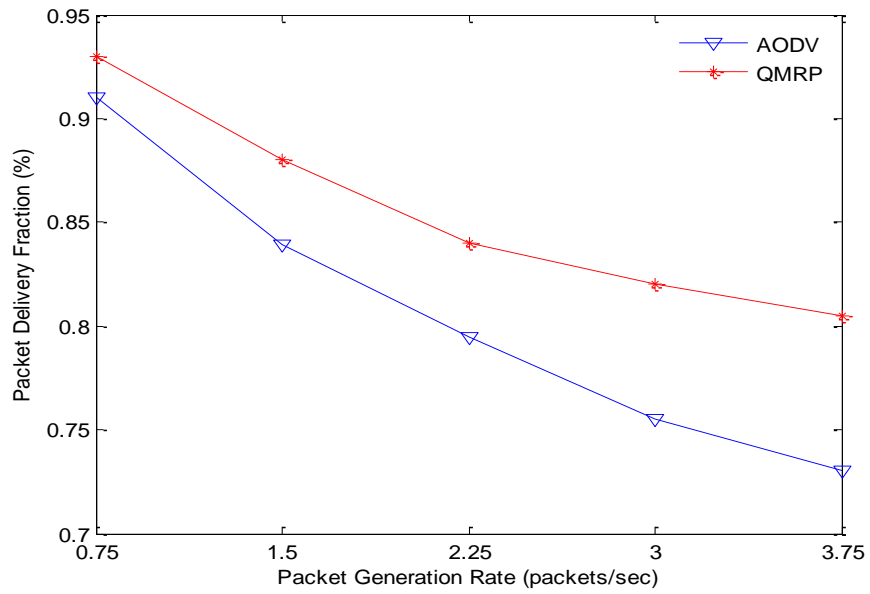


Figure 4.10 Packet Delivery Fraction (varying load)

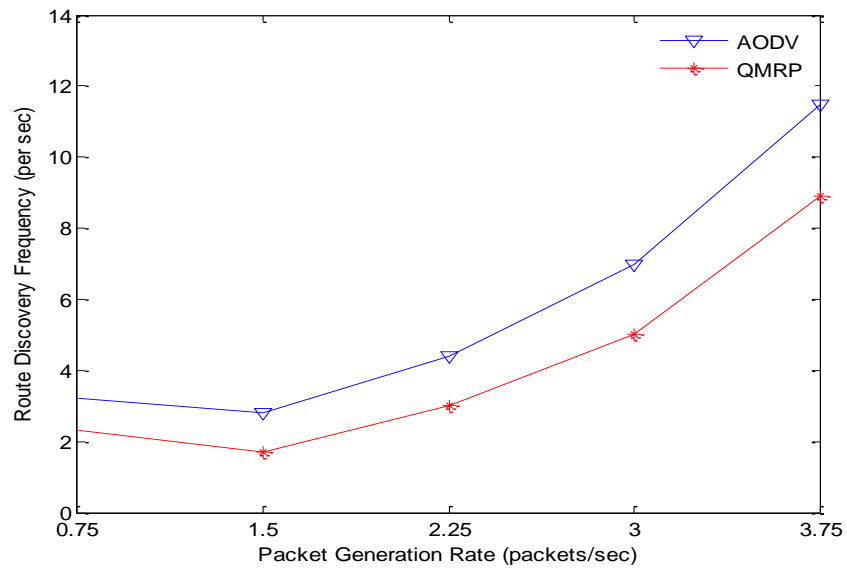


Figure 4.11 Route Discovery Frequency (varying load)

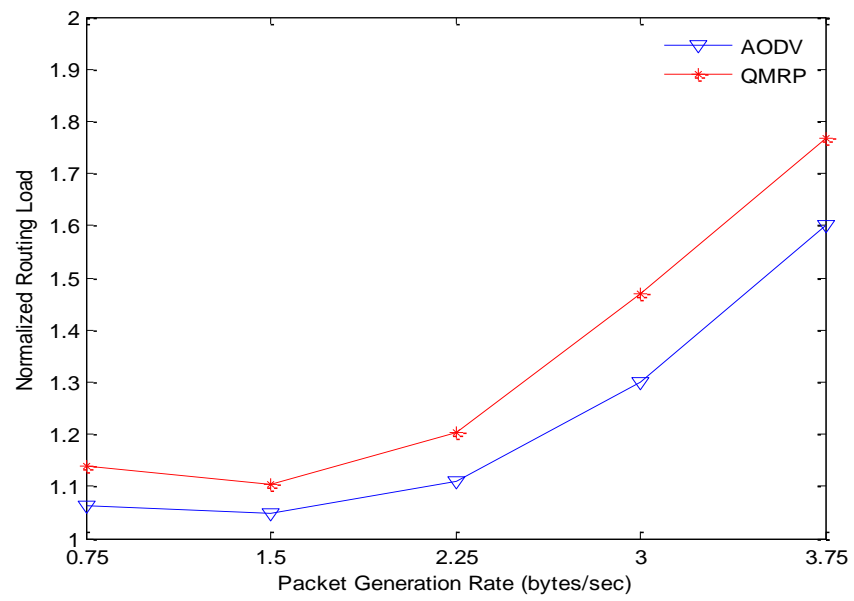


Figure 4.12 Normalized Routing Load (varying load)

4.4 Summary

Performance evaluation of QMRP vs. AODV has been performed in this Chapter. Three sets of experiments have been carried out to test the proposed protocol. The first is varying mobility of nodes, which is an important factor in testing the robustness of the protocol and effectiveness against the dynamics of the network since this affects the nodes to move out of range which means some links through such nodes will fail also this may cause other links to be created and new paths to form. This experiment has shown that the proposed algorithm outperforms AODV in three out of the four factors that are the most crucial for a routing protocol to fail or succeed. QMRP achieves lower end to end delay by avoiding congested nodes when discovering and establishing paths during the route discovery process as well as considering reliable links because SNR was considered in the route discovery process. Also, QMRP has shown improvement in packet delivery ratio, this is due to the fact that the protocol achieves the following when finding a new path; first, it is a node disjoint protocol which means links fail independently, so one path would fail through such node/link, which will decrease the number of lost packets. Second, dropped packets are forwarded on alternate paths that are available as back up paths. Third, routes in QMRP are more reliable and stable as compare to routes in AODV. In addition to the fact that QMRP is a node-disjoint protocol and multipath which means it initiates route discovery less frequent than a single path AODV, it takes into consideration the quality of the link by being aware to the changes and dynamics in topology of a mobile ad hoc network as well as the characteristics of the wireless channel. However, QMRP is not a perfect protocol and there is always a trade of, so the drawback of the protocol is that it has more overhead since each route discovery process involves more overhead than that of AODV because

it find more than one path in each process. Nonetheless, the increase in routing overhead is less than 10%.

In the experiment when the offered load increases the performance of both protocols degrade, however, QMRP is better in all case of; delay, packet delivery fraction and route discovery frequency, but AODV shows less routing overhead than the proposed protocol.

5 DYNAMIC SUPPRESSION BROADCAST SCHEME FOR VEHICULAR AD HOC NETWORKS- VANETS

5.1 Introductions

Vehicle communications have been known for many applications. Vehicular ad hoc network (VANET) is an infrastructure-less, impermanent, autonomous and self organized ad hoc network where nodes are mobile vehicles that communicate through the wireless link at high speed without the existence of central unit or access point [66] [67] [68] and could be equipped with communication devices such as Global positioning system (GPS) and Personal digital assistant (PDA), where vehicles may also communicate with road side units (RSU). Many projects already exist in different parts of the world [69] [70] [71] in Europe, [72] in the U.S. and [73] in Japan.

Even though VANETs considered as a subset of MANETs since both of them are multihop wireless networks, there are differences between them; high speed of vehicles in VANET which causes unexpected topology, number of vehicles is unknown in advance in a certain map; node density is unpredictable and irregular [67], power is not an issue in VANETs while in MANETs it is; since mobile nodes are battery power most of time also its not connected to a source unlike the case in VANET. The high mobility causes links in VANET to be destroyed accordingly information dissemination becomes a harder task to achieve, since paths may be invalid before they even utilized. Also, communication in VANET depends heavily on broadcasting a message to all other vehicles in a certain geographical region [74].

VANETs have many three main applications [75], (i) safety improvement on the road, (ii) transportation improvement and (iii) decrease the harmful effects of transportation on the environment. Data dissemination in VANET enables vehicles to share and exchange messages. One of the most crucial uses of VANET is safety and intelligent transport applications such as

pre accident warning in order to improve safety on the road during emergency situations [76] [77]. Also, broadcasting is used for enhancing navigation and entertainment, weather and traffic purposes [78].

Many safety applications have been presented in [79]. The authors in [80] surveyed the majority of safety applications, the summary of the most important applications are given in table I.

5.2 Broadcasting in VANETs

Broadcasting refers to delivering of a message for all vehicles throughout the network for a certain purpose. Broadcasting is a critical factor for data dissemination in a multihop wireless network. Like VANETs. Broadcast protocol must be efficient in the sense that it has the ability to deliver the message for all vehicles in a certain region; that is certain reachability, while using minimum resources such as bandwidth and at the same time reduces latency since the main goal for broadcasting protocols in VANET is safety application [76] [77]. Reachability is the ability of the broadcast scheme to deliver the message to as many vehicles as possible out all vehicles available in a certain map; reachability could be expressed in probability form as in equation (5.1)

$$R = \frac{V_{Rec}}{V_N} \quad \text{Equation 5.1}$$

Where R: is the reachability, V_{Rec} : number of vehicles received the message and V_N : total number of vehicles in the map.

Table 5.1 Vehicular Safety Applications

Type	Safety Applications	Communication Type	Traffic Information
Intersection Collision Avoidance	Traffic signal violation warning	I to V	Pedestrian crossing
	Stop sign movement assistance	V to I I to V	Vehicle position and velocity
	Blind merge warning	I to V	Vehicle position and velocity
Information from other Vehicles	Pre-accident sensing	V to V	Safety sensor coordination on seat belt and airbags
	Cooperative collision warning	V to V	Vehicle position, velocity and acceleration
	Emergency electronic brake light	V to V	Vehicle position, velocity and deceleration
Public Safety	Approaching emergency vehicle warning	V to V	Emergency vehicle ahead yield
	Post-crash warning	V to V	Disabled vehicle due to accident or mechanical fault
Sign Extensions	Curve speed warning	I to V	Curve location, curve speed limits, curvature, road surface condition
	Work zone warning	I to V	Distance to work zone, road closure, reduced speed limit

* I: infrastructure and V: vehicle

Also, broadcast scheme must be capable of maintaining connectivity of the network as oppose to disconnection of the network. Connectivity is an important factor to assure data dissemination

throughout the network. Connectivity refers to the probability that the network is connected at certain time in a given time interval [81], to achieve this task a vehicle must be within transmission range of another vehicle connected to the rest of the network; transmission range refers to the transmission radius sufficient to maintain connectivity of network; (i.e. two vehicles are considered connected if they are within each other transmission range).

A broadcast scheme must minimize resources usage (i.e. bandwidth), this depends on the number of rebroadcasts that a message has to go through to reach the destination as well as the number of vehicles that are rebroadcasting the message.

The simplest form of broadcasting is flooding; each node (vehicle) in the network upon receiving a message from any other node rebroadcast the message further to its neighbors, flooding has many downsides on the efficiency of the network; it increases redundant rebroadcasts, contention and collisions leading to what's known as the broadcast storm problem [68] [82].

The authors in [68] were one of the first to discuss the implications and consequences of broadcast storm problem, also they have proposed different solutions to minimize the effects of broadcast storm; these solutions can be categorized into (i) probabilistic, (ii) counter-based, (iii) distance-based, (iv) location-based and (v) cluster-based.

Probabilistic approach: the authors in [74] proposed three schemes to alleviate the broadcast storm problem in VANETs; the three schemes are referred to as (i) weighted p-persistence, (ii) slotted 1-persistence and (iii) p-persistence. The main suppression technique of the previous three schemes is a combination of probabilistic and time based rebroadcast. The authors in [83] have proposed Receipt estimation alarm routing (REAR) that is probability based broadcast protocol. REAR chooses the relay node based on the probability of reception of a message for the node, which is based on the signal strength and delivery ratio; based on that the protocol

chooses the next relaying node while other nodes remain silent to lessen contention and decrease collisions and hence a void broadcast storm.

Distance approach: in distance based approach farthest vehicles are given higher priority by reducing the waiting time for these vehicles. The authors in [84] proposed Urban multihop broadcast (UMB) uses RTS/CTS mechanism to solve the hidden terminal problem and divides the road into sections according to the direction of dissemination and choose the relying node in the farthest section. In [85] Ad hoc multihop broadcast (AMB) is an improved version of UMB. In [86] the authors proposed distance-based protocol called Distance Differ Transmission (DDT) protocol, the vehicle upon hearing the transmission of a message defer transmission of the message, by imposing this condition prevention of broadcasting of an emergency message occurs.

To deal with the limitations in DDT, the authors in [87] proposed the Directional Broadcast (DIB) protocol, DIB uses request to broadcast and clear to broadcast (RTB/CTB) mechanism, nonetheless if the farthest vehicle is out of transmission range of the sender broadcasting may fail because of the difference in speed between the two vehicles [88]. The authors in [89] proposed a modified version of UMB called the Smart broadcast (SB) the difference between UMB and SB is the later does assigns the contention window based on the location of a vehicle from the source vehicle, as a result of this modification SB has faster message propagation time [90].

Location approach: in [90] the authors have surveyed broadcast and geocast protocols for VANETs. The majority of broadcast protocols use the position to determine the next node to relay information to accomplish disseminating the required information. One of the earliest

broadcasting algorithms in VANET proposed by [91] is Vector-base tracking detection (V-TRADE), the protocol suffers from high control overhead, so it's not practical. The Multihop vehicular broadcast (MHVB) [92] creates a backfire zone, if the vehicle in this zone, then it does not relay the broadcast message.

5.3 Motivation and Objectives

The choice of transmission range is not a straight forward operation, when the transmission range is too long, then the communication link is more stable which might have negative impact on other factors in the network and if the transmission range is just enough to communicate with the neighboring vehicle; this reduces interference and increases throughput [93].

Broadcasting without caution can cause tremendous effects on the performance of VANETs.

To better understand the severity of the broadcast storm problem in MANETs as well as VANETs, Figure 5.1 shows a simple scenario of two nodes (vehicles) A and B, if the two nodes are within transmission range, then the intersection between the two circles is covered more than once for the same broadcast message, if there were N nodes within transmission range then there would be an overlapping region between N nodes (i.e. there is a region covered by N broadcasted messages), this shows how much overhead would a broadcast scheme has if simple broadcast is used without any imposed condition.

If vehicle A broadcasts a message and vehicle B upon receiving the message rebroadcast the same message, if the area covered by vehicle A denoted by A and the area covered by vehicle B is B , then $A \cap B$ is the region covered by both A and B and so the region benefit from B broadcast is A^c complement of A, now this region is $A^c = \pi r^2 - A \cap B$. To find the overlapping region:

If one of the circles is placed on the rectangular coordinate system with its center at the origin, then the equation of this circle is given by the equation $x^2 + y^2 = r^2$ solving for y as

$y = \sqrt{r^2 - x^2}$ now to find the intersection area between the two vehicles A and B assuming the distance between the vehicles is d as in Figure 5-3.1

$$INT = A \cap B = 4 \int_{d/2}^r \sqrt{r^2 - x^2} dx \quad \text{Equation 5.2}$$

Then, $x = r \sin \theta$ and $x^2 = r^2 \sin^2 \theta$ and $dx = r \cos \theta d\theta$ by substituting the value of x in equation 5.2, and INT is the intersection area between the two circles and with the assumption of best case scenario when the two vehicles are far at distance equal to the transmission range; $d = r$ the equation becomes

$$INT = 4 \int_{r/2}^r \sqrt{r^2 - x^2} dx \quad \text{Equation 5.3}$$

If $x = \frac{d}{2} = \frac{r}{2}$ then the value of $\theta = \frac{\pi}{6}$ and when the value of $x = r$ then $\theta = \frac{\pi}{2}$

$$INT = r^2 \left(\frac{2\pi}{3} - \frac{\sqrt{3}}{2} \right) \quad \text{Equation 5.4}$$

This implies that the area covered by a new rebroadcast is given by the difference between the area of B and the intersection between A and B as in 5.5

$$\pi r^2 - INT = r^2 \left(\frac{\pi}{3} - \frac{\sqrt{3}}{2} \right) \approx 0.61 \pi r^2 \quad \text{Equation 5.5}$$

The previous result shows that the best coverage that can be accomplished through the second broadcast is 61% or less, this means that if broadcast is used without caution can cause tremendous waste of bandwidth and resources in addition to high contention and collisions and longer delays, which is the result obtained in [68] the authors also showed that by the fourth broadcast the additional coverage is less than 0.05%.

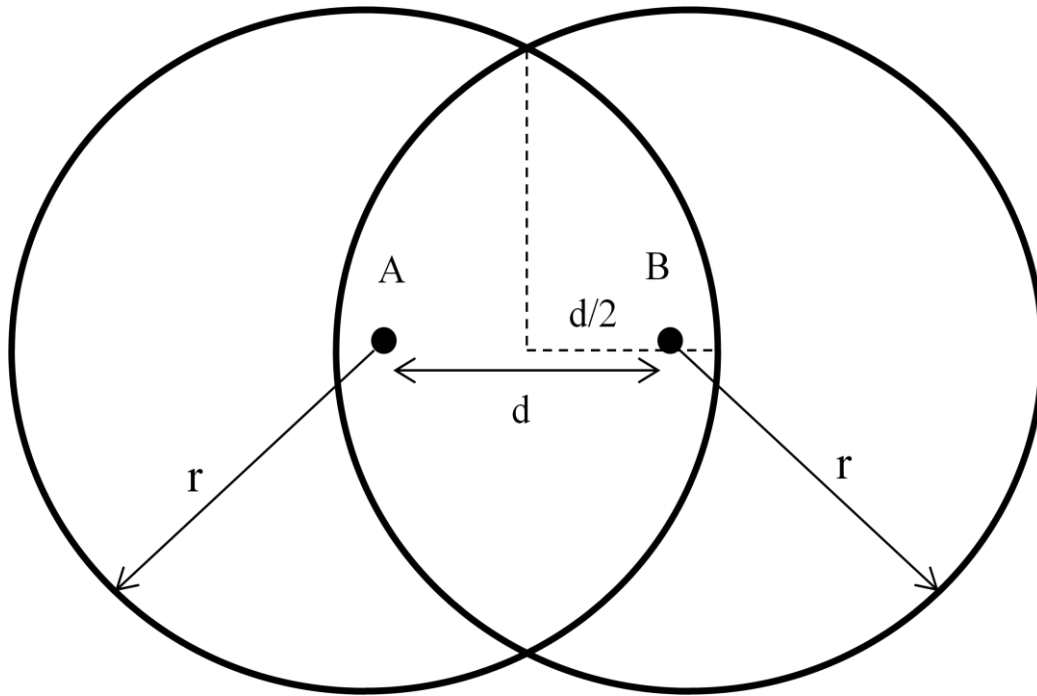


Figure 5.1 Intersection Between Two Vehicles Within Transmission Range

In this work the broadcast storm problem in VANETs is being investigated as it has been explained in 5.2; the broadcast storm increases network overhead as well as end to end delay and decreases the overall throughput of the network. The objective of this study is to alleviate the broadcast storm problem in VANETs by proposing a broadcast scheme.

The contribution of this work is two-fold; (i) propose the Dynamic Suppression Broadcast Scheme (DSBS) for VANETs by measuring the signal strength of a message arriving from another vehicle and based on that the vehicle makes the distance estimation for the arriving message then makes the decision on whether to rebroadcast the message or not, (ii) to maintain connectivity of the network through complete reachability while at the same time minimizing the number of rebroadcast messages. In DSBS no information about neighboring vehicles and no central controller are required.

5.4 Dynamic Suppression Broadcast Scheme (DSBS)

The dynamics of the proposed protocol consists of two stages as shown in Figure 5.2. The first stage occurs when a vehicle hears a broadcast message for the first time. If the vehicle is within 90 m region (i.e. SNR of the received message is greater than 34 dB), the vehicle will not rebroadcast the message. If the vehicle located in the outer ring, it has high priority broadcast time between 0-50 msec, if the vehicle is in the inner ring, it has low priority broadcast time between 75-95 msec. Giving higher priority to farther vehicles means these vehicles have shorter back off time so they rebroadcast earlier versus low priority broadcast vehicles that are closer to the source of the broadcast. It is worth noting here that high priority and low priority times should not be too small or too large, too small may cause collisions between far vehicles and too large may cause longer delays which defeat the purpose of the early emergency warning messages for safety applications.

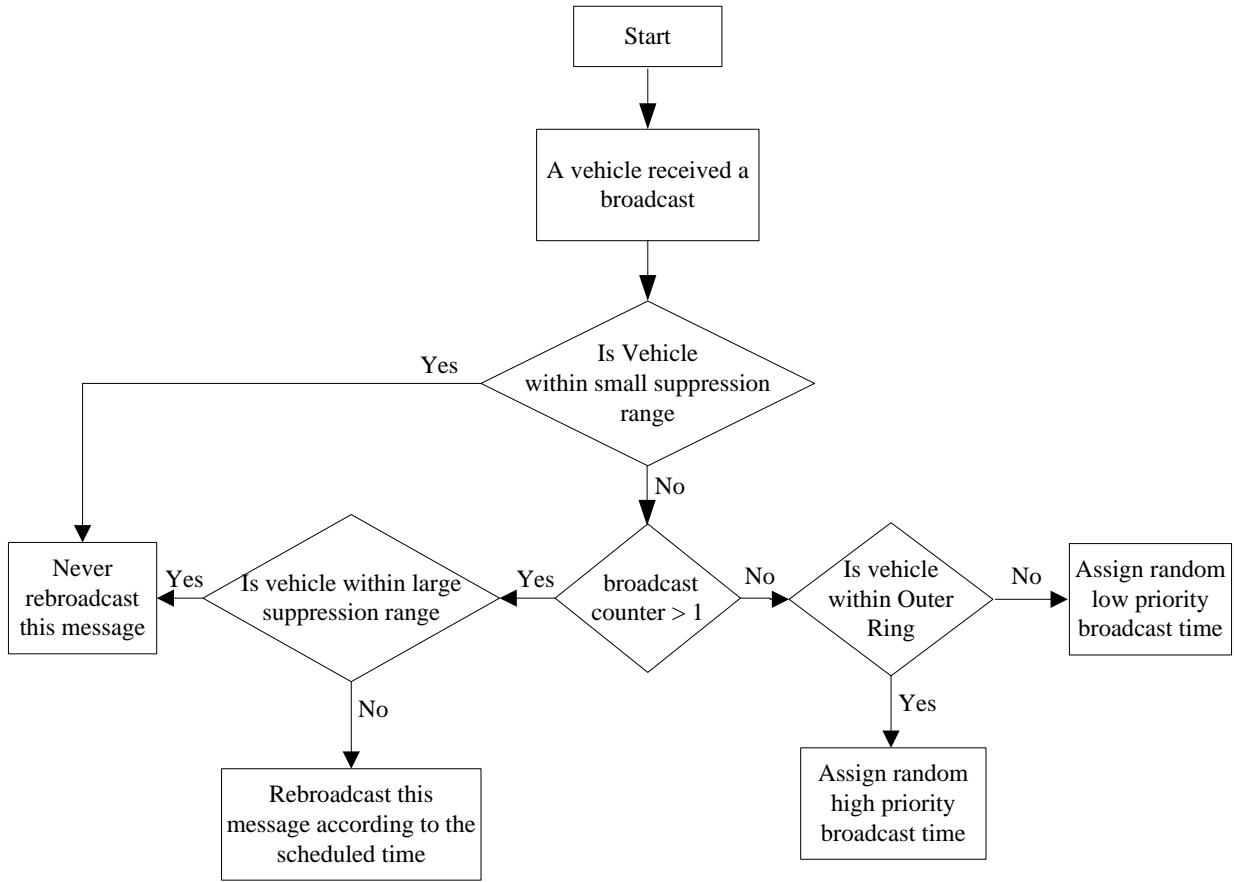


Figure 5.2 Dynamics of DSBS

Second stage serves to suppressing nearby neighbors of rebroadcasting vehicle; if the vehicle has received a broadcast before and is located within the large suppression range 175 m region (i.e. SNR of the received message between 33- 23.5 dB) it will not rebroadcast the message.

To further explain how the protocol works, the following example shows a scenario. Suppression ranges are shown in Figure 5.3 as can be seen in this figure the transmission range has been divided into three different regions; the smallest circle is the primary suppression range where the radius is 90 meters (m) which corresponds to the SNR threshold greater than 34 dB, where no vehicle in this region can rebroadcast a message that it has received.

Vehicles in the inner ring (middle circle) have low priority broadcast time since these vehicles are close to the source broadcasting the message; the range for this inner ring is between 91-200 meters. The outer ring has been given a higher priority in order to achieve reachability using minimum number of broadcasts and reduces latency; all values for the three different regions are shown in table 5.2 below that is based on the Figure 5.7 which is based on the values taken from Opnet [64].

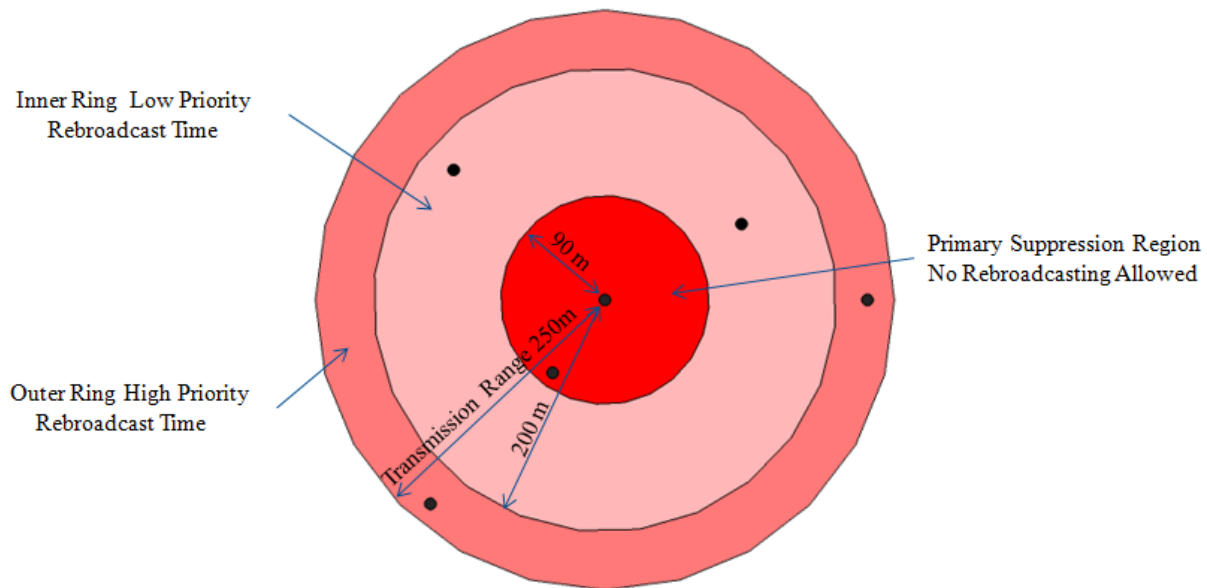


Figure 5.3 Different Suppression Regions Around A Vehicle

Figure 5.4 shows the vehicle in the outer ring of the source node broadcasting a message; this is in the high priority rebroadcast time ring since it falls between 200-250 meters from the source vehicle so it has a random high priority broadcast time between 0 to 50 milliseconds (msec). Now the vehicle in the inner ring will have a low priority rebroadcast time between 75 to 95 msec, however, this vehicle falls within the large suppression range of 175 m from the vehicle in the outer ring so, its counter for that message is more than one since it has received the message from the vehicle in the outer ring as a result its scheduled rebroadcast is cancelled.

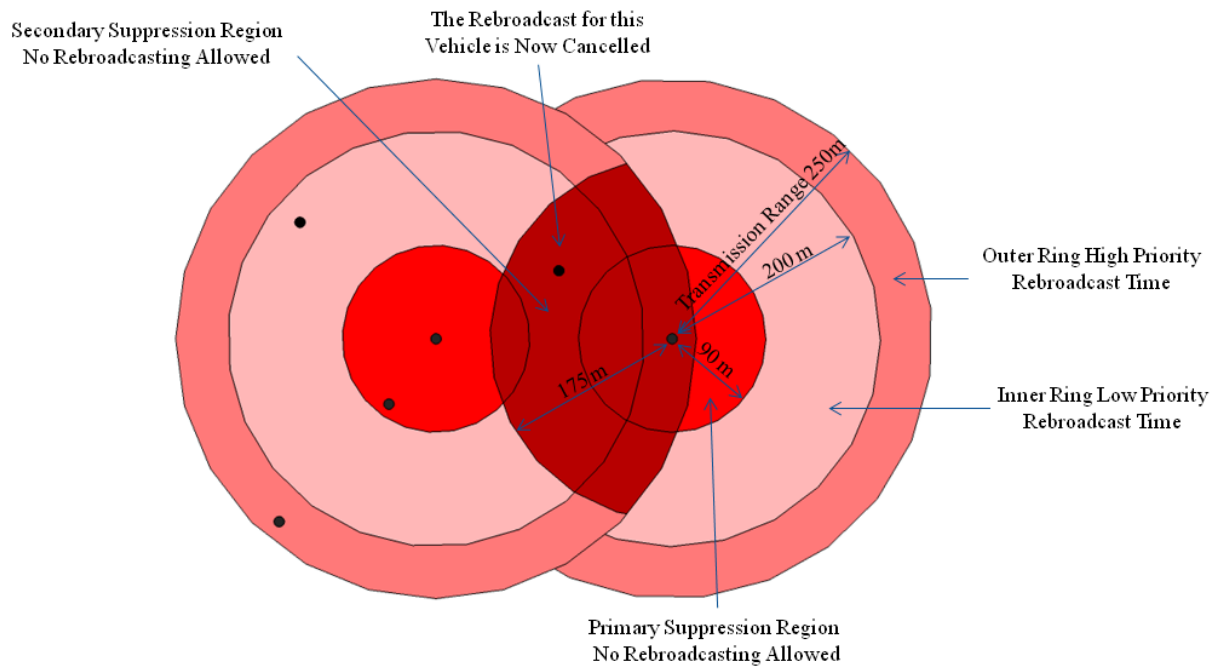


Figure 5.4 A Vehicle In Large Suppression Range Cancels Rebroadcast

As can be seen in Figure 5.5 the vehicle in the outer ring with high priority rebroadcast time will rebroadcast the message received from the original source, also the figure shows stage 2 of the scheme where any vehicle located in this region will cancel its scheduled rebroadcast.

Figure 5.6 shows a vehicle in the low priority time region has performed its scheduled rebroadcast after all high priority vehicles have finished their rebroadcasting.

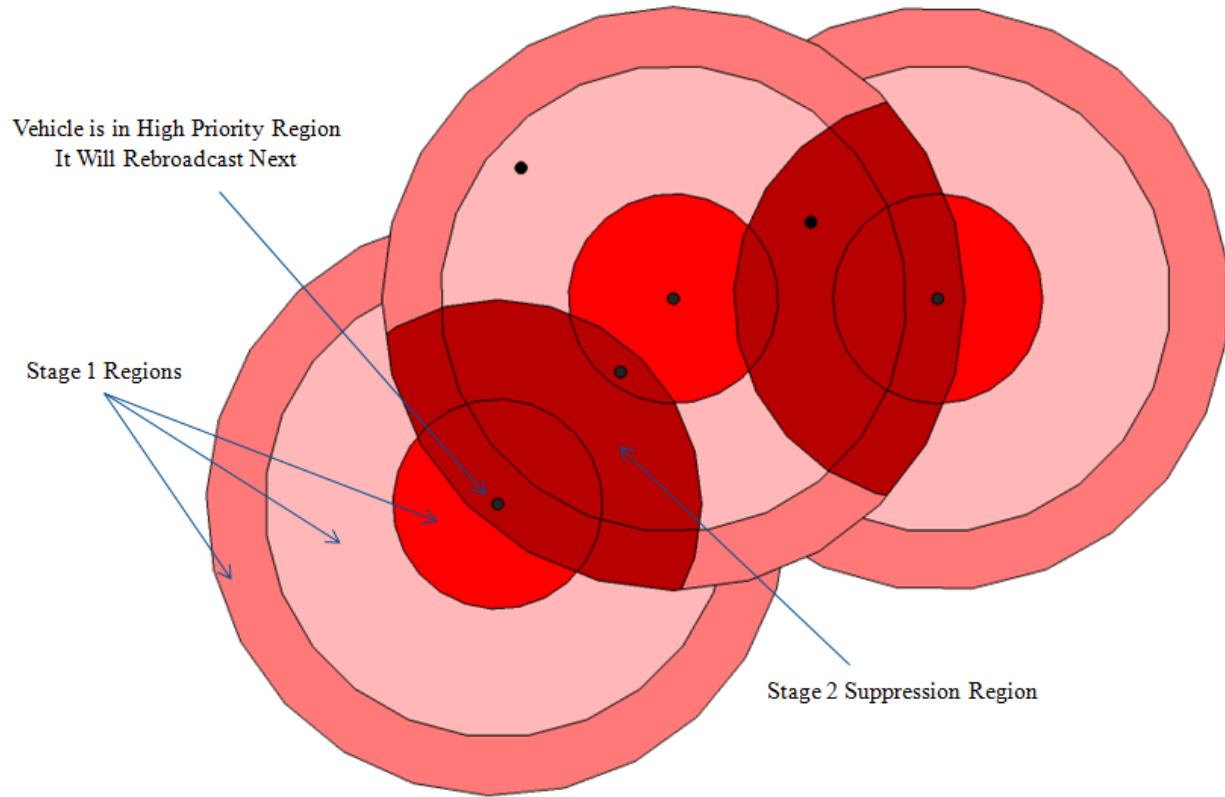


Figure 5.5 A Vehicle Rebroadcasting In High Priority Region

Table 5.2 Suppression Regions

Range	Distance in Meters	Action
Primary Suppression Range	0 - 90	Never rebroadcast
Inner Ring	91 - 199	Low priority rebroadcast time
Outer Ring	200 - 250	High priority rebroadcast time
Large Suppression Range	91 - 175	If counter > 1 never rebroadcast

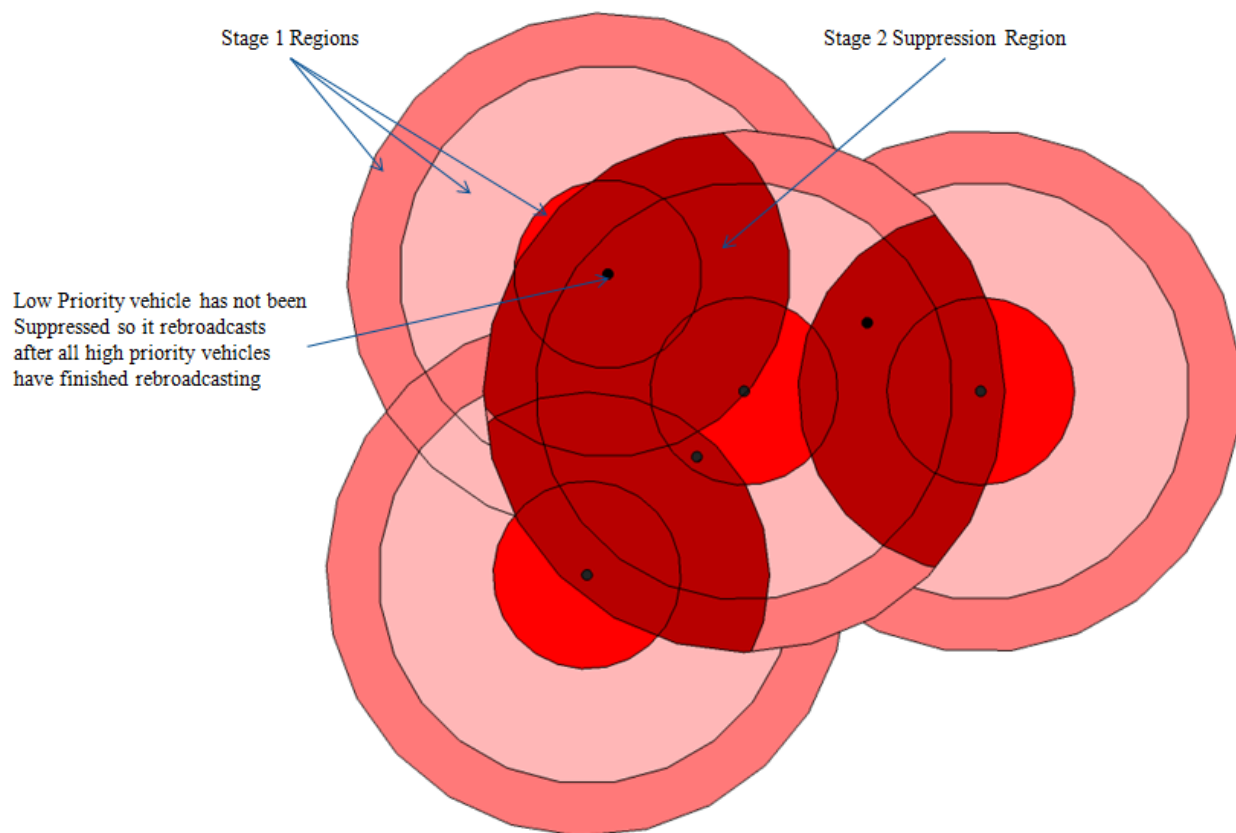


Figure 5.6 A Vehicle Rebroadcasting In Low Priority Region

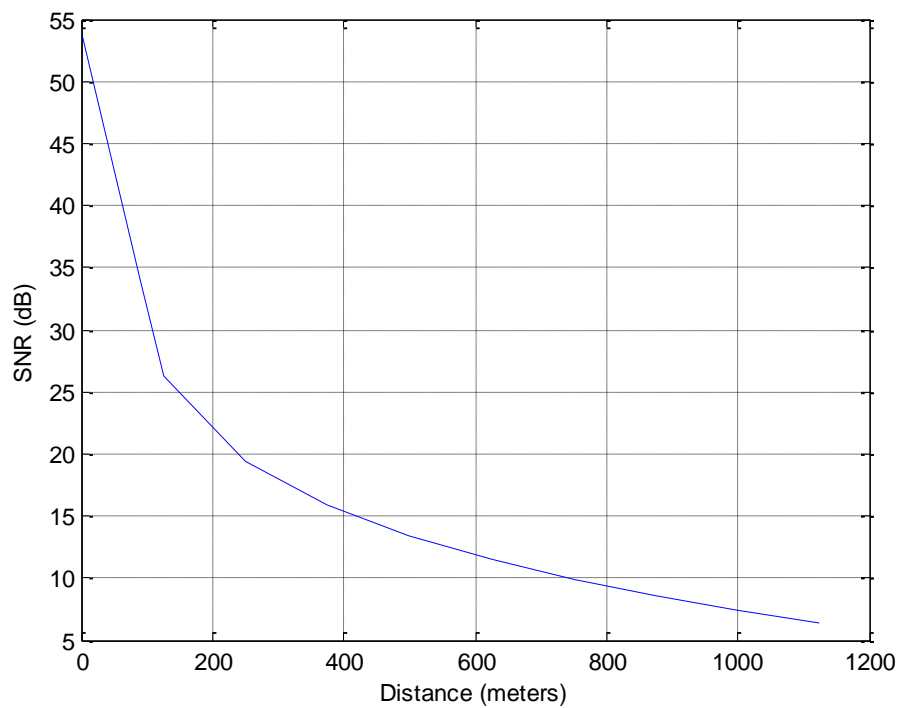


Figure 5.7 SNR vs. Distance

Through intensive simulations by randomly generating vehicle density ρ vehicles/ km² from 10-70 vehicles / km² the following results in Table 5.3 has been obtained relating vehicle density to its optimum suppression range.

Table 5.3 Correlation Between Vehicle Density and Suppression Range

Vehicle Density ρ : Vehicles/km ²	Large Suppression Range in meters	Corresponding Range in m
$1 < \rho < 40$	$28\sqrt{\rho}$	28-175
$42 < \rho < 56$	$4 * \rho$	172-220
$\rho \geq 56$	225	225

The table 5.3 gives the suppression range as a function of vehicle density; these results were not obtained through mathematical analysis, rather, through discrete estimation. Based on the previous results shown in this table the proposed scheme uses the large suppression range of 175 m in the second phase of the protocol.

As can be seen in Figure 5.8 the probability of a vehicle being in the outer ring is the difference in area between the areas of the two rings; the distance from the source is greater than 200 and less than 250 can be computed as follows, if the area of the outer ring is denoted by A_o and the area of the inner ring is denoted by A_i then probability of a vehicle being in the outer ring is given as $P(out_{ring}) = \frac{A_o - A_i}{A_o} = 0.36$ assuming uniform distribution of vehicles throughout the map.

So this means that there is 36% probability of a vehicle being in the outer ring, this is another reason for choosing the large suppression range of 175 m in addition to the simulation results that determines the suppression range based on vehicle density.

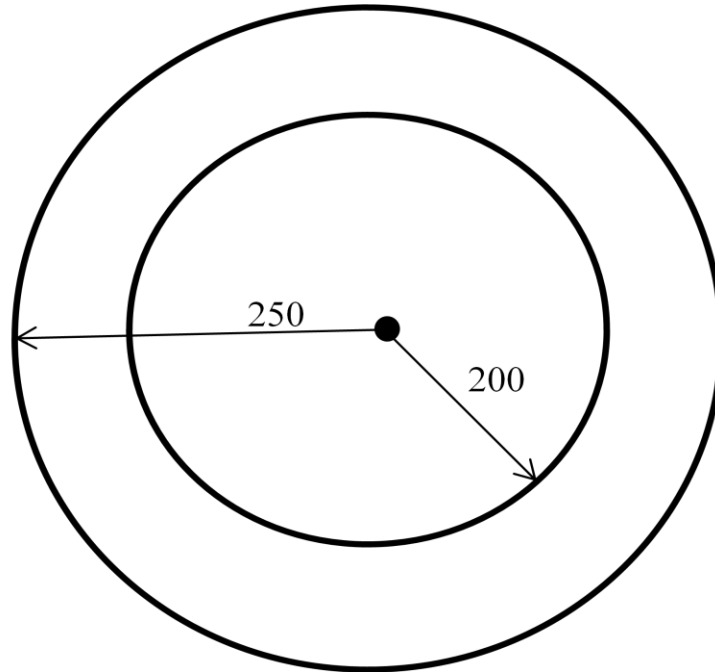


Figure 5.8 Probability of A Vehicle In High Priority Region

5.5 Simulation Environment

5.5.1 Free Space Path Loss Model (FSPL)

The Free space path loss model is adopted in this study to simplify the analysis of the proposed broadcast scheme. A linear path loss for a given channel is defined as the ratio between the transmitted to the received power as equation 5.8 [94]

$$Pl = \frac{Pt}{Pr} \quad \text{Equation 5.6}$$

Where Pt is the transmitted power and Pr is the received power

$$Pl \text{ in (dB)} = 10 \log_{10} \frac{(4\pi df)^2}{c^2} \quad \text{Equation 5.7}$$

5.5.2 Simulation Parameters and Performance Metrics

MATLAP simulation package is used to analyze the performance of the proposed DSBS. Each vehicle in the network broadcast a message only once during the simulation at different random

time. Each reading in all scenarios is the average of 10 runs. The rest of the simulation environment parameters are summarized in the Table 5.4.

Table 5.4 Simulation Parameters for DSBS

Parameter	Value
Transmission Range	250 m
Simulation Time	300s
Map size	2000 m x 1000 m
Number of vehicles	20-120
Packet size	256 bytes
Mobility Model	Manhattan
Speed	Uniform between 5-15 m/sec
Pause time	0 s
Propagation model	Free space

In this experiment the following metrics are considered to evaluate the proposed broadcast scheme.

- (i) Reachability: that is the percentage of vehicles out of all vehicles in the map that received a broadcast message.
- (ii) Percentage of rebroadcast: percentage of vehicles out of all vehicles in the map that rebroadcast a received message

The following schemes have been compared to evaluate the proposed scheme.

- (i) Flooding; where each vehicle receiving a message rebroadcast the message once regardless of its location from the source vehicle broadcasting a message.
- (ii) Small suppression range; this is similar to the basic flooding technique where all vehicles receiving a message rebroadcast the message and the only suppression range is the small range of 90m radius; any vehicle within this range will not rebroadcast the message.

- (iii) Fixed suppression range; utilizes the small and the large suppression range of 90 and 175 meters respectively. This algorithm does not need any additional equipment except for the transmitter and the receiver. The suppression ranges have been chosen as a good balance based on the results obtained through the discrete estimations.
- (iv) Dynamic suppression range in this scheme the assumption is that all vehicles are equipped with GPS. The vehicle density information is available via GPS and road side units (RSU), the large suppression range is assigned as a function of vehicle density. Generally speaking, low vehicle density yields a small suppression range vs. high vehicle density that results in a larger suppression range (i.e. as the number of vehicles increase so does the suppression range), this way the number of rebroadcasts is minimized. The larger the total area of suppression region, the larger the proportion of suppression region to the total area of the source vehicle transmission range.

5.6 Results and Discussion

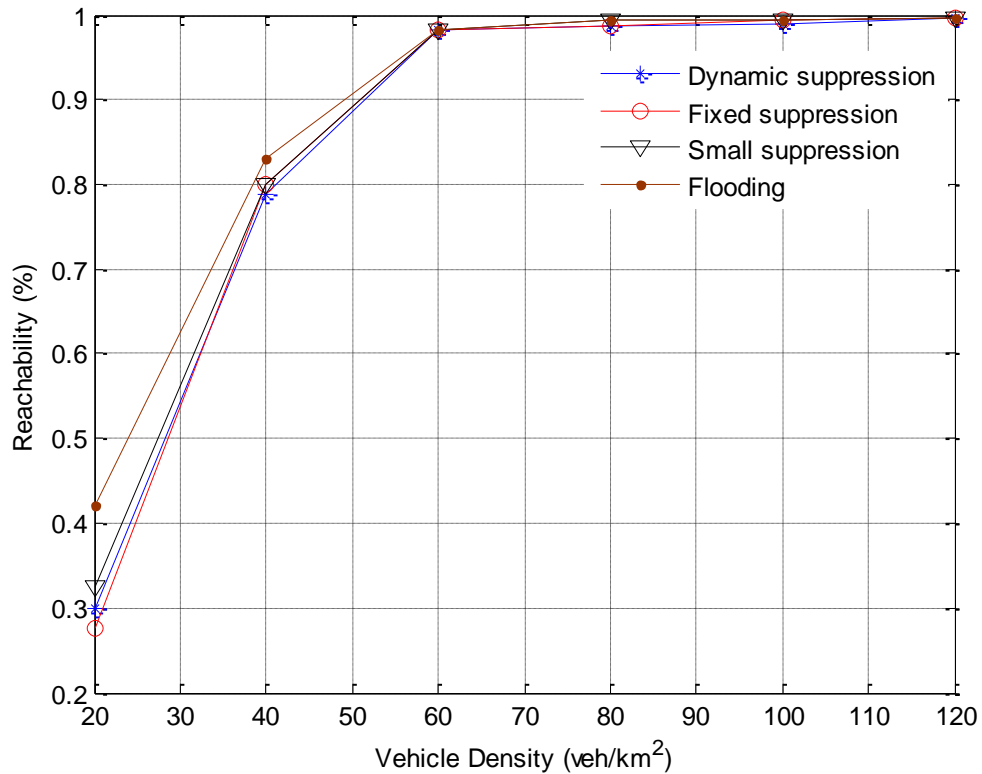


Figure 5.9 Reachability vs. Vehicle Density

Figure 5.9 shows the reachability for all four different broadcast schemes. As the number of vehicles increases so does the reachability achieved, it is also evident that DSBS has the same efficiency as flooding, but at much lower cost in terms of number of rebroadcasts as in figure 5.10. The reachability after vehicle density of 40 vehicles per km² is 100% which means that the proposed scheme is very practical in the sense that it does not require any special equipments and efficient in the sense it maintain connectivity of VANETs meant for safety applications.

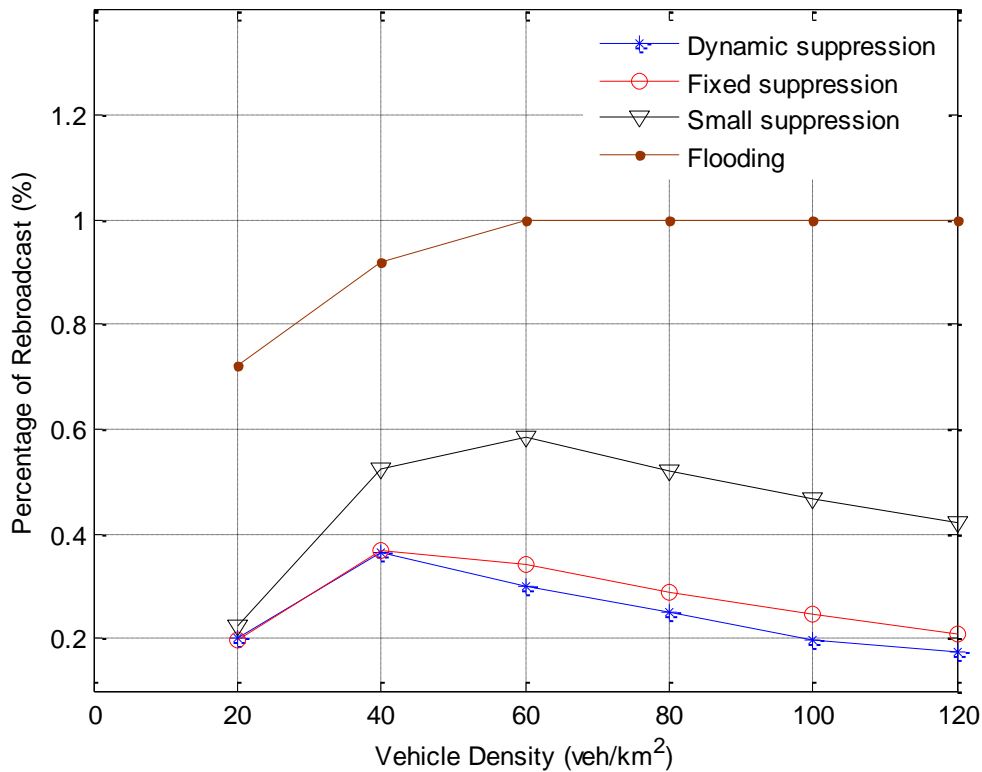


Figure 5.10 Percentage of Rebroadcasts vs. Vehicle Density

As can be seen in Figure 5.10 it is clear that the proposed broadcast scheme has much lower number of rebroadcast vehicles than the flooding broadcast mechanism by about 80% in high density VANET; when vehicle density is 120 vehicles per km², this is due to the fact that the flooding scheme rebroadcast each message once, so the number of rebroadcasts is 100% versus DSBS that utilizes the value of SNR from the message and based on the value the vehicle decides whether to rebroadcast the message or not and that is why there is a significant difference between the two schemes.

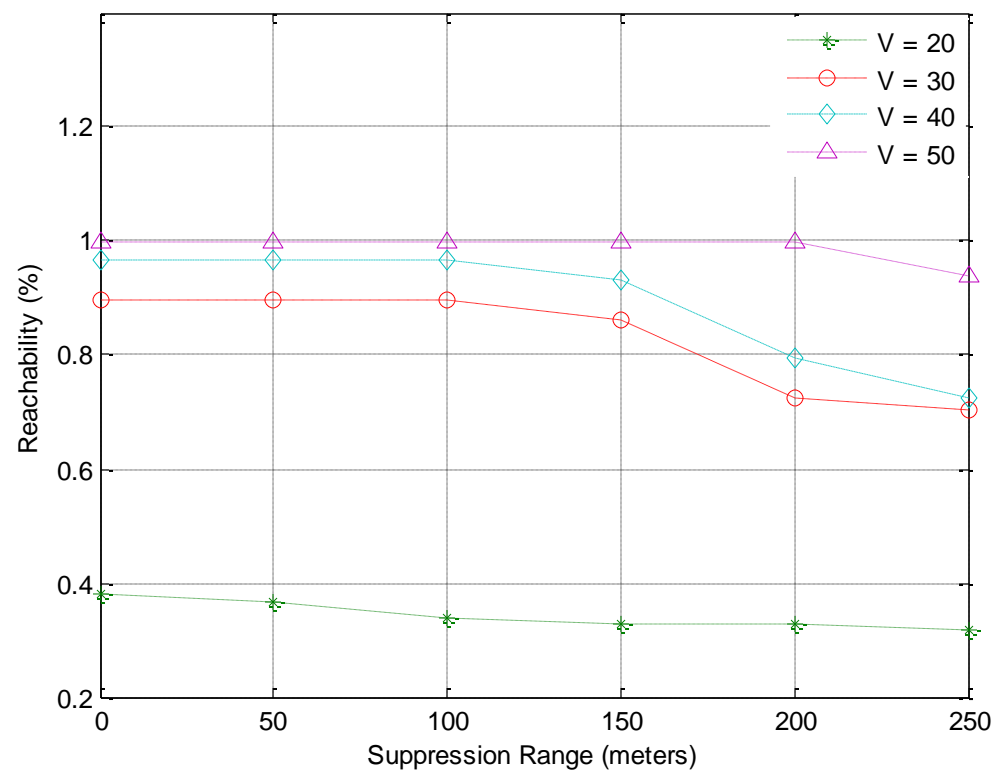


Figure 5.11 Reachability vs. Suppression Range

The reachability versus suppression range for different vehicle densities is illustrated in figure 5.11. The figure shows that as the vehicle density increases the suppression range could also increase without compromising the reachability as well as the connectivity of VANET. As can be seen in the figure when vehicle density is 30 or more the suppression range could increase up to 175 meters with minimum reachability of 80% and maximum of 100% when the density is 50 vehicles per km². This confirms the large suppression range in the formula devised for choosing this range as well as dividing the transmission range into different priority zones as in Table 5.3.

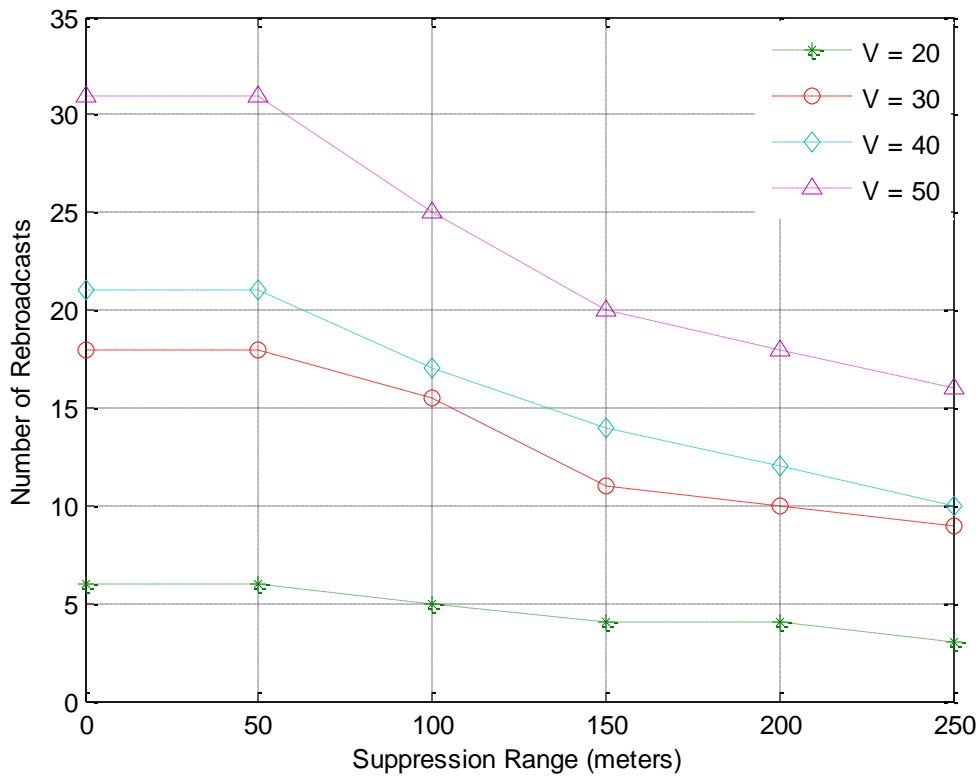


Figure 5.12 Number of Rebroadcasts vs. Suppression Range

Figure 5.12 shows number of rebroadcasts versus suppression range for different densities. This figure related to the previous figure 5.11 to achieve the presented reachability. For an average number of vehicle of 40 vehicles per km^2 in an urban environment it is sufficient that 35% of vehicles to rebroadcast a message to achieve about 85% coverage out of all vehicles in a map of size 2000 m by 1000 m using a suppression range of 175 meters. For the case of 50 vehicles per km^2 to achieve 100% coverage for an emergency warning message about 40% of the vehicles in the map need to rebroadcast.

5.7 Summary

Chapter five discussed the problem of broadcast storm and how this problem may lead to significant degradation in network's throughput due to the contention at the MAC layer that results in increasing number of collisions and cause longer delays.

Section two discussed broadcasting in VANET; its applications, previous work proposed to solve the broadcast problem, its deficiencies and limitations. In section three objectives and contribution of this study were laid out. The proposed dynamic suppression broadcast scheme is presented in section four.

The protocol works in two stages the first stage basically suppresses close nodes to the source generating the broadcast message and the second stage works to suppress nearby nodes, the decision is being taken locally at each node based on the estimated distance from the value of SNR in the received message. A full explanation is given for the problem and the proposed solution is also illustrated through a set of figures, where far nodes are given higher priority to rebroadcast and closer nodes are given lower priority.

A devised formula that relates suppression range and node density in a VANET is also presented. An intensive set of simulations is presented to show the pros of the proposed scheme for safety application in VANETs. The last section presents results and discussion of these results. The conclusion of the proposed scheme is reducing significantly the unnecessary rebroadcasts and at the same time accomplishes the same reachability as the flooding scheme.

A dynamic suppression scheme is more efficient, simple and does not need extra equipment except for the transmitter and receiver. The scheme achieves 100% reachability while decreasing number of rebroadcasts which alleviates the broadcast storm problem in VANETs.

6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In a dynamic environment like MANET on demand multipath routing protocols can achieve many aims such as but not limited to lower delay, less frequent route discovery processes, improve load balancing, network resilience through network fault tolerance and increase packet delivery fraction.

This thesis proposed QoS-Aware multipath routing protocol (QMRP); a multiple path node-disjoint protocol that considers channel conditions when establishing multiple paths between source-destination pairs in wireless ad hoc networks to overcome the limitations of other single path; AODV.

QMRP uses the EPD as a metric to choose the route which takes into consideration the SNR at the physical layer as well as the actual data rate from the MAC layer in addition to the node's average queuing delay to reflect the link quality and the medium utilization around the node, respectively, without loss of generality QMRP introduces the new load -significant in case of time-sensitive applications-; that is introduced by the node requesting a path to a destination in the computation of the expected path delay to capture the real channel conditions. QMRP does self load balancing by avoiding congested nodes along the path. As results show, QMRP protocol outperforms the AODV protocol in terms of average end to end delay, packet delivery fraction, route discovery frequency. On the other hand, QMRP has insignificant more routing overhead than that of AODV.

In VANET environment where critical applications are mostly for safety through disseminating emergency warning messages it is crucial for a broadcast scheme to be efficient, simple and minimize the usage of network resources. Because of the aforementioned reasons the second part

of this thesis was dedicated to try to solve the broadcast storm problem in VANETs. A new broadcast scheme was devised based on a formula that was a result of intensive simulations to determine an optimized suppression range for a broadcast message. The proposed scheme called dynamic suppression broadcast scheme shows a promising results by achieving almost 100% reachability while at the same time reduce the number of rebroadcasts throughout the network.

6.2 Future Work

The work presented in this document opens many avenues for future work that will explore and focus on the analytical and statistical analysis of QMRP vs. other multipath routing protocols. Also more investigation of the performance of QMRP with IEEE 802.11e, since 802.11e was developed to offer QoS capabilities to wireless networks through categorizing different traffic types into classes of service.

Most of QoS-aware routing protocols in literature assume a perfect channel and neglecting the fact that it's never the case due to multipath fading and shadowing so, more thorough research of the protocol is needed under realistic physical channel conditions such as Rayleigh fading channel since this is usually the case for MANET's environment rather than the exception.

Also, utilizing cross layer design approach to adaptively accommodate and maintain a QoS provided though out the life time of a connection instead of admitting many and not fulfilling the requirements of each connection especially for time sensitive applications, this could be achieved through the design of QoS-aware routing protocols that are robust against mobility.

More research is needed to improve the MAC layer to allow simultaneous usage of all available paths in multipath routing protocols.

For VANETs more work could be done to measure and analyze the performance of the proposed broadcast scheme; delay for EWM is a critical factor as well as number of collisions at the MAC

layer also study of the scheme under different mobility models to fit high way scenarios could be investigated. The proposed scheme could be improved in many ways to be suitable for all environments other than urban areas; such as high way scenarios. One of the factors that could be an addition to DSBS is the velocity and direction of moving vehicle to make the decision on whether to rebroadcast a received message or not.

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