MEDIUM ACCESS CONTROL AND ENERGY-EFFICIENT ROUTING FOR MOBILE AD-HOC NETWORKS

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SUMMARY

A *mobile ad hoc network* (MANET) is an autonomous system of mobile nodes that are connected by wireless devices without any fixed infrastructure support or any form of centralized administration. In such a network, nodes are able to reach destinations beyond their direct wireless transmission range by routing the packets through intermediate nodes. This characteristic requires each mobile node to operate not only as a host but also as a router, with a basic multi-hop routing capability, and must be willing to forward packets for other nodes.

Village radio system [1] is a kind of wireless ad hoc network, which is characterized by mobile nodes and relays, low and variable channel capacity, and dynamic topology due to node mobility. The original routing algorithm for village radio system is simply a classical flooding mechanism, where every village radio terminal retransmits each message when it receives the first copy of the message. Simultaneous transmission of the same packet by multiple users is allowed, while neither signal collision nor contention will cause a receiving problem in village radio system. This is achieved by exploiting the broadcast nature of radio waves and enabling the receiving terminal to combine the individual signals to produce a stronger signal instead losing the information due to interference. However, the network-wide flooding is highly energy-consuming which will quickly drain the village radio terminals' limited energy resources, thus we developed a new routing algorithm for village radio system.

We present an innovative source-initiated on-demand routing to exploit the robustness of the village radio system while significantly reducing the energy consumption. This protocol, Village Radio Routing Protocol (VRRP), does not introduce any new messages e.g. route request (RREQ) packet in route discovery; routers can infer routes from broadcast messages. The protocol operates in an energy-efficient manner by minimizing flooding of messages after nodes have learned routes from messages, and eventually stop flooding after a route has been established. To support the new routing protocol, we also enhanced the village radio's time division multiple access (TDMA) based medium access control (MAC) protocol. Our simulation results show that this enhanced MAC protocol performs better in the village radio network than the IEEE 802.11 MAC protocol does. Our simulation results also show that this new routing scheme is quite suitable for original flooding-based village radio network, which no existing ad-hoc routing protocol can be used. This routing scheme is also effective as it provides fairly high packet delivery at both high and low mobility settings. Furthermore, this routing scheme is energy-efficient as it substantially reduces packet flooding.

In addition, we have carried out simulations to compare the performance of VRRP with popular ad hoc routing protocols, e.g. AODV and DSR. We show that our routing protocol VRRP exhibits a significant reduction in routing overhead, and provides a considerable amount of energy saving over AODV and DSR.

CHAPTER 1 INTRODUCTION

1.1 Overview and Motivation

Due to rapid technological advances in wireless data communication devices and laptop computers, wireless communications between mobile users is becoming more indispensable than ever before, and wireless networks have become increasingly popular since 1970s. Their main advantages are the mobility that they offer and the flexibility of installation in places where a wired network cannot be easily deployed. There are currently two variations of mobile wireless networks. The first is known as the infrastructure network, i.e. a network with fixed and wired gateways while the other is the infrastructureless mobile network, commonly known as a mobile ad hoc network (MANET).

A MANET is an autonomous system of mobile nodes that are connected by wireless devices without any fixed infrastructure support or centralized administration. MANETs are also known as Self-Organizing networks, which are rapidly deployable with dynamic topology and do not depend on wired network infrastructures. In such a network, nodes are able to reach destinations beyond their direct wireless transmission range by routing the packets through intermediate nodes. This characteristic requires each mobile node to operate not only as a host but also as a router, with a basic multi-hop routing capability.

MANETs are developed to operate in a wide variety of environments, from military scenarios or emergency rescues (with hundreds of nodes) to low-power sensor networks (with potentially, thousands of nodes). MANETs have mostly been used in the military sector, while successful examples of ad hoc radio networks in the commercial sector are few so far. Now, researchers turned to the small-scale personal area networks, instead of the large-scale networks. That is, the products will mainly focus on facilitating communication between a user's personal devices. The ad hoc network functionality will also enable the interconnection of different users' devices.

In a MANET, routers can be mobile. The network topology can change, and likewise, the addressing within the topology can change. In this paradigm, an end user's association with a mobile router determines its location in the MANET. Due to the fundamental change in the composition of the routing infrastructure, (that is, from fixed, hard-wired, and bandwidth-rich to dynamic, wireless, and bandwidth-constrained), the routing algorithms must be reworked.

MANETs have several characteristics that differentiate them from fixed multi-hop networks.

- Dynamic topologies – since nodes are free to move arbitrarily, the network topology, which is typically multi-hop, may change randomly and rapidly at unpredictable times.
- Energy-constrained operation – some or all of the nodes in a MANET may rely on batteries for energy, making power conservation a critical design criterion for these nodes.
- Bandwidth-constrained, variable capacity, and possibly asymmetric links – the network has low capacity, especially when the mobility is high. Another effect is that MANETs often operate in heterogeneous wireless environment with significantly varying bandwidth-delay characteristics.
- Wireless vulnerabilities and limited physical security – while there are existing

link-layer security techniques, a lot of work is still needed on security.

This study focuses on routing protocol research and development on MANETs. Traditional networks (both mobile and non-mobile) have been designed for low-delay, high-throughput, and scalability. These are the criteria for designing mobile ad hoc networks too. In addition, MANETs require a routing protocol to be simple, loop-free, quick to converge and low in overheads. Thus, many challenges prevail in designing a routing protocol for MANETs. Some of these problems are listed as below,

- Lack of centralized entities
- Rapid node movement→ changing network topology
- Wireless communications
- Limited battery power/transmission range of some nodes
- Reliability, survivability and availability

Generally, routing in mobile ad hoc networks (MANETs) is challenged by mobility and dynamics of mobile devices. New routing protocols for MANETs are required because classical routing algorithms cannot cope with constant topology changes in such networks and the use of wireless media. All nodes in MANETs are capable of movement and can be connected dynamically in an arbitrary manner. There are no fixed routers in these networks; nodes function as routers, which discover and maintain routes to other nodes in the network. They also have the ability to reconfigure and reorganize when the network topologies change.

The numerous routing protocols proposed for mobile ad hoc networks over the last few years are generally classified into two categories: table-driven and demand-driven, with those possessing characteristics of both, referred to as hybrid protocols.

Table-driven routing protocols try to maintain consistent, up-to-date routing information from each node to every other node in the network. Examples of table-driven routing protocols are Destination-Sequenced Distance-Vector routing protocol (DSDV) [3], Clusterhead Gateway Switch Routing protocol (CGSR) [4] and Routing Protocol (WRP) [5]. However, table-driven routing is inefficient because of excessive routing messages from the periodic exchange of updates among the nodes. Several studies have confirmed this [2][8].

Unlike table-driven routing, demand-driven routing creates routes only when desired by the source node. Examples of reactive routing protocols are Ad Hoc On-Demand Distance Vector (AODV) routing [6], Dynamic Source Routing (DSR) [7], Location-Aided Routing (LAR) [9], and Signal Stability based Adaptive Routing (SSA) [10]. Essentially, these protocols search for a route by flooding a route request packet to the network. When the search target or an intermediate node with a cached route hears the request, it replies by sending a route reply packet to the source. On-demand protocols have been found to generate less routing overhead and higher packet delivery as compared to table-driven protocols [2][8] , e.g. DSR and AODV have consistently fared well in many simulation studies [2]. However, they still introduce additional control packets in route discovery, which is the major cause for increasing routing overhead. When the network topology keeps changing very quickly due to high mobility of nodes in the network, the overhead will increase drastically.

Although numerous routing protocols have been presented, there is not a particular algorithm or category of algorithms which can work best for all MANET scenarios. Each routing protocol has advantages and disadvantages, and fits well for certain situations. Hybrid protocols combine the techniques of table-driven and demand-driven protocols trying to obtain an optimal solution.

Since most mobile ad hoc networks are battery-operated systems, they are energy and bandwidth constrained. Power and energy efficient design becomes one of the most important design concerns for MANETs. Low energy consumption extends battery's lifetime, reduces the cost for system maintenance, and increases the system's lifetime when recharging or replacement is not possible (e.g., military networks in a battlefield or sensor networks). Thus, we want to reduce control messages in route discovery, which leads to smaller routing overheads and savings in energy consumption. Consequently, mobile nodes can last longer, which is a big advantage in many applications of MANETs, and is particularly important for military uses.

This thesis concentrates on achieving energy-efficient unicast routing in multi-hop wireless ad hoc networks. The goal of the energy-efficient routing protocol is to increase the life of mobile nodes and the network. Moreover, we have worked on cross-layer design for ad-hoc wireless networks, which deals with designing the layers of the network jointly to improve the system. The idea that we have is that the power control, signal design, transmitter and receiver design in the physical layer, and scheduling in MAC layer should interact with routing in the networking layer. In this study, we have addressed both MAC and network layers, with cross-layer research instead of focusing on one layer. By doing so, we obtained a more efficient solution for our target network. Lastly, this thesis also included the goal to generate a simulation model that could be used as a platform for both current and further studies within the area of ad hoc networks.

1.2 Thesis Contributions

In this study, we develop a source-initiated on-demand routing protocol aimed at not introducing any new messages in route discovery in a village radio network. This thesis makes three important contributions.

- Presented in [27], a novel routing protocol, *Village Radio Routing Protocol* (VRRP), that fits well for village radio network is proposed. In addition, by implementing the MAC protocol, *Village Radio Protocol* (VRP) [1], routing-layer design complexity and energy wastage are reduced.

- The new *Village Radio Routing Protocol* (VRRP), as presented in [27] and further in chapter 5, is one of the first attempts to not introduce any new messages in route discovery.

- Presented in [27], a simulation model has been set up, and simulation studies have been performed to gauge the performance of the new routing protocol. It shows that VRRP has greatly improved energy efficiency at a small price of slightly lower packet delivery ratio and higher end-to-end delay. In addition, by using implicit route discovery, the routing overhead in the network is substantially reduced.

1.3 Thesis Organization

The rest of the thesis is organized as follows. In chapter 2, the basic and most important requirements of mobile ad hoc networks are discussed. In Chapter 3, several general concepts on mobile ad hoc networking are introduced, followed by a survey of current MANET routing protocols. In the next chapter, we first introduce our target scenario, i.e. the village radio network. Then we describe the medium access control for village radio network, which is a multi-hop Preamble based Time Division Medium Access protocol. In chapter 5, we present the routing protocol. A description of our simulation tool is presented in chapter 6. The simulation models and results are given in chapter 7. Finally, we will state our conclusions and further work to be done to optimize this new protocol.

CHAPTER 2 MOBILE AD HOC NETWORK (MANET)

2.1 Characteristics and Requirements of MANET

Mobile Ad hoc Networks differ from conventional wireless networks in several ways. In conventional wireless networks, nodes are connected to a wired network infrastructure and only the last hop is wireless. In MANETs, which are also known as Self-Organizing networks, a wired network infrastructure is not available. With their own routing protocols and network management mechanisms, MANETs are multi-hop wireless networks where nodes are also routers, and rapidly deployable with dynamic topology. In this section, we will discuss the important characteristics and requirements of MANET. Later, in the next chapter, we will assess several existing MANET routing protocols based on these requirements.

2.1.1 Limited Energy Source

In a wireless mobile ad hoc network, energy is a critical resource for battery-powered nodes. A node may have only limited energy capacity, but may be required to function for a longer period of time and do considerable computing work. This severe limitation makes it crucial for the routing protocol to be highly energy-efficient. In other words, nodes must consume the least amount of energy possible while still delivering fairly high percentage of traffic to the end-user. Low energy consumption extends battery’s lifetime, reduces the cost for system maintenance, and increases the network’s lifetime when battery recharging or replacement is not allowed (e.g., military networks in a battlefield or sensor networks). Consequently, mobile nodes can last longer, which is a big advantage in many applications of MANETs, and is especially important for military uses. Several solutions to minimize energy consumption at the network layer have been proposed and they are discussed below,

- Minimize Routing Overhead.

  Routing overhead can be in the form of periodic route updates for table-driven routing algorithms, route discovery packets for on-demand routing, or any other form of traffic that is intended for routing purposes. As transmission consumes energy, minimizing the routing overhead must be one of the goals of routing protocols to conserve energy. On-demand protocols have been found to generate less routing overhead and higher packet delivery as compared to table-driven protocols [2][8]. However, they still introduce additional control packets in route discovery, which is the major cause for increasing routing overhead. When the network topology keeps changing very quickly due to high mobility of nodes in the network, the overhead will increase drastically. Thus we want to further reduce control messages in route discovery, which leads to smaller routing overhead and more savings in energy consumption.

- Power-Off Radio When Idle.

According to the IEEE 802.11 standard, a wireless interface can be in *awake* state, *doze* state or *off* state [20] – we may say that a node is in a certain state, when its wireless interface is in that state. In the *off* state, the wireless interface consumes no power. Similarly, in the *doze* state, a node cannot transmit or receive, and consumes very little power. In the *awake* state, a node may be in one of three different modes, namely, transmit, receive, and idle modes, and consumes somewhat different power in each mode. The motivation of this approach is due to the fact that a significant amount of energy is consumed even in the idle mode, i.e. when there is neither transmission nor reception of network layer packets occurring. This is due to the CSMA/CA (collision avoidance) mechanism in IEEE 802.11, which requires each *awake* node to continually listen to the channel. However, directly manipulating the radio transceiver from the network layer may not be an elegant approach considering the design difficulty of routing protocol and device complexity of nodes. It is more appropriate to implement the radio switch-off process at the MAC layer where it can be efficiently coordinated with the channel access algorithm. It has been demonstrated that turning off radios intelligently at the MAC layer can reduce overall energy consumption by approximately 50% [17].

2.1.2 Topological Changes

In a MANET environment, wireless nodes are expected to move, enter or leave the network randomly, thus breaking of connectivity is anticipated every now and then. When nodes come into radio range of one another, new connections are established. Therefore, the topology of the network changes from time to time.

The depletion of energy in nodes can cause topological changes too. When a node dies out, it cannot participate in the routing process resulting in disconnections. A routing protocol for mobile ad hoc networks must therefore be designed to be robust against topological changes. One possible solution is to discover and store more than one route to a destination during route discovery, and later when one route breaks, the packets can be routed via alternative routes. Multi-path routing can reduce the frequency of route discovery and increase the robustness of a protocol against topological changes. Consequently, the routing overhead caused by route discovery can be decreased but the maintenance cost of multiple routes in terms of routing packets need to be considered to achieve a complete evaluation of the routing overhead [15].

2.1.3 Low and Variable Channel Capacity

To minimize energy consumption due to transmissions, nodes will have a very low channel capacity. For example, the PicoRadio project estimates that a future PicoNode will have a very low data rate, between 1 to 10 bits per second [16]. As a result, communication overhead must be minimum to fully maximize the channel capacity. Asymmetric links are also anticipated; hence, the protocol must also provide support for these kinds of links.

2.1.4 Large Scale Deployment

The capability to extend the mobile ad hoc network is determined, partially, by the scaling characteristics of the routing protocols used. Large-scale deployment of the network requires the routing protocols to be scalable. From a technical standpoint, routing protocols scale well if their resource use grows less than linearly with the growth of the network.

To address scalability, the routing protocols can fall into three classes: flat routing, hierarchical routing, and geographic position information assisted routing approaches [18]. The flat routing protocol can be further divided into two categories, namely, proactive routing and on-demand routing. Unfortunately, most flat routing schemes only scale up to a certain degree. Proactive routing protocol maintains consistent, up-to-date, global routing information in the network, and stores it in routing tables.

When wireless network size and mobility increase (beyond certain thresholds), on one hand, excessive routing update overhead is generated due to frequent exchanges of routing information network wide, resulting in over consumption of the bandwidth. Consequently, data traffic is blocked, rendering it unfeasible for bandwidth limited wireless ad hoc networks. Similarly, routing table size grows linearly with network size. Both the high routing storage and processing overhead make it impossible for flat proactive routing schemes to scale well to large network size. Reactive or on-demand routing protocols are intended to remedy the scalability and routing overhead problems since they only require nodes to establish and maintain routing information when needed. Thus, reactive routing protocols exhibit lower storage and processing overhead even in very large networks as long as mobility is low and traffic is light. In a large network with highly dynamic node movement and heavy traffic load to many different destinations, however, reactive routing can incur huge amounts of flooding packets in search of destinations and leads to very high routing control overhead. In a network of 100 nodes and 40 sources with uniform traffic pattern, the results in [19] show that both DSR and AODV generate more routing overhead than actual throughput. It has clearly shown the scalability problem of the reactive routing protocols.

Typically, when wireless network size increases (beyond certain thresholds), current flat routing schemes become infeasible because of large storage and processing overhead. Thus reducing routing control overhead becomes a key issue in achieving routing scalability. One possible solution is by making the routing algorithm hierarchical. An example of hierarchical routing is the Internet hierarchy, which has been practiced in wired network for a long time. Wireless hierarchical routing is based on the idea of organizing nodes in groups and then assigning nodes different functionalities inside and outside of a group. Both routing table size and update packet size are reduced by including in them only part of the network (instead of the whole), thus control overhead is reduced. The most popular way of building hierarchy is to group nodes geographically close to each other into explicit clusters. Each cluster has a leading node (cluster head) to communicate to other nodes on behalf of the cluster. The major advantage of hierarchical routing is the drastic reduction of routing table storage and processing overhead [18]. But there is one potential problem of hierarchical routing, that is, some leading nodes (cluster heads) may actually lose energy more quickly than other non-special nodes. Thus hierarchical routing may run into conflict with the energy-efficiency requirements of MANET.

Geographic position information assisted routing approaches use location information for directional routing to reduce routing overhead. The storage overhead is also limited to a small table for storing routing and location information of neighbors. Nonetheless, additional overhead for location services (including location registration and location databases lookup) [18] is introduced and must be considered. In general, network scalability is limited by: control and storage overhead, degree of mobility, network density, and traffic load. We summarize the important characteristics and requirements relevant to the network layer or routing protocol design in Table 2.1.

Table 2.1: Characteristics of MANET and the consequential requirements on routing protocols

Characteristics	Requirements
Limited energy source	(1) Minimize routing overhead (2) Power-off radio when idle.
Topological changes	Multiple routing
Low and variable channel capacity	(1) Minimize routing overhead and packet header (2) Support asymmetric links
Large scale deployment	Scalable routing: (1) Flat routing (2) Hierarchical routing (3) Geographic poison information assisted routing

2.2 Village Radio Network Overview

Village radio network [1] is a kind of wireless ad hoc network, which is characterized by mobile nodes and relays, low and variable channel capacity, and dynamic topology due to node mobility. In this study, we concentrate on three main layers: the physical, media access control (MAC), and network layers. A physical link is created between two radios for communication. The physical layer handles the communication across this physical link, which involves modulating data onto the medium in a way that can be demodulated by the intended receiver. Next, the MAC layer provides the service of coordinating the access to the medium, since many radios coexist in the same radio frequency environment where signals can interfere with each other. Above the MAC layer, the network layer resolves the path for a packet to take, when nodes that are not within physical radio range of each other wish to communicate, through other nodes that forward packets on their behalf. This forwarding of packets is often referred to as multi-hop networking, and the nodes doing so are referred to as routers. In village radio network, active terminals in the network will act as routers, and rebroadcast signals from neighbors to extend their range.

The uniqueness of village radio network [1] is that signals are allowed to take multiple paths through the network simultaneously without distorting them. After a signal has passed through the multi-path network, the receiving node can combine the individual signals to produce a stronger signal instead of losing the information due to interference. Therefore, the signal arriving at the destination is a composite of the signals from various paths. Though innovative, energy consumption had not been a requirement of the initial design. Large-scale deployment of village radio network also needs to be addressed to determine network scalability.

CHAPTER 3 A SURVEY OF AD HOC ROUTING PROTOCOLS

Many routing protocols for MANET have been proposed over the last few years, but problems remain to be solved before any standard can be realized for MANET routing protocols. In this chapter, we first introduce several general concepts in routing, and then we present a brief survey of mobile ad hoc routing protocols. A further study is provided on the on-demand routing protocols, and two of the most typical on-demand routing protocols are discussed in details. A simulation study will be carried out in chapter 7 in order to provide a quantitative and qualitative analysis on how these protocols may perform in a village radio network, i.e. our target network. The analysis is based on the most important requirements of MANET (in particular a village radio network) relevant to the network layer, which we have determined in Chapter 2.

3.1 General Concepts

Because many of the proposed ad hoc routing protocols have a traditional routing protocol as an underlying algorithm, it is necessary to understand the basic operation for conventional protocols like link state, distance vector and source routing.

3.1.1 Link-State Routing

In link-state [25] routing, each node maintains a view of the network topology with a cost of each link to its directly connected neighbors. To keep these views consistent and up-to-date, each node periodically broadcasts the link costs of its entire outgoing links to all other nodes in the network using flooding. This is also done whenever there is a change in topology or link costs. As a node receives the link-state information, it updates its view of the network topology and applies a shortest path algorithm to choose the next hop for each destination. Note that asynchronous link cost updates may give rise to short-lived routing loops; however, they disappear by the time update messages have propagated throughout the network.

The Open Shortest Path First Protocol (OSPF) [25] is one of the most widely used link-state routing protocol, where each node calculates and broadcasts the costs of its outgoing links periodically or whenever a link failure occurs, and Dijkstra's shortest path algorithm [25][26] is applied to calculate routes and determine next-hops from the sum of all the accumulated link-state knowledge.

3.1.2 Distance-Vector Routing

In distance-vector [25] routing, each node monitors the cost of its outgoing links and calculates the shortest distance (or lowest cost) to every other node in the network. Each node constructs a distance-vector containing the distances or costs to all other nodes; it regularly disseminates that vector to its directly connected neighbors rather than broadcasting this information to all nodes in the network. The receiving nodes then use this distance-vector information to update their routing tables by using shortest path algorithm.

For each destination i, every node j maintains a set of distances or costs, $d_{ik}(j)$, where k ranges over the neighbors of i. Node k is treated as the next hop node for a data packet destined for i, if $d_{ik}(j) = \min \forall k\{d_{jk}(j)\}$. To keep these distances up-to-date, whenever there is any change of this minimum distance because of link cost changes, the new minimum distance is reported to the neighboring nodes. If, as a result, a minimum distance to any neighbor changes, this process is repeated.

The main disadvantage of distance-vector routing is the formation of both short-lived and long-lived routing loops. The primary cause is that the nodes choose their next-hops in a completely distributed manner based on information that can be stale. Another major problem is the *count-to-infinity problem* or the slow-convergence problem. Loops are usually avoided by annotating a path, including the penultimate node in the route records, or providing a destination-generated sequence number on route updates. Count-to-infinity between two adjacent nodes can be eliminated by using the *split horizon* technique. To hasten the convergence, *triggered updates* are allowed when link failures are detected.

Compared to link-state routing algorithm, distance-vector algorithm requires less storage space and is easier to implement. However, on the downside, distance-vector algorithm is less stable, generates more control overhead, and does not respond to topology changes or nodes failures rapidly. In mobile ad hoc networking, several proposed routing protocols adopt distance-vector routing as their underlying routing algorithm, and make respective modifications to the conventional distance-vector routing protocol to suit their own needs. The examples are DSDV [3], CGSR [4], WRP [5] and AODV [6]. DSDV, WRP and AODV also utilize periodic hello messages to facilitate local connectivity management.

3.1.3 Source Routing

Source routing generically refers to the routing technique where the packet to be routed carries in its header the complete, ordered list of nodes through which the packet must traverse. The key advantage of source routing is that intermediate nodes do not need to maintain up-to-date routing information in order to route the packets that they forward, since the packets themselves already contain all the routing decisions. However, source routing does have a weakness since each packet carries a slight overhead containing the source route of the packet. The overhead grows when the packet has to traverse more hops before reaching the destination. Thus the packets sent will be bigger due to the overhead.

3.1.4 Flooding

In a mobile ad hoc network, many routing protocols use broadcast to distribute control information, that is, send the control information from an origin node to all other nodes. A widely used form of broadcasting is flooding [26], which generally refers to the routing technique where a packet is forwarded by a router from any node to every other node or part of nodes in the network except the node from which the packet arrived. The origin node sends its information to its neighbors, which refer to all nodes that are within the originator’s radio range in the wireless case. The neighbors relay it to their neighbors and so on, until the packet has reached all nodes in the network. To ensure that a node will only relay a packet once, certain sequence number has been used. This sequence number is increased for each new packet a node sends. In some cases, flooding also refers to broadcast to part of the network, when used in multicast packets.

Flooding is a way to distribute routing information updates quickly to every node in a large network. The Internet's Open Shortest Path First (OSPF) protocol, which updates router information in a network, uses flooding. Flooding is also widely used in ad hoc networks, but is inefficient when the ad hoc network is very dense.

3.1.5 Unicast and Multicast

Unicast is communication between a single sender and a single receiver over a network. The term exists in contradistinction to multicast, communication between a single sender and multiple receivers, and anycast, communication between any sender and the nearest member of a group of receivers in a network. An earlier term, point-to-point communication, is similar in meaning to unicast. The new Internet Protocol version 6 (IPv6) supports unicast as well as multicast and anycast.

3.2 MANET Routing Protocols

3.2.1 Protocol Overview and Classification

In this section, a number of MANET routing protocols are reviewed with a special emphasis on the demand-driven routing protocols. Several representative MANET routing protocols are discussed in particular. However, this study will not attempt to come up with a detailed description of every existing protocol due to the large volume of ad hoc routing algorithms available. Complete surveys have been conducted by [12][13].

The numerous MANET routing protocols can be broadly classified into two categories: table-driven and demand-driven, with those possessing characteristics of both, referred to as hybrid protocols. Table-driven or pro-active routing protocols require the maintenance of consistent, up-to-date routing information from each node to every other node in the network. Every node adopts one or more routing tables, which contain basic routing information including the next-hop and the number of hops to every known destination, and additional helpful information that varies according to different routing protocols. For example, the Wireless Routing Protocol (WRP) [5] is a table-based protocol that requires each node to maintain four routing tables: (a) distance table, (b) routing table, (c) link-cost table, and (d) message retransmission list (MRL) table. Unlike fixed network routing protocols, MANET routing protocols require nodes to update route information in response to frequent topology change in the network. In order to keep fresh and consistent routing information, the nodes exchange route information periodically by propagating updates throughout the network. This has the advantage of minimizing delay in obtaining a route when initiating traffic to a destination and quickly determining whether a destination is researchable. The disadvantage of periodic propagation of updates is that significant network resources can be consumed. Furthermore, the resources used to establish and re-establish unused routes are entirely wasted. Destination-Sequenced Distance-Vector routing protocol (DSDV) [3], Clusterhead Gateway Switch Routing protocol (CGSR) [4] and Routing Protocol (WRP) [5] belong to this category.

To avoid setting up and maintaining unused routes in MANETs, source-initiated demand-driven or on-demand routing is proposed. On-demand routing is also called reactive routing because nodes are not required to maintain any routes in advance; routes are searched and maintained only when source nodes need to send traffic to destination nodes. In MANETs, the network topology is in continuous flux – existing paths are broken and new paths are made as the nodes move. As a result, the cost of maintaining unused routing information in MANETs is much higher than in a fixed/static network. Thus, demand-driven routing protocols, which discover routes only when desired, are more efficient than table-driven routing protocols. Pure on-demand, location-aided, and beaconing-based routing protocols fall under this category. Examples of pure on-demand routing protocols are Ad Hoc On-Demand Distance Vector (AODV) routing [6], and Dynamic Source Routing (DSR) [7]. An example of location-aided routing is Location-Aided Routing (LAR) [9]. Two ad hoc protocols that use beaconing have been proposed: Signal Stability based Adaptive Routing (SSA) [10] (uses signal strength) and Associativity-Based Routing (ABR) [14] (uses associativity). We will further discuss on-demand routing protocols in section 3.2.2.

Hybrid routing combines the strategies in both table-driven and on-demand to get the best of both worlds. Table 3.1 presents a comparison of table-driven protocols, and Table 3.2 presents a comparison of on-demand protocols.

Table 3.1: Comparisons of the characteristics of table-driven routing protocols

Type	Table-driven		
Protocol	DSDV	CGSR	WRP
Routing Philosophy	Flat	Hierarchical	Flat
Metrics	Shortest Path	Shortest Path	Shortest Path
Convergence	Active	Active	Active
Loop Free	Yes	Yes	Yes, but not instantaneous
Routing Overhead	High	High	High
Radio-off operation	No	No	No
Scalability	No	Yes	No
Summary	Routing table exchange	Routing table exchange	Routing table exchange

Table 3.2: Comparisons of the characteristics of on-demand routing protocols

Type	On-demand				
Protocol	AODV	DSR	LAR	SSA	ABR
Routing Philosophy	Flat	Flat	Flat	Flat	Flat
Metrics	Freshest & Shortest Path	Shortest Path	Shortest Path	Associatively & Stability	Associatively & Shortest Path
Convergence	Passive	Passive	Passive	Passive	Passive
Loop Free	Yes	Yes	Yes	Yes	Yes
Routing Overhead	Moderate	Moderate	Low	Moderate	Moderate
Radio-off operation	No	No	No	No	No
Scalability	Yes	Yes	Yes	Yes	Yes
Summary	Route discovery	Route discovery	Route discovery	Route discovery	Route discovery

3.2.2 On-demand Routing Protocols

On-demand routing protocol consists of two major processes: a route discovery process and a route maintenance process. The route discovery process is initiated when a node requires a route to a destination, by broadcasting a route request packet. Each intermediate node receiving the route request records the link over which it was received and re-broadcasts the route request. The intermediate nodes also make sure that duplicate route request packets will be dropped without being rebroadcast. The destination eventually receives the request over each viable route and can select one based on metrics (e.g. hop-count or latency) included in the request. When the request reaches the destination, a route reply packet is sent back to the source, instantiating routing information at the appropriate intermediate nodes. Similar to table-driven routing protocols, each node stores the routes information in the format of route cache or route table. Once the reply reaches the source, data traffic can be sent to the destination.

On-demand protocols do not spend resources in establishing and maintaining unneeded routes, but the route discovery process itself spends some amount of resources, which is potentially expensive. Route discovery introduce extra control messages: the route request packet and route reply packet. In particular, the route request packet is flooded throughout the network until it reaches the destination or an intermediate node with a cached route to the destination. This global search could generate significant traffic in the network, especially in large and highly connected networks. In normal flooding, each node will forward the route request packet on its entire outgoing links except for the one on which the packet was initially received. Flooding is highly redundant and highly energy-consuming since each node receives the route request degree times and the request can propagate far beyond destination. Some techniques to reduce the number of "redundant" transmissions in the route request broadcast flooding process are listed as below,

- Using a sequence of hop-limited route requests rather than a single pervasive request
- Utilizing location information to direct rebroadcast to a expected zone [9]
- Using the degree of association stability or signal strength heuristics for determining most productive re-broadcast.
- Trading the reduced traffic load obtain by using probabilistic re-broadcast against the risk that the request does not reach the destination.

The route request flooding process also causes the problems of contention and collision. Because nearby nodes will receive and re-broadcast messages at roughly the same time, contention happens when senders can hear each other and collision happens when senders cannot hear each other. Adding random delay to re-broadcast will reduce collision.

On-demand protocols introduce inherent route set-up latency, which can be both high and variable. Route latency becomes much more variable than the constant-time table-lookup associated with proactive protocols. Many on-demand protocols specify that an intermediate node that has a route to the destination may send a route reply on its behalf which can decrease route latency to some degree, but this also requires stricter cache correctness and higher resistance to faulty cache data.

Movement of nodes that lie along an active route will affect the routing to this route's destination. As the nodes move, existing routes can be broken but new routes can also become available, thus route maintenance process is introduced to keep cached route information up-to-date and guarantee high data packet delivery. The route maintenance process is initiated when route failures are detected. Failed or expired routes are deleted, and the node (can be either a source or an intermediate node) that detects the route failure, will re-initiate route discovery to establish a new route to the destination if the route is still needed. Route maintenance depends on the failure detection model provided by lower layers. If only upper layer (i.e. end-to-end) failure detection is available, then route discovery must be reinitiated at the source node. If hop-by-hop failure detection, based on link layer or passive acknowledgements, is used then it may be possible to do a localized route discovery to repair the broken routes. Some protocols incorporate proactive "hello messages" into the route maintenance process. The maintenance procedure of a route ends when the destination of the route becomes inaccessible along every path from the source or when the route is no longer desired. Two of the most popular reactive routing protocols are DSR and AODV.

3.2.3 Dynamic Source Routing (DSR)

DSR [7] allows nodes to dynamically discover a route across multiple network hops to any destination by using source routing instead of hop-by-hop routing. It does not use periodic router advertisement messages, thereby reducing network bandwidth overhead and avoiding large amount of routing updates throughout the ad-hoc network, particularly during periods when little or no significant node movement is taking place. Moreover battery power is conserved on the mobile nodes, by not sending and receiving the advertisements. The nodes can switch themselves into "sleep" or "idle" mode when not busy with transmitting or receiving signal, which helps to reduce nodes' power usage considerably.

DSR protocol consists of two major mechanisms: route discovery and route maintenance. The global search procedure is employed in route discovery, where any source node wishing to send traffic to a destination node broadcasts a route request (RREQ) packet in the network. The route request packet will first be received by the hosts within the original initiator's transmission range, and then be rebroadcast if the destination has not been reached, or none of the intermediate nodes know a route to the destination. The RREQ propagates through the network until either the destination or a node with a route to the destination is reached. When either of these happens, a Route Reply (RREP) is unicast back to the originator of the route discovery.

The route to return the RREP packet back to the originator of the route discovery can be retrieved in several ways. If symmetrical links are assumed in the network, the destination may reverse the hop sequence in the route record from the route request packet, and use this route to send the route reply packet. To do this, DSR checks the route cache of the replying node. If a route is found, it is used instead. DSR also adopts an alternative way by piggybacking the RREP packet on a RREQ targeted at the initiator of the route discovery to which the host is replying. This means DSR can support route discovery in the absence of symmetrical links. If the route discovery is successful, the initiating host receives a route reply packet listing the sequence of network hops through which it may reach the destination. And the new route is stored in the route cache with a time stamp.

Route maintenance in DSR monitors the continued correct operation of the route in use and informs the senders routing errors if any. It is used when a link breaks, rendering specified path unusable. When route maintenance detects a failure on an active route, a route error message is sent back to the source node. When this error message is received, the hop in error is deleted from the host’s route cache, and all routes that contain this hop are truncated at that point. Route maintenance can be performed using the hop-by-hop acknowledgements, or the end-to-end acknowledgements if the particular wireless network interfaces or the environment in which they are used are such that wireless transmissions between two hosts do not work equally well in both directions. With hop-by-hop acknowledgements, the particular hop in error is indicated in the route error packet, but with end-to-end acknowledgements, the sender may only assume that the last hop of the route to this destination is in error.

3.2.4 Ad Hoc On-Demand Distance Vector Routing

The Ad Hoc On-Demand Distance Vector (AODV) [6] routing protocol enables dynamic self-starting multi-hop routing in MANET. By using hop-by-hop routing, AODV can reactively establish route table entries at each node. AODV is fundamentally a combination of Dynamic Source Routing (DSR) and Destination-Sequenced Distance Vector (DSDV) algorithms. It coalesces the Route Discovery and Route Maintenance mechanisms of DSR with the hop-by-hop routing of proactive DSDV. DSR fares well in terms of throughput and end-to-end delay over a variety of environmental conditions such as host density and movement rates; however, it generates high overhead when host movement in the network is very frequent. As a proactive routing protocol, DSDV requires each mobile node to maintain a complete list of routes, one for each destination in the ad-hoc network. But this procedure almost always exceeds the need of any particular mobile node, resulting in a waste of limited resource in MANET. AODV is designed to eliminate the weakness of both DSR [7] and DSDV [3], and is intended for an ad-hoc network whose links are frequently changing. Three types of message are introduced in AODV for its operations: Route Request, Route Reply, and Multicast Route Activation messages, which are UDP/IP messages.

AODV is a reactive or on-demand protocol, which only initiates a path/route discovery process whenever a new route to a destination is needed. This destination can consist of either a single node or a multicast group. The source node will broadcast to all its neighbors a Route Request (RREQ) packet, containing the source address, the source sequence number, a broadcast ID, the destination address, the destination sequence number as well as a hop count. Hop count is the number of hops from the source's IP Address to the node currently handling the request. The pair of source’s IP address and broadcast ID uniquely identifies a RREQ. This enables a node to discriminate and discard duplicate RREQ since it may receive multiple copy of the same RREQ from different neighbors. The two sequence numbers incorporated in the RREQ packet are used to assure freshness information about the routes, specifically, the destination sequence number is used to maintain the freshest route to the destination, while the source sequence number assures the freshness of reverse route to the source. Given the choice between two routes, the requesting node always selects the node with the greater sequence number. Note that, similar to DSDV, destination sequence number also guarantees that no routing loops can form.

As the RREQ propagate through the network, each node receiving an RREQ establishes a reverse route back to the source of the RREQ. To set up a reverse route, each node records the address of the neighbor from which it received the first copy of RREQ. These reverse routes are kept valid for at least enough time for the RREQ to travel across the network and produce a reply to requesting node. When the RREQ reaches the destination or a node with a fresh enough route to the destination, a Route Reply (RREP) is generated and unicast back to the source through the reverse route.

A Route Reply message (RREP) contains the information: the source and destination addresses, destination sequence number, hop count and the lifetime. Lifetime is the time for which the nodes receiving the RREP consider the route to be valid. As the RREP traverses back to the sender of RREQ, each node caches the previous hop from which the RREP came, updates its timeout information for route entries to the source and destination, and records the latest destination sequence number for the requested destination. Thus when the first RREP reaches the source node, a route from source to destination is created. The source can update its routing information if it learns a better route from later RREP messages.

For route maintenance, AODV enables nodes to transmit periodic *hello* messages to detect link failures. Alternatively, AODV briefly specifies an option that allows for the use of link layer acknowledgements for transmission failure detection. Once the next hop becomes unreachable, the node that detected the link breakage will remove the matching route entry from its route table, and propagates an unsolicited RREP with a fresh sequence number and a hop count of infinite to all active upstream nodes along the broken route. The message will eventually arrive at the source that can choose to either stop data transmission or restart the route discovery process.

The weakness of AODV is that it only supports one route for each destination. In fact, any form of multi-path technique could always perform significantly better than single path routing [15], but there is a prerequisite that the alternative route will not break earlier than the one in use. Maintaining invalid multiple routes simply wastes network resource, and should be avoided. In a network with continuously changing topology due to high node mobility, multi-path routing may not always be a wise choice. However, multi-path routing may be useful in high mobility situations to provide redundant paths that could be called upon to achieve high connectivity and quick response in determine backup/standby routes.

The advantage with AODV compared to source routing based protocols like DSR is that AODV makes connections from the ad-hoc network to a wired network like the Internet easier. Moreover, by using reactive approach AODV has greatly reduced the number of routing messages in the network. AODV has introduced three types of message: Route Request, Route Reply, and Multicast Route Activation messages, which are UDP/IP messages. The routing overhead can still be high for a bandwidth and energy limited ad-hoc network, when the network topology changes frequently and the traffics are heavy.

In this study, we will introduce a new routing protocol (chapter 5), which is based on the concept of AODV’s route discovery mechanism, but operates in a special way to further reduce routing overhead by not introducing any routing messages in route discovery.

CHAPTER 4 MULTI-HOP TDMA-BASED MAC PROTOCOL

4.1 Overview of Village Radio Network

Village radio network [1] is a kind of wireless ad hoc network, which is suitable for both voice and data transmission for small groups of less than a hundred terminals. The village radio is a terminal that co-ordinates with similar terminals around it to form a time division multiple access (TDMA) network. No base station or special devices are needed to manage the network. The terminals autonomously establish the critical functions that form the backbone of the network, including routing and synchronization. When a village radio terminal is activated within reasonable proximity of similar radios, it becomes part of a self-organizing communications network.

There are two classes of terminals in the village radio network: active terminals and passive terminals. The active terminals form the backbone of the network by synchronizing to each other and establishing a common TDMA frame in which all communication occurs. The active terminals also act as routers, and propagate signals from neighboring terminals to extend their range. Passive terminals are simpler devices that can access the network but do not participate in routing or synchronization. For an active terminal, the routing and synchronization modules are always turned on, even when the terminal's local transceivers are inactive. This is to make sure that the network will function well and all the traffic can be delivered appropriately. However, the routing and synchronization functions are highly energy-consuming which will quickly drain the nodes' limited energy resources, thus passive terminals are introduced to conserve energy. The transceiver module of a passive terminal is identical to an active terminal so that it can access the network in the same way as an active terminal. The difference is that the passive terminal does not act as routers, nor transmit synchronization signals. The passive terminal only transmits and receives its own data messages, which significantly reduces its power consumption.

In village radio network, any terminal can send radio messages through the network using any modulation format that meets the network's bandwidth and timing specifications. Terminals are able to reach destinations beyond their range by routing signals through neighboring terminals. The initial routing algorithm is simplified considerably by exploiting the broadcast nature of radio waves and allowing the signal to take more than one path through the network at the same time. After a signal has passed through the multi-path network, the receiving node can combine the individual signals to produce a stronger signal instead losing the information due to interference. Therefore the signal arriving at the destination is a reinforcement of the signals from various paths.

4.2 Multi-hop TDMA-based MAC Protocol

Village radio network is a TDMA-based network. The TDMA frame is divided into a series of time slots according to the number of active terminals in the network. The first slot is used for synchronization signals and the rest are data slots for carrying traffic. The data slots are further divided into sub-slots as show in the Figure 4.1.

Village radio network requires that all the wireless nodes be synchronized to a common TDMA frame. As presented in [1], the clock synchronization mechanism has been implemented by allowing each node act as both a slave, locking its clock frequency to the rest of the network, and a master, pushing the network frequency to match its own reference. Thus, we assumed that the clock synchronization problem has been solved in the physical layer.

The Village Radio Protocol (VRP) refers to the TDMA-based MAC-level protocol, which allocates different sub-slots for nodes to send and receive packets. These sub-slots form a data slot, and the data slots form a TDMA frame. VRP supports multi-hop routing, and is a preamble-based TDMA MAC protocol. Each TDMA frame contains a preamble slot besides the data transmission slots. We assume that there is no contention in the preamble phase. Within the preamble, every node has a dedicated sub-slot and uses it to broadcast the destination node ID (identifier) of an outgoing packet. Each active node has a data transmission slot to send packets. During the data slots, the source node will broadcast packets, while other nodes listen and relay the packets.

In a certain TDMA time-slot, the source node broadcasts its packet during the first sub-slot and the remaining active nodes in the network use the following sub-slots to rebroadcast the packet through the network to its destination. When an active node receives the data packet in one sub-slot, it relays the packet in the next sub-slot.

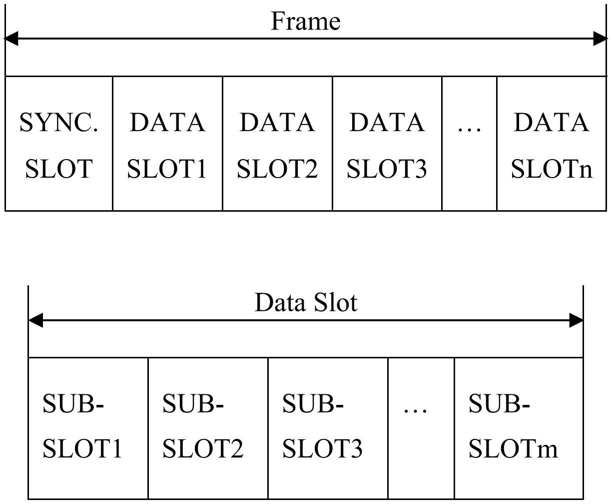


Figure 4.1: (a) Layout of the TDMA frame and (b) Details of one data slot

The basic Village Radio Protocol (VRP) [1] is based on three simple rules applied at each active terminal:

1. When an active terminal detects sufficient signal energy in one sub-slot, it rebroadcasts a copy of the signal in the next sub-slot.
2. A terminal can only transmit a signal once during any given slot.
3. A terminal cannot rebroadcast a signal across slot boundaries.

The first rule informs a terminal to forward a signal only if it has enough energy to meet a certain quality standard. After receiving the signal in the current TDMA sub-slot, these terminals simultaneously retransmit it in the next TDMA sub-slot. The second rule forces the signal to propagate away from the source terminal as it transmits through the network; thus the possible routing loops are prevented. The last rule, but not the least, is applied to stop rebroadcasting a signal after it reaches the end of its time slot. So according to this algorithm, the signal is terminated when all of the terminals in the network have transmitted the signal or when all of the sub-slots within a TDMA time slot have been used up.

There should be enough sub-slots within each TDMA slot so that rule 3 seldom needs to be used. However if there are more than enough sub-slots within each TDMA slot, rebroadcast continues on even if the destination has been reached. To minimize energy consumption, we have determined that the optimal value for the number of sub-slots (S_{opt}) within each TDMA data slot is one third of the total number of the active nodes in the network (N), and the number of data slot in a TDMA frame ($N_{data\text{-}slot}$) equals to the total number of the active nodes in the network (N). Let T_{TDMA} be the time interval for a TDMA frame. The equations are listed below,

$$S_{opt} = \left\lceil \frac{N}{3} \right\rceil \tag{1}$$

$$N_{data-slot} = N \tag{2}$$

$$T_{TDMA} = T_{sub-slot} \times S_{opt} \times N_{data-slot} = T_{sub-slot} \times \frac{N^2}{3} \tag{3}$$

The setting of an optimal slot size not only reduces unnecessary rebroadcast, but also guarantees enough sub-slots within each data slot for nodes to perform rebroadcast until the destination has been reached. Below is the proof of the correctness of our determined value $\left\lceil \frac{N}{3} \right\rceil$ for parameter S_{opt} in VRP.

Proof:

Assuming that all the wireless nodes are connected to an imaginary main cable or link called the bus. Suppose two nodes are randomly placed on a bus network; that is, each is placed independently, and the position of each is chosen from a uniform distribution over the length of the bus network, which is the total number of active nodes in the network (N).

The normalized length of the bus is 1. X_1 and X_2 denote the normalized distances from the left end of the bus network, and are real-valued variables between 0 and 1. Given the placement of the first node at a given distance X_1 from the left end of the bus network, the other node will be to the left of the first node with probability X_1 and to the right with probability $(1-X_1)$. Given that it is to the left, its expected distance from X_1 is $X_1/2$, and given that it is to the right, its expected distance is $(1-X_1)/2$. Thus, the expected normalized distance between X_1 and X_2, given X_1, is

$$E\{| X_2 - X_1 | | X_1\} = \frac{(X_1)^2}{2} + \frac{(1-X_1)^2}{2}$$

Averaging over X_1, we then have the expected normalized distance between X_1 and X_2:

$$E\{| X_2 - X_1 |\} = \int_0^1 \frac{(X_1)^2}{2} + \frac{(1-X_1)^2}{2} dX_1 = \frac{1}{3}$$

Given that the actual length of the bus network is N, i.e., the total number of active nodes in the network, the expected distance between the two nodes is $N \times \frac{1}{3}$. We conclude that the maximum number of hops allowable between any two nodes in the network is $\left\lceil \frac{N}{3} \right\rceil$. Hence, we show that the number of sub-slots (S_{opt}) within a data slot is $\left\lceil \frac{N}{3} \right\rceil$ [26].

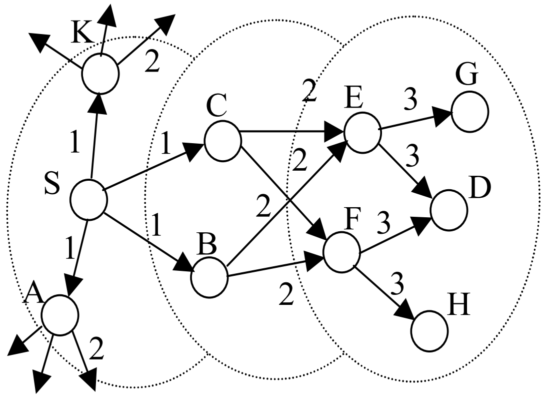


Figure 4.2: An example of the TDMA-based MAC protocol

Figure 4.2 shows how this MAC protocol is applied to support the multi-hop routing in the network. Assuming that the number of active nodes in the network (N) is 10, the number of sub-slots within each TDMA data slot is 3, according to equation (1). Let S and D be the source and destination nodes. The other active nodes in the network are A, B, C, E, F, G, H and K. When there is data to send from S to D, we assign a data slot, e.g. Data Slot 2 (DS2) to this connection in the preamble phase. Hence in the first sub-slot of DS2, S transmits its data packet. Nodes A, B, C and K within the radio range of node S will receive the packet and rebroadcast the signal in the next sub-slot. In the second sub-slot, these four nodes simultaneously rebroadcast the original message. Since nodes E and F are within their radio range, by rule 2, the source node S cannot perform any transmission in the same data slot again. In the third sub-slot, nodes A, B, C and K are disabled by rule 2; nodes E and F rebroadcast the signal, and signal reaches the remaining nodes in the network including destination D. By rule 3, broadcast will stop at the end of sub-slot 3.

The sub-slot techniques allow mobile nodes to relay multi-hop transmission for the network. Simulation results have validated the determination of S_{opt} for the TDMA-based MAC protocol, as shown in chapter 7.

Multi-path routing allows the signals to pass through many paths at the same time, rather than finding a single path through the network. In fact, the Village Radio Protocol (VRP) has employed multi-path routing but without any specific controls, which on one hand makes the network more reliable and keeps a high packet delivery (due to multi-path routing). While on the other hand, VRP performs in a highly energy-consuming way, since it is based on pure flooding, and does not maintain any routing information in the network. Since the terminals just do rebroadcast with no need to know the actual routing information, they work well if the power is sufficient. But if terminals have only limited battery power, e.g. sensor, mobile phone, and PDAs, this protocol does not work well.

Switching off the radio when idle can help mitigate the energy problem to some degree. We make VRP radios power off when not actively transmitting or receiving packets. Considering the design difficulty of routing protocol and device complexity of nodes, we have avoided directly manipulating the radio transceiver from the network layer; however, we have implemented the radio switch-off process at the MAC layer where it can be efficiently coordinated with the channel access algorithm.

Moreover, redundant data packet rebroadcast is generated due to nodes' lack of the knowledge of routing information, resulting in over consumption of the bandwidth and consequently blocks data traffic, rendering it unfeasible for bandwidth limited wireless ad hoc networks when traffic load are heavy. In general, the pure original MAC layer protocol VRP does not work well in an energy-constrained and heavy-traffic environment. Our further work is to devise a routing protocol in the network layer that is based on the algorithm described above but takes into consideration the energy problem.

CHAPTER 5 VILLAGE RADIO ROUTING PROTOCOL (VRRP)

An effective routing algorithm is the most critical technology in a mobile ad hoc network (MANET). The major drawback of table-driven MANET routing protocols is the generation of excessive routing messages due to periodic exchange of updates among the participants. Several studies have confirmed this poor behavior [2][8]. In an energy-constrained setting, excessive routing overhead not only degrades the performance of the protocol but also shortens the lifetime of nodes. Table-driven schemes are therefore not efficient for energy-constrained nodes.

To solve or lessen the problem of excessive routing overhead in table-driven routing, on-demand or reactive routing was proposed. In this approach, nodes only reactively set up and maintain routes to required destinations, when there is traffic to send. On-demand protocols have been found to generate lesser routing overhead and higher packet delivery as compared to proactive protocols [2][8].

In this study, we will develop an on-demand routing protocol aimed at minimizing energy consumption and maximizing channel capacity for use in a dynamic wireless network. We posed more rigorous requirements on the new protocol in reducing routing overhead while keeping high network throughput in the presence of changing topology. We also require the protocol to consume minimal amounts of energy possible. Moreover, the characteristics of our MAC protocol do not work well with any current routing protocol (even the typical MANET routing protocol, such as AODV [6] and DSR [7]), resulting in more difficult challenges on the routing protocol design. Generally, there is no existing routing protocol that fits the village radio network.

In the rest of the chapter, we will present the new routing scheme known as **Village Radio Routing Protocol (VRRP)**. A new route discovery technique will be introduced that allows data packet discovery of routes while not introducing any extra control packet in route discovery.

5.1 Protocol Overview

VRRP is a source-initiated on-demand routing protocol, which uses data-packet-flooding (as in the original Village Radio network) to do route discovery instead of using an additional route request packet (RREQ).

Similar to most reactive protocols, VRRP has three phases of operation, namely route discovery, route maintenance and route deletion. Route discovery occurs when a node has data to send but has no available route. The route discovery mechanism enables the discovery and use of uni-directional links to fully utilize available channel capacity. To make the protocol robust against topology changes, discovery of multiple routes to a particular destination is encouraged.

VRRP routing typically selects the shortest path to a destination, based on simple metrics such as delay. This approach works well for the network's best-effort model, but it does not provide adequate support for effective resource allocation and optimization. An alternative approach can be to take the least used route, which aims at balancing the traffic load over as many nodes as possible.

VRRP does not introduce any new messages in route discovery. Moreover, VRRP does not cache data packets that a node has forwarded for further use when the link or downstream node fails, because it can quickly react to link failure and instruct the node to revert from unicast back to broadcast immediately. Caching is not needed since the data packet can be processed immediately. Since data packets are not cached in network layer, homologous caching mechanism is made in the MAC layer where the node that detects link failure can retransmit the same data. This leads to small routing overhead and savings in energy consumption.

Route maintenance occurs only when all active routes fail. In such a case, the node detecting a link failure attempts to repair a local route by performing a route discovery process and broadcasting the data packet that has failed to reach its next hop. If this attempt fails, the node broadcasts an error message containing the unique ID of the data packet that was not transmitted successfully.

Once the next hop becomes unreachable, the node upstream of the break will delete the corresponding entry of the interrupted hop from its route cache, and all routes which contain this hop must be truncated at that point. However, the node does not need to inform its upstream nodes to delete their routes for the pair of source and destination. In fact, the link failure is localized to the node that has detected the link failure, and only this node performs route deletion. If no route error is reported, deleting the whole route is not necessary.

In the following discussion, we describe in detail the internals of VRRP. First, the route cache management is described. Then, the details of the route discovery, route maintenance and route deletion are discussed, and finally, we present a summary of the protocol operation.

5.2 Route Cache Management

VRRP requires each node to maintain a route cache for storing routing information. Next-hop information and other details needed to properly forward data packets are stored in the route cache. The route cache keeps the following information for each route entry: source, destination, next hop, hop count, and expiration time for each entry. The parameters, source and destination, are used together to identify data packet flow coming from a source-destination pair. This is essential since we have no extra control packet in route discovery. Hop count is the number of hops to the destination. A hop count of zero means that the destination is within the immediate neighborhood, and a hop count of infinity means that the destination is unreachable. The information contained in the route cache is shown in Table 5.1.

Table 5.1: Route Cache

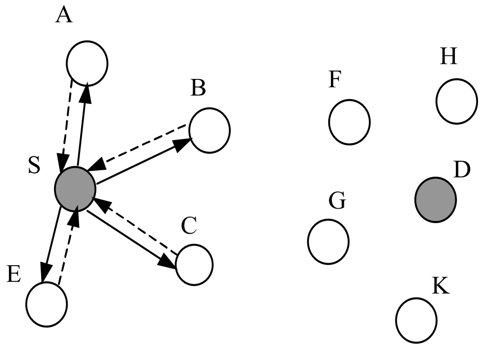
Source	Address of the source node that has data to send
Destination	Address of the destination node
Next Hop	Address of the next hop node
Hop Count	Number of hops from the destination. Set to 0 by destination, incremented as being forwarded
Expiration time for the route cache entry	The timeout for the route cache entry is reset to current time plus *ACTIVE_ROUTE_LIFE* each time the route entry is used to transmit a data successfully

5.3 Route Discovery

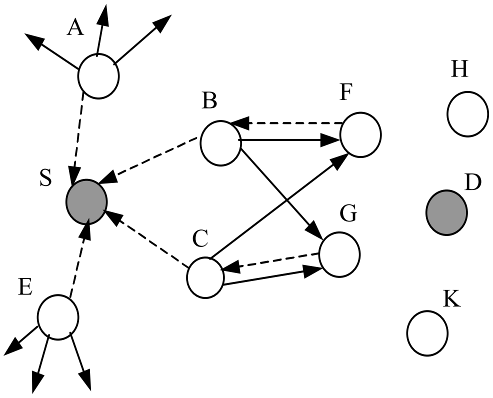
VRRP is a source-initiated on-demand routing protocol with an aim of not introducing any new messages in route discovery. The route discovery process is triggered when a non-existent route is needed for a destination. VRRP is unique in route discovery; it discovers routes on demand directly from the broadcast data packets. On route discovery, the source node will broadcast its data packet to all of its one-hop neighbors, as illustrated in Figure 5.1 (a). All neighboring nodes receive the packet and can do one of two things. If a path to the destination is in their route cache, the intermediate nodes respond authoritatively during route discovery, minimizing network overhead. Else, the nodes re-broadcast the data packet according to the three routing rules of VRP (section 4.2).

The data packet will eventually flood the entire network and find a route to the destination node by finding the destination node itself, or a cached route in another node. A reverse route is set up as the data packet travels from a source to a destination or from a source to an intermediate node, which has a route to the desired destination. To set up the reverse path, a node records the address of the neighboring node from which it received the data packet. The formation of reverse path is illustrated in Figure 5.1 (a) (b) and (c). As the data packet travels from a source to various nodes including intermediate nodes and the destination node, it eventually sets up the reverse path from all active nodes, i.e. nodes that receive the data packet, back to the source as illustrated in Figure 5.1 (c). The information of the reverse route are stored in the route cache (section 5.2), and the lifetime of the reverse route REV_ROUTE_LIFE is set to be long enough for the data packet to flood the network and generate a reply to the sender.

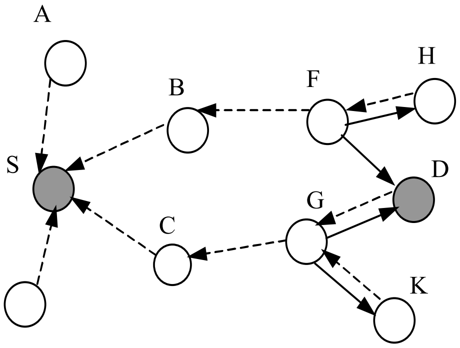
Note that VRRP requires nodes to record the address of exactly one of the neighboring nodes from which it received the data packet so that a reverse path is established. However, each node can have more than one neighboring nodes that send it the same data packet due to the uniqueness of village radio network [1] that signals are allowed to take multiple paths through the network simultaneously without distorting them. After a signal has passed through the multi-path network, the receiving node combines the individual signals to produce a stronger signal instead losing the information due to interference. Therefore the signal arriving at the receiving node is a reinforcement of the signals from various neighboring nodes. VRRP use minimum delay criterion to determine which neighboring node as the next hop on the receiving node's reverse path. That is when a node receives multiple copies of a data packet, it records the address of the neighboring node from which it received the first copy of the data packet. An example is shown in Figure 5.1 (b), node G received multiple copies of data packet from B and C, and since G received the copy from node C first, it determined that the next hop on the reverse path from G to S is C. In Figure 5.1 (c), the destination D received multiple copies of data packet from F and G, but D received the copy from node G first, so D determined that the next hop on the reverse path from D to S is G. By using minimum delay criterion in establishing a reverse path, VRRP guarantees a path from source to destination with lowest delay.



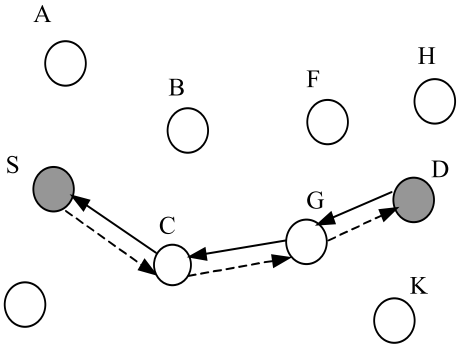
(a) Source S broadcasts data packets searching for destination D. All of its one-hop neighboring nodes receive the packet, set up a reverse link to S, and store the information of the reverse link in their route cache respectively. The reverse links AS, BS, CS and ES are established as shown.



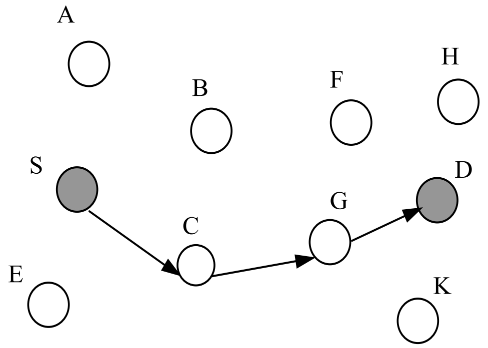
(b) Nodes A, B, C and E re-broadcast the data packet according to the three routing rules of VRP, the one-hop neighboring nodes F and G receive the packet. F set up a reverse link to B, and G set up a reverse link to C according to minimum-delay criterion. The information of the reverse link is stored in their route cache respectively. The reverse links FB and GC are established as shown.



(c) Nodes F and G re-broadcast the data packet according to the three routing rules of VRP, the one-hop neighboring nodes H, K and D receive the packet. The destination node **D** is reached by the data packet coming from F and G. D set up a reverse link to G, H set up a reverse link to F, K set up a reverse link to G according to the minimum-delay criterion. The information of the reverse link is stored in their route cache respectively. The reverse links DG, HF and KG are established as shown. The destination D waits for a while before replying.



(d) The destination node D decides that a stable route between S and D has been found, and send a route reply packet (RREP) back to S along the reverse path D-G-C-S. The forward path from S and D has been established as RREP travels from D to S, as shown in dashed line.



(e) The source node S receives the RREP, and decides that the route S-C-G-D has been established as shown.

Figure 5.1: The formations of reverse path and forward path.

Destination nodes need to keep a record of the data packets received from every source. After a certain period of data transmission, destination nodes will decide when to inform the source that a stable route can be established, and then a route discovery response will be sent along the reverse route. This approach is to avoid sending unnecessary reply message to the source when a burst of data is transmitting in a highly dynamic MANET scenario, and thus reduce routing overhead. However, for long-period traffic transmissions in a MANET where the node mobility is rather low, the topology change is less frequent, VRRP can be simplified to not record the traffic that a destination node receives, and the destination node will send a route discovery response along the reverse route once the destination receives a data packet from the source. In general, monitoring traffic from the destination helps improve the robustness of our routing protocol.

When a destination node decides that a stable route becomes available, it will send a unicast route reply packet (RREP) back to its neighbor from which it received the data packet. Figure 5.1 (d) represents the forward path setup as the RREP traverse from the destination to the source node. The information included in the RREP is shown in Table 5.2. The hop count is initialized to zero when the destination node sends a RREP, and it is incremented every time a route reply packet is forwarded to the corresponding previous hop. If a node is on the path between the source and destination, it sets up a forward pointer to the node from which it received the RREP. The node also updates its timeout information for route entries to the source and destination nodes by extending a period of ROUTE_REPLY_LIFE and ACTIVE_ROUTE_LIFE respectively. If a node is not on the path, it will not receive the RREP, and will delete the reverse pointer after a period of ACTIVE_ROUTE_LIFE. If no path to the destination node exists, the data packet will be dropped when its data slot expires. The intermediate node needs to listen for the path discovery response so that it can set up the forward route for a certain pair of source and destination nodes. The intermediate node will decide that it is on the path between the source and destination if it hears transmissions on both directions between the source and destination nodes. Thus when RREP successfully reaches the source node, a forward path or a route to destination has been established, as illustrated in Figure 5.1 (e).

Table 5.2: Route Reply

Source	Address of the source node that has data to send
Destination	Address of the destination node
Previous Hop	Address of the previous hop node
Hop Count	Number of hops from the destination. Set to 0 by destination, incremented as being forwarded
Lifetime	The period of time during which a Route Reply is alive

During the route discovery period, energy consumption is drastic due to pure packet flooding. After a route has been discovered, a host will specify the route a data packet must take by looking up the source and destination in its route cache. In this way, we reduce unnecessary re-broadcasting after a period of transmission, and therefore conserve energy.

5.4 Route Maintenance

Route maintenance is started when a node along an active route notices a link that has gone down. Broken links but not the whole routes are then deleted and new route discovery process is initiated. To ascertain whether a route is up or down, VRRP uses link layer feedback, if this is available. In this study, we use link layer feedback that is implemented in the TDMA-based MAC protocol. When the MAC protocol can no longer send a data packet to a neighbor, the link to the neighbor is regarded as broken, and the distance is marked with value infinity.

In many wireless networks, a hop-by-hop acknowledgement is utilized at the data link level in order to provide early detection and retransmission of lost or corrupted packets. In wireless networks, which do not support such lower-level acknowledgements, an equivalent acknowledgement known as *passive acknowledgement* [7] can be utilized if the sender is able to hear the next-hop receiver transmitting the packet again on its way further along the path, i.e. the sender can operate its wireless network interface in promiscuous mode. In our study of VRRP, we implemented a hop-by-hop acknowledgement mechanism in the data link layer (namely VRP), with an additional rule that the acknowledgement has a higher priority to be processed than data packet according to VRP. And VRP assures that there is no collision or contention in transmissions, detailed explanations are presented in section 6.3 and [27]. We assume that a data packet is transmitted successfully from the node to its next hop when the node receives an acknowledgment from the next hop. Otherwise, we assume that a link along an active route goes down when there is no acknowledgment coming from the next hop. Once the next hop becomes unreachable, the corresponding entry of the failed hop is removed from the route cache of the node that detected the link breakage, and all routes that contain this hop must be truncated at that point. However, there is no need for the node to inform its upstream nodes to delete their routes for the pair of source and destination. The link failure is localized to the node that has detected the link failure, and only that node performs route deletion. If no error message reported, deleting the whole route is not necessary.

The node that encounters link breakage, source or intermediate, will re-initiate the route discovery procedure to establish a new route to the destination. In such a case, the node attempts to discover routes by broadcasting its data packets to all of its 1-hop neighbors within its propagation range. If this attempt fails, the problem node need to send the source node a route error (RERR) message containing the unique ID of the data packet that was not transmitted successfully. The detailed information included in the RRER is shown in Table 5.3. After receiving the RERR, if the source node still desires the route, it can reinitiate route discovery.

Table 5.3: Route Error

Error Source	Address of the node that encounters the routing error
Data Source	Address of the source of the data packet
Data Destination	Address of the destination of the data packet
Data ID	The sequence number of the data packet that causes the error

Due to the per-hop link layer feedback, a link failure can be discovered immediately, and the node can revert from unicast back to broadcast immediately. Caching is not needed since the data packet can be processed immediately.

5.5 Route Deletion

A link failure feedback from the lower layer will provoke the route deletion. In the mobile ad hoc network, active routes are frequently changed and the request for route reconfiguration frequently occurs because of node movement. As a result, data is lost. Reliable data transmission is more difficult when the mobile nodes move continuously and rapidly. Since our MAC layer protocol (VRP) provides hop-by-hop reliable transmissions, packet losses occur only during node or link failures. If data loss is detected by any node between source and destination, VRRP will know exactly which node has encountered the link failure on the route, and then respond quickly and locally. Namely, when a node (problem node) finds the next hop unreachable during data transmission, it will delete the corresponding entry in the route cache, broadcast the packet to all its 1-hop neighbors (executed in MAC layer), and reactivate the route discovery (executed in network layer). If this attempt fails, e.g. when there are no nodes within the problem node's radio range or all nodes around the problem node are running out of power, an error message will be propagated to the source node indicating there is an unreachable destination in the network. Note that we have manipulated both the MAC layer and network layer, and the cross-layer operation has made our design simpler but elegant.

The deletion of a route will also occur if an entry has not been used within a specified lifetime.

5.6 Protocol Operation Summary

To close this chapter, we present a summary of the protocol operation process in Figure 5.2.

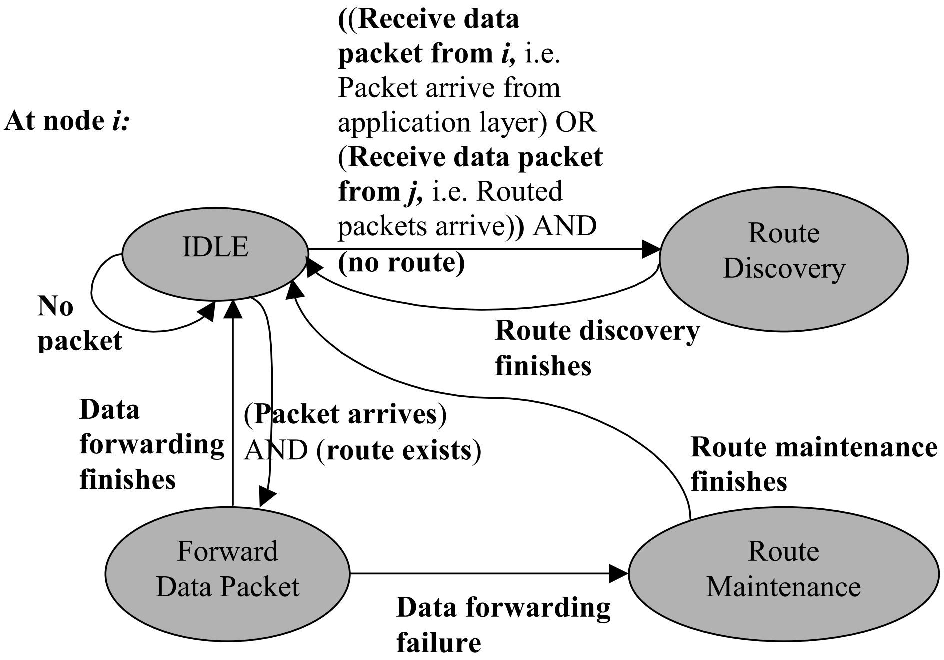


Figure 5.2: VRRP Operation

CHAPTER 6 SIMULATION MODEL DESIGN

In this chapter, we will discuss the simulation models used in the study. The simulation models were developed based on the characteristics and requirements of village radio network discussed in chapter 2. The simulations were executed in the network simulator *ns-2* [21], which will be discussed in the following section.

6.1 Network Simulator Overview

Network simulator (*ns-2*) is a discrete event simulator developed for networking research by the University of California at Berkeley and the VINT project [21]. The Rice Monarch Project formerly known as CMU Monarch Project [22], has contributed substantial wireless and mobility extensions to the *ns-2* network simulator that enable it to accurately simulate mobile nodes connected by wireless network interfaces, including the ability to simulate multi-hop wireless ad hoc networks. Moreover, *ns-2* provides important support for simulation of TCP, unicast and multicast routing protocols over wired and wireless (local and satellite) networks. The newest version of *ns-2* also provides power consumption simulation support.

Figure 6.1 depicts a schematic of a mobile node that implemented in *ns-2*. The mobile node makes uses of a routing agent for the purpose of calculating routes to other nodes in the network. When packets are sent from the application agent and are received by the routing agent, the routing agent will decide a path that the packet must travel through in order to reach its destination and stamps it with this information. It then sends the packet down to the link layer, which uses an Address Resolution

Protocol (ARP) to decide the hardware addresses of neighboring nodes and translate IP addresses to their correct interfaces. When this information is known, the packet can be sent down to the interface queue and awaits a signal form the Medium Access Control (MAC) Protocol. When the MAC layer is ready to send the packet to the channel, it fetches the packet form the head of the queue and hands it over to the network interface which in turn sends the packet onto the radio channel. From there this packet is copied and delivered to all network interfaces at the time at which the first bit of the packet would begin arriving at the interface in a physical system, based on the distance between the nodes and the speed of light. Each network interface stamps the packet with the receiving interfaces properties and then invokes the propagation model.

Regarding the packet reception process, the propagation model uses the “transmit” and “receive” stamps to determine the power with which the interface will receive the packet. The receiving network interfaces then use their properties to determine if they have successfully received the packet, and send it up to the MAC layer if appropriate. If the MAC layer receives the packet with no error reported, it sends the packet up to the link layer that passes the packet to the mobile entry point. From here the packet reaches a demultiplexer, which will make a decision on where to send the packet. If the packet has reached its final destination, the “address demux” will pass it to the “port demux”, which will hand the packet to the proper application agent. Otherwise, the address demux shall pass the packet to the default target of the address demux, and the packet shall be forwarded again. Thus, the routing agent at this node will be called on to assign the packet a next hop and pass it back to lower layer. And the procedure will be repeated.

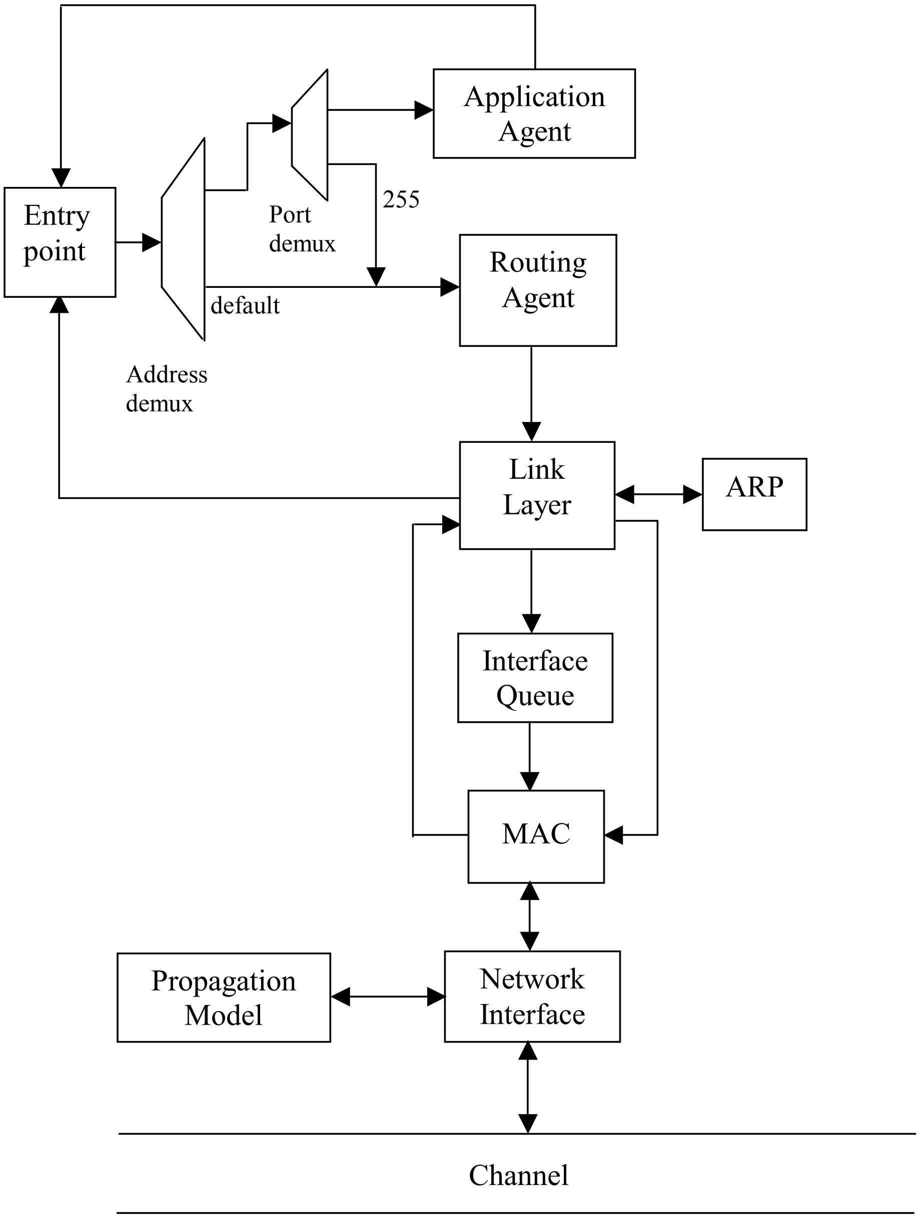


Figure 6.1: Schematic of a mobile node under ns-2

Current version of *ns-2* with the CMU Monarch wireless extensions [22] can simulate multi-hop wireless mobile ad hoc networks; however, it provides no support for accurately simulating the physical aspects of multi-hop wireless Village Radio networks or the MAC protocol needed in such environments. In this simulation study, we made some modifications to *ns-2* to allow accurate simulation of our target mobile wireless networks, i.e. village radio networks. We followed the basic mobile node structure under *ns-2*, but have made certain extensions to *ns-2* in physical, MAC and routing layers. We have implemented the VRP (Chapter 4) in the MAC layer and the VRRP (Chapter 5) in the routing layer respectively in the network simulator *ns-2*. With the new elements provided by our extensions to *ns*, it is possible to construct detailed and accurate simulations of village radio network, a TDMA-based ad hoc network. The following sections will describe more about the important layers implemented in our simulation study.

6.2 Physical Layer Model

To accurately model the physical layer, *ns-2* includes a radio propagation model that supports propagation delay, capture effects, and carrier sensing [23]. The radio propagation model combines both a free space propagation model and a two-ray ground reflection model. When a transmitter is within the reference distance of the receiver, we use the free space model where the signal attenuates as $1/r^2$. Outside of this distance, we use the ground reflection model where the signal falls off as $1/r^4$ [23].

The implementation of the physical layer is based on the design of village radio network where the radio receiver can combine the individual signals to produce a stronger signal instead losing the information due to interference. Therefore VRP allows simultaneous transmission of the same packet by multiple users, while neither signal collision nor contention will cause a reception problem in the village radio network.

Each mobile node has one or more wireless network interfaces, with all interfaces of the same type (on all mobile nodes) linked together by a single physical channel. When a network interface transmits a packet, it passes the packet to the appropriate physical channel object. This object then computes the propagation delay from the sender to every other interface on the channel and schedules a "packet reception" event for each. This event notifies the receiving interface that the first bit of a new packet has arrived. Last, the packet is passed up to the MAC layer.

In order to compute energy consumption of each node, an energy model has been implemented as a node attribute in the network simulator. The energy model represents level of energy in a mobile host. The energy model in a node has an initial value, which is the level of energy the node has at the beginning of the simulation. It also has a given amount of energy usage for every packet it transmits and receives. The energy of a mobile host will be decremented for every transmission and reception of packets at the node. How was the amount of energy decremented for every packet transmission (or reception) computed? Multiply the packet transmission (or reception) time by the transmitting (or receiving) power required by the node's interface or physical layer . When the energy level at the node goes down to zero, no more packets can be received or transmitted by the node.

6.3 Medium Access Control

The original link layer of *ns-2* has implemented the complete IEEE 802.11 [20] standard Medium Access Control (MAC) protocol Distributed Coordination Function

(DCF) for mobile ad hoc networks, but *ns-2* provides no support for accurately simulating a multi-hop TDMA-based MAC Protocol needed in our target environments. Thus we have implemented the VRP (Chapter 4) into *ns-2* as the Medium Access Control protocol for our simulations of village radio network.

According to the multi-hop TDMA-based MAC Protocol VRP, there is no existence of nodes contend for the wireless medium. The transmission of each packet, unicast or broadcast, is scheduled by a TDMA algorithm that assigns the wireless channel for transmission of a data packet to avoid contentions and to reduce the probability of collisions. An Acknowledgment (ACK) follows each correctly received unicast packet to the sender, which retransmits the packet a limited number of times until this ACK is received. Broadcast packets are not acknowledged by their recipients to reduce energy consumption.

If the MAC layer is idle when an incoming packet is handed up from the network interface, it simply computes the transmission time of the packet and schedules a "packet reception complete" event for itself. When this event occurs, the MAC layer verifies that the packet is error-free, performs destination address filtering, and passes the packet up the protocol stack.

6.4 Address Resolution

The Address Resolution Protocol, ARP [24] is implemented in *ns-2* to resolve IP addresses to hardware MAC addresses, since the routing protocol VRP operates at the network layer using IP addresses. The address translation by ARP takes place before the packets pass down to the MAC layer.

6.5 Interface Queue

The interface queue is implemented for packet buffering. Each node has a queue for packets awaiting transmission by the network interface that holds up to 50 packets and is managed in a drop-tail manner. When a packet comes from the network layer, the link layer will check its next hop address. If the next hop address is an IP address, it needs to be translated to a hardware MAC address by ARP. Once the hardware address of a packet's next hop is known, the packet is inserted into the interface queue before going to the MAC layer in case the MAC layer is busy. The MAC layer then takes packets from the head of the interface queue and sends them to the network interface when appropriate.

CHAPTER 7 SIMULATION STUDIES AND PERFORMANCE COMPARISONS

In this chapter, we present two simulation studies (simulation studies I and II) for our target mobile ad hoc network, i.e. village radio network. We evaluate our design in two steps. First, in simulation study I, we evaluate the MAC protocol and routing protocol design in a series of small scale networks, where node mobility is very high, and traffic load is moderate. Then, in study II, we simulate our protocols in a relatively large-scale network, where node mobility can be either very high or low, and traffic load varies from light to heavy. Such a two-step simulation study has twofold purposes: it enables us to validate our protocol design in the first place, and also enables us to make a comprehensive measurement of our energy-efficient routing protocol's performances under various traffic loads and different node mobilities.

The simulations were conducted using the latest version of the network simulator (ns-2.1b9). In these studies, we model a mobile ad hoc network as a set of mobile wireless nodes deployed in a predetermined two-dimensional area. We implemented the original Village Radio Protocol, VRP, and our proposed routing protocol, VRRP, in the network simulator and optimized their performances. The rest of the chapter is organized as follows: In section 1, we define the metrics used in testing the performance of this new protocol. In the following section, we develop necessary simulation models to be used in evaluating the performances of the new protocols, and then make comparisons of the simulation results. In section 3, we present further simulation studies of VRRP and results. Finally, we will state our conclusions and further work to be done to optimize this new protocol.

7.1 Performance Metrics

The following are performance metrics used in evaluating of the routing protocols:

- Packet delivery ratio: The total number of data packets delivered divided by the total number of data packets sent.
- End-to-end delay: The delay experienced by every successfully delivered data packet. The time measurement was done at the application layer.
- Normalized routing overhead: The total number of routing messages sent and forwarded throughout the entire simulations divided by the total number of data packets delivered.
- Energy consumption: The total energy consumed per node, which is measured in Joules. The smaller this value is, the more energy efficient the routing protocol is, and vice versa.

7.2 Simulation Study I

In this study [27], we organized the simulations into two sets. In the first set, the nodes do not perform any routing, just flooding as in the original VRP. The nodes re-broadcast any packet received, which is highly energy consuming. Our first objective is to validate our *ns-2* implementation of the multi-hop TDMA-based MAC protocol which is used to support the routing layer in village radio network. The goal of the second simulation set is to measure the ability of VRRP to react to network topology change while continuing to successfully deliver data packets to their destinations and show that it reduces energy consumption in the network.

7.2.1 Simulation Model

The study used networks of 10, 20, 30 and 40 mobile nodes in a 1000m×250m area. Each simulation is run for 900 seconds. Our traffic sources are chosen to be constant bit rate (CBR) sources, and the number of sources in the network is chosen to be half of the number of mobile nodes in the network. The movement model used is the "random waypoint" model [2], in which each node remains stationary for pause time seconds, then moves toward a randomly chosen destination at a randomly chosen speed, with maximum speed of 30 m/s. Upon reaching the destination, the node pauses again for *pause time* seconds, selects another destination, and proceeds there as previously described, repeating this behavior for the duration of the simulation. We ran our simulations with movement patterns generated for 7 different pause times: 0, 30, 60, 120, 300, 600 and 900 seconds. Zero signifies constant mobility, and 900s represents a stationary network. We generated scenario files with 70 different movement patterns, 10 for each value of pause time. The radio range of each node is 250m. The bandwidth of wireless interface device is modeled to be 2 Mbps. The wireless interface consumes 1.6W for transmission and 1.2W for reception, with no energy consumption for listening. The energy in the nodes was set to 100 joules. The interface queue is a 50-packet drop-tail priority queue. The protocol parameters that yielded the best performance in the VRRP simulation-I are listed in Table 7.1.

Table 7.1: Constants used in the VRRP simulation-I

ACTIVE_ROUTE_LIFE	Active Route Lifetime	6 seconds
ROUTE_REPLY_LIFE	Route Reply Lifetime	6 seconds
REV_ROUTE_LIFE	Reverse Route Lifetime	50 seconds

7.2.2 Simulation Results

The simulation results presented are from over 70 trials. Figure 7.1 shows packet delivery ratio as a function of the number of nodes in the network. When the nodes do not perform any routing algorithm, close to 100% packet delivery can be achieved. The results confirm that and the *ns-2* implementation of the multi-hop TDMA-based MAC protocol is correct. The results also become the criteria for performance evaluation of VRRP, since we cannot simply compare the performance VRRP with any of the existing ad hoc routing protocol. VRRP does well with 10 or 20 nodes (equivalent to 5 or 10 sources) in the network, delivering 98% and 93% of originated data packets respectively. At 40 nodes (equivalent to 20 sources), VRRP can deliver 88% of originated data packets. The packet delivery ratio of VRRP decreases with increasing number of nodes/sources in the network. As the mobility rate increases, VRRP also shows a decrease of packet delivery ratio. One possible reason is because we have not included the implementation of the link layer breakage detection in our first version of MAC protocol implementation in this section. Thus, the packet loss is mainly due to mobility in the network. We will provide results of the simulation with the implementation of link layer breakage detection to show the performance differences in section 7.3.

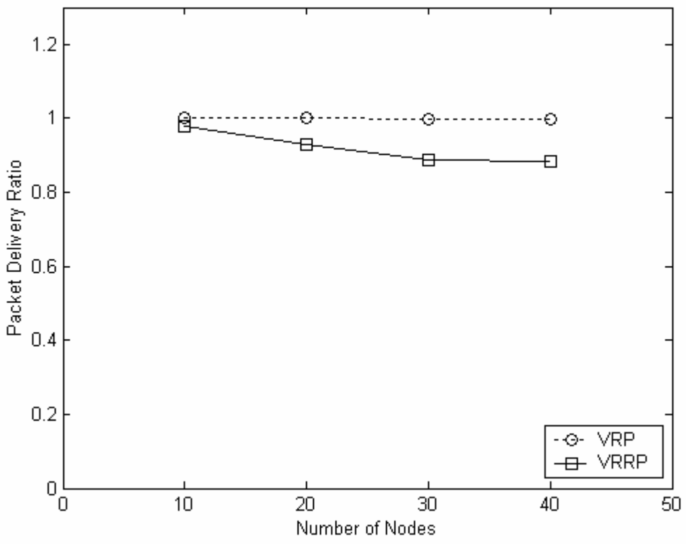


Figure 7.1: Percentage of packets successfully delivered as a function of the number of nodes in the network

Figure 7.2 shows the average end-to-end delay experienced by every successfully delivered data packet as a function of the number of nodes in the network.

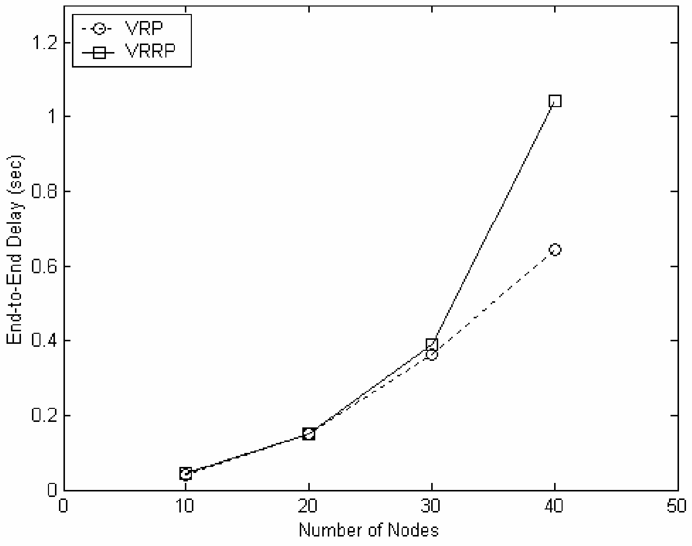


Figure 7.2: End-to-end delay as a function of the number of nodes in the network

Figure 7.3 shows the normalized routing overhead as a function of the number of nodes in the network. The end-to-end delays of both VRRP and VRP (no routing) are highly sensitive to increasing number of sources. In addition, VRRP shows only a slightly higher end-to-end delay than that of VRP at 5, 10 and 15 sources. However, at 20 sources in the 40-node network, the end-to-end delay of VRRP is 1.6 times that of VRP. In terms of normalized routing overhead, VRRP's advantage is highly significant. In the 40-node network with 20 sources, VRRP generates a normalized overhead of merely 0.165, which is less than 5% of the overhead of DSR and AODV [11]. Since no route request packet is generated in route discovery, a node only process the route reply packet and set up a path to its corresponding next hop according to the information in the route reply. This leads to small routing overhead and savings in energy consumption. Consequently, mobile nodes can last longer, which is a big advantage of VRRP.

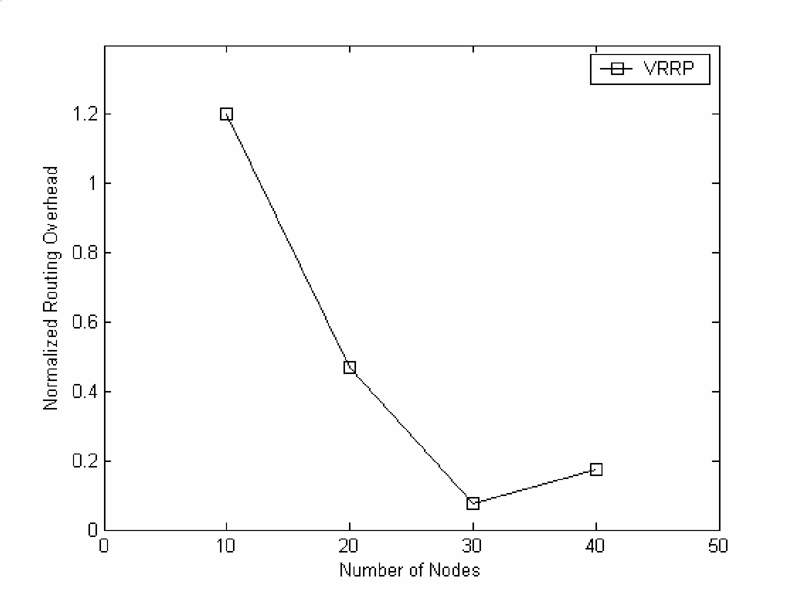


Figure 7.3: Normalized routing message overhead as a function of the number of nodes in the network

Figure 7.4 shows the energy consumption as a function of the number of nodes in the network. VRRP exhibits significant advantage over VRP (with no routing) in terms of energy consumption. At 20 sources, VRP consumes around 34.8 joules/node, while VRRP consumes 14.7 joules/node, only two-fifths (2/5) that of VRP. VRRP's advantage is highly significant, the energy consumption of VRRP on average is less than one half that of VRP. Compared to VRP, VRRP can greatly reduce re-broadcasting after routes have been established in the network. Moreover, VRRP's energy consumption is less sensitive to the increase in the number of nodes/sources than VRP. As the number of nodes in the network increases from 20 to 40, VRP shows a more than two-fold rise from to 16.9 joules/node to 34.8 joules/node, while VRRP shows only a slight increase by around 47% from 10.0 joules/node to 14.7 joules/node in terms of energy consumption.

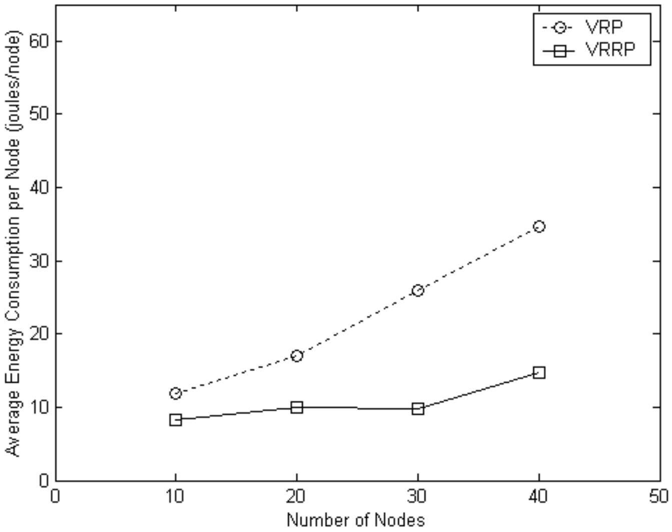


Figure 7.4: Average energy consumption per node as a function of the number of nodes in the network

7.3 Simulation Study II

In this study, we expand the network size to 50 nodes, and perform simulations in two steps. The first part is to study the scalabilities of VRP and VRRP to traffic load. The second part is a performance comparison among VRRP (with VRP implemented at MAC layer in *ns-2*), DSR and AODV. In the simulations of DSR and AODV, *ns-2* implements the IEEE 802.11 MAC protocol's Distributed Coordination Function at MAC layer. We test the performances of VRRP in both high mobility and low mobility scenarios, in terms of packet delivery ratio, end-to-end delay, normalized routing overhead, and energy consumption. The goal of the simulation is to measure the ability of VRRP to react to network topology change while continuing to successfully deliver data packets to their destinations in a rather larger network. We also make a comparison of VRRP's performance in high and low mobility scenarios. Moreover, we intend to show that designing the layers of the network jointly will improve the system performance. Our simulation study of the village radio network is among the foremost studies of the cross-layer design for wireless mobile ad hoc network.

7.3.1 Simulation Model

The simulations were performed using *ns-2* with the CMU Monarch wireless extensions [22]. We use the MAC layer model described in chapter 4. The interface queue is a 50-packet drop-tail priority queue. The dimension of simulation topography was set to 1000 meters by 250 meters, with 50 wireless nodes randomly spread in the area. Each of the simulation is run for 900 seconds. The movement model used is the "random waypoint" model [2], in which each node remains stationary for pause time seconds, then moves toward a randomly chosen destination at a randomly chosen speed. Since our objective is to evaluate the scalability of VRRP with respect to degree of mobility, we considered both high and low mobility scenarios in simulation study II. For the low mobility scenario, we assume that the maximum speed of each node is 3 m/s, and nodes move at randomly chosen speeds that are uniformly distributed within [0, 3 m/s]. While for the high mobility scenario, we assume that the maximum speed of each node is 30 m/s, and nodes move at randomly chosen speeds that are uniformly distributed within [0, 30 m/s]. In both scenarios, we ran the simulations with movement patterns generated for seven different pause times: 0, 30, 60, 120, 300, 600 and 900 seconds. Zero signifies constant mobility, and 900s represents a stationary network. For each value of pause time, we generate ten different scenarios. Thus, we generated scenario files with 70 different movement patterns for high and low node mobility respectively.

In this study, we use a simple traffic model, where the source generates data packets destined for the sink at a steady rate. The source and sink are modules associated with nodes. And there is no flow or congestion control. The traffic sources are chosen to be constant bit rate (CBR) sources, and the packet size is set to 512 bytes. The traffic is always between a pair of source and sink nodes, and the traffic load is defined in terms of connections. A connection is a unicast conversation from a source node to a sink node. To gauge the performance of the routing protocol under different traffic loads, the number of connections is varied over a wide range in the simulation experiments. Thirteen different values for the number of CBR connections in the network are used: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, and 65. Since we generated thirteen different application traffic patterns for each movement pattern, a total of 910 ($13 \times 7 \times 10 = 910$) different scenario files are generated for high and low node mobility respectively. Compared with simulation study I, simulation study II provides diverse scenario files to VRRP simulation, and is more complete.

The radio range of each node is 250m. The bandwidth of the wireless interface device is modeled to be 2 Mbps. The wireless interface consumes 1.6W for transmission and 1.2W for reception [28]. With energy conservation performed, the interface consumes 50 mW for listening. The energy in the nodes was set to 300 joules. Table 7.2 lists the values used in the VRRP simulation-II.

Table 7.2: Constants used in the VRRP simulation-II

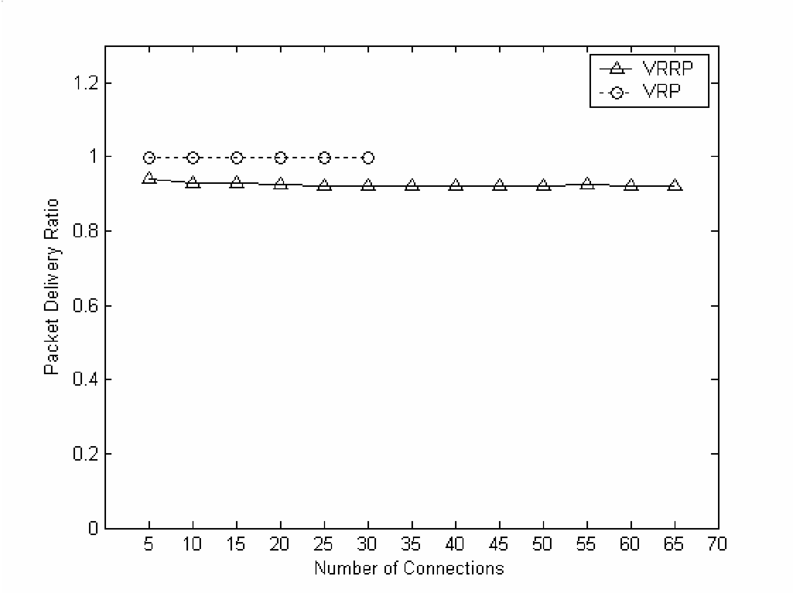
ACTIVE_ROUTE_LIFE	Active Route Lifetime	10 seconds
ROUTE_REPLY_LIFE	Route Reply Lifetime	10 seconds
REV_ROUTE_LIFE	Reverse Route Lifetime	60 seconds

Note that in the simulation study I, we used in the MAC protocol implementation the predefined value of the optimal number of sub-slots (S_{opt}) within each TDMA data slot, which is one third of the total number of the active nodes in the network (N). However, an optimization for the value of the S_{opt} is possible in the simulation study II. Considering the dimension of the simulation topology (1000m×250m) and the radio range of each node (250m), we can safely assume that all useful routes in the ad hoc network are less than the hop limit of 10, thus we reconfigure the S_{opt} to be one fifth of the total number of the active nodes in the network (N), i.e. $S_{opt} = \left\lceil \frac{1}{5} \times N \right\rceil$.

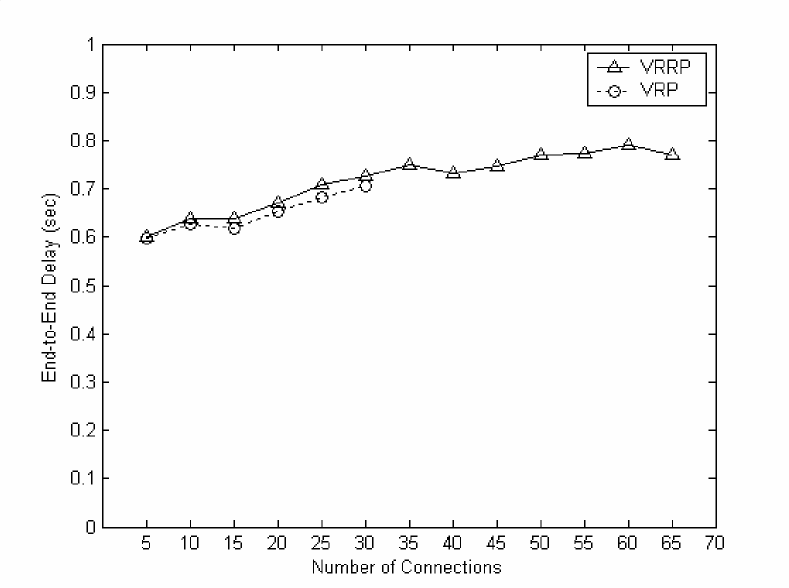
7.3.2 Performance Evaluation in Low Mobility Scenarios

Figure 7.5 illustrates the performance of VRP and VRRP as a function of traffic load in low mobility scenarios. The simulation results here are averaged over 910 different runs for all the 13 distinct traffic patterns, 70 runs for each traffic pattern. In order to prevent topology specific skewing of results, the results for each traffic pattern are averaged over 70 runs for all the 7 distinct pause time values, 10 runs for each pause time value. These scenarios of different traffic patterns were simulated with the purpose of evaluating the behavior of the protocols as the number of traffic connections increases. We typically expect an on-demand protocol to suffer as the number of traffic connections increase. However, as shown in Figure 7.6 (a), the packet delivery ratio of VRRP decreases only slightly with the increasing number of connections, dropping by merely 2% from 94% (at 5 connections) to 92% (at 65 connections). In other words, VRRP scales well to increasing traffic load, which is a significant advantage over VRP. VRRP exhibit only a slightly higher end-to-end delay than that of VRP at all connections. Moreover, the delay of VRRP is not very sensitive to increasing number of connections. At 50, 55 and 65 connections, the delay of VRRP is almost the same. VRRP shows an approximately 30% increase in the delay from 0.602s to 0.771s as the number of connections increases from 5 to 65.

Note that when the nodes do not perform any routing algorithm, close to 100% packet delivery can be achieved. These results validate that the MAC protocol VRP works well in a relatively large size network (50 nodes) with moderate traffic load in low mobility scenarios. The simulation results also show that VRP cannot scale well under heavy connection load. When workload in the network exceeds 30 connections, VRP fails to function due to heavy congestion in the network. However, VRRP can perform well under heavy traffic load (65 connections or more). VRRP has doubled the network capacity at a small price of slightly lower packet delivery ratio and higher end-to-end delay, exhibiting a significant advantage over VRP. Furthermore, VRRP accommodates traffic growth well: as the number of connections increases from 30 to 65 connections, the packet delivery ratio decreases by only 0.2% from 92.2% to 92.0%, and the end-to-end delay increases by merely 6% from 0.728 to 0.771 second.



(a) Packet delivery ratio



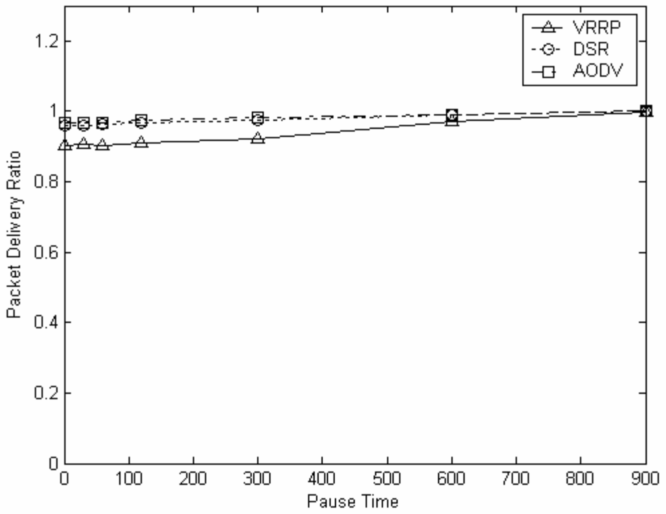
(b) End-to-end delay

Figure 7.5: Performance of VRP and VRRP as a function of traffic load in low mobility scenarios.

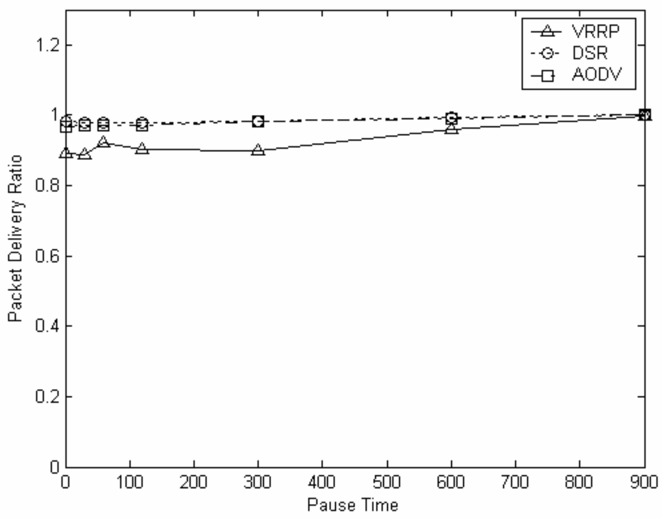
Figure 7.6 shows the packet delivery ratio as a function of pause time with varying numbers of CBR traffics in low mobility scenarios. DSR and AODV do not show much performance advantage over VRRP, although they show a slightly higher packet delivery ratio (6% higher on average). In higher load scenarios with 60 connections, DSR and AODV lead VRRP by 8% at 0 pause time. The packet delivery ratio for all the protocols decrease as the rate of mobility increases. But the decrease in this metric has not been influenced by traffic load very much. In 10-, 30-, and 60-connection scenarios, the packet delivery ratio of VRRP incurs a drop of approximately 10% from 900s pause time to 0s pause time.

The worse packet delivery ratio and delay occur when the pause time is 30 seconds is expected. If the pause time is zero, the nodes are in constant mobility, which means although the absolute speed of nodes is high the relative speed of nodes may not be.

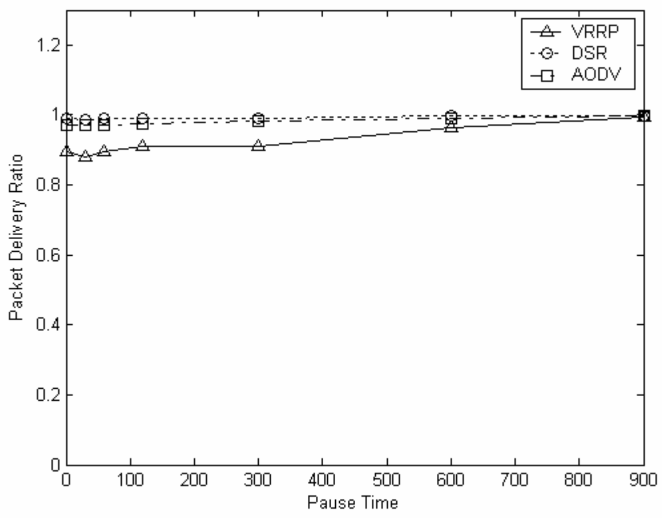
On the other hand, if the pause time is 30 seconds, each node remains stationary for a short period of 30 seconds, and then moves toward a randomly chosen destination at a randomly chosen speed, which makes node movement more irregular. Thus, the node movement at pause time 30s can be less regular and predictable than at pause time 0s. Consequently, the packet delivery at pause time 30s can be the lower than at pause time 0s. If the pause time is 900s, the network is in stationary, VRRP achieves the highest packet delivery ratio (almost 100%) since there is no link breakage due to node mobility.



(a) 10 connections



(b) 30 connections



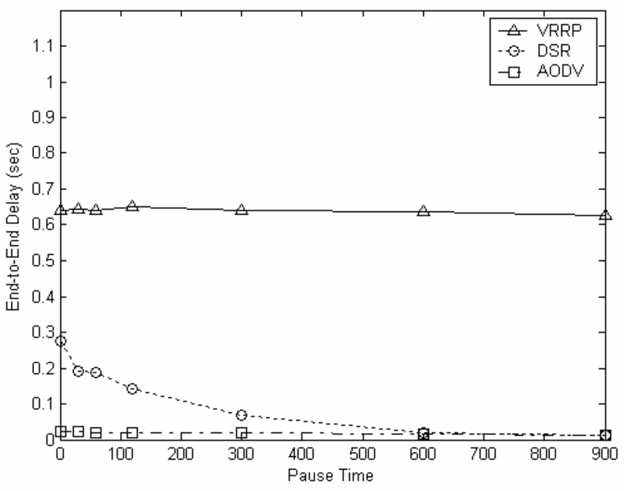
(c) 60 connections

Figure 7.6: Fraction of successfully delivered data packets as a function of traffic load in low mobility scenarios.

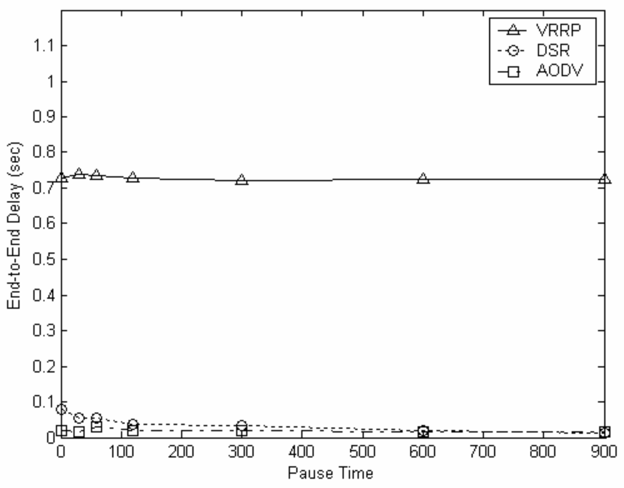
Figure 7.7 shows the end-to-end delay as a function of pause time with varying numbers of CBR traffics in low mobility scenarios, and averaged over 70 trials. VRRP exhibits larger end-to-end delay than DSR and AODV. The worse delay of VRRP is expected, since the MAC protocol we used for VRRP simulation is a

TDMA-based protocol, while the MAC protocol we used for the simulation of DSR and AODV is the IEEE 802.11 MAC protocol. The TDMA MAC protocol can incur large end-to-end delay, as each node has to wait for its scheduled time slots to transmit a packet. According to the algorithm of our multi-hop TDMA-based MAC protocol described in chapter 4, the larger the network size is, the longer the time a node has to spend in waiting for its scheduled time slot, thus the larger the end-to-end delay can be. Typically the end-to-end delay of VRRP is in excess of 0.6s. Such high delays will render certain services, such as multimedia-streamed services, difficult to be supported. This inherent weakness of high delay will also make VRRP incompetent to support real-time communication (approximately 20ms delay). One possible approach to overcome high delay is to reduce the length of the sub-slot, and decrease the number of sub-slots within each TDMA slot as well. There should be enough sub-slots within each TDMA frame to support multi-hop routing and to prevent data loss before packet is propagated successfully to the destination. Furthermore, if nodes are equipped with the knowledge of network size and wireless radio range, it is possible to set a smallest optimal value for the number of sub-slots (S_{opt}) within each TDMA data slot.

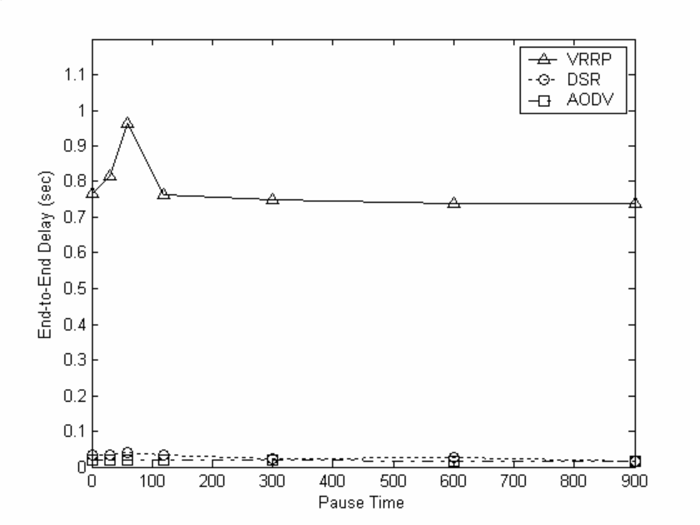
The delay of VRRP is not very sensitive to mobility rate. At 10 connections, VRRP shows a 2% increase from 0.628s to 0.641s in terms of delay as mobility rate increase from 900s pause time to 0s pause time. At 30 connections, VRRP shows a merely 0.6% increase from 0.723s to 0.728s in the delay, and at 60 connections, VRRP shows a 4% increase from 0.740s to 0.767s in the delay.



(a) 10 connections



(b) 30 connections



(c) 60 connections

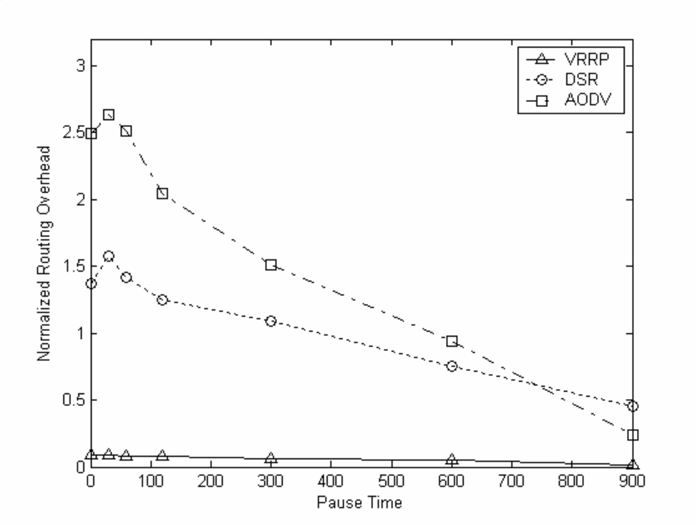
Figure 7.7: End-to-end delay as a function of traffic load in low mobility scenarios.

Figure 7.8 shows the normalized routing overhead as a function of pause time with varying numbers of CBR traffics in low mobility scenarios, and averaged over 70 trials. AODV shows the largest routing overhead at all mobility rates (pause times of 0, 30, 60, 120, 300 and 600 seconds), while DSR shows the largest routing overhead when the nodes remain stationary. VRRP outperforms AODV and DSR at any mobility rate, always showing the least routing overhead. At 10-connection and 0 pause time, DSR and AODV generate the normalized routing overhead of 1.37 and 2.49, respectively, while VRRP generates only 0.09. At 30-connection and 0 pause time, DSR and AODV generate the normalized routing overhead of 1.39 and 2.35, respectively, while VRRP generates only 0.09. At 60-connection and 0 pause time, DSR and AODV generate the normalized routing overhead of 1.22 and 2.10, respectively, while VRRP generates only 0.10. Note that VRRP's overhead is 7% that of DSR and 4% that of AODV at 10-connection and 0 pause time; 6% that of DSR and 4% that of AODV at 30-connection and 0 pause time; and 8% that of DSR and

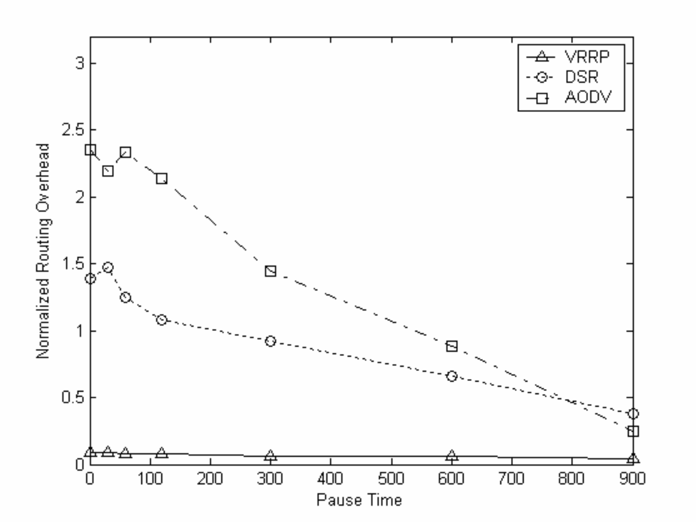
5% that of AODV at 60-connection and 0 pause time. VRRP's significant advantage over DSR and AODV in terms of normalized routing overhead is expected since no route request packet is generated in route discovery; a node only processes the route reply packet and sets up a path to its corresponding next hop according to the information in the route reply. This leads to small routing overhead and savings in energy consumption. Consequently, mobile nodes can last longer, which is a big advantage of VRRP.

The normalized routing overhead of VRRP is not very sensitive to the increasing number of traffic. While the normalized routing overhead increases as the number of traffic increases, the rise is only around 10%, when the number of traffic changes from 10 to 60 simultaneous connections.

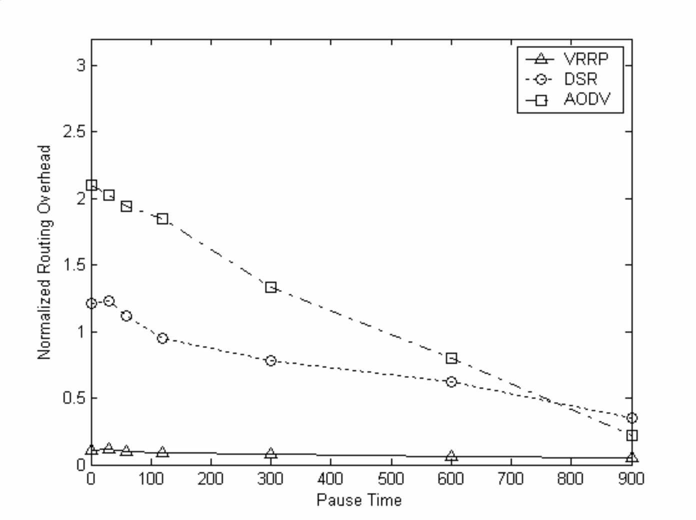
The routing overhead of the protocols is also affected by node mobility. The observable trend is for the routing overhead to rise as the rate of mobility rises. At 60 connections, AODV shows the biggest change as its routing overhead increases ten-fold from 0.21 to 2.10, DSR shows a more than three-fold increase from 0.35 to 1.22, while VRRP shows the smallest change as its routing overhead increases two-fold from 0.05 to 0.10. This result suggests that VRRP is the least sensitive to mobility, which is a significant advantage over AODV and DSR. Moreover, routing packet overhead has an effect on the congestion seen in the network and also helps evaluate the efficiency of a protocol. Low routing overhead is desirable in low-bandwidth environments and environments where battery power is an issue.



(a) 10 connections



(b) 30 connections

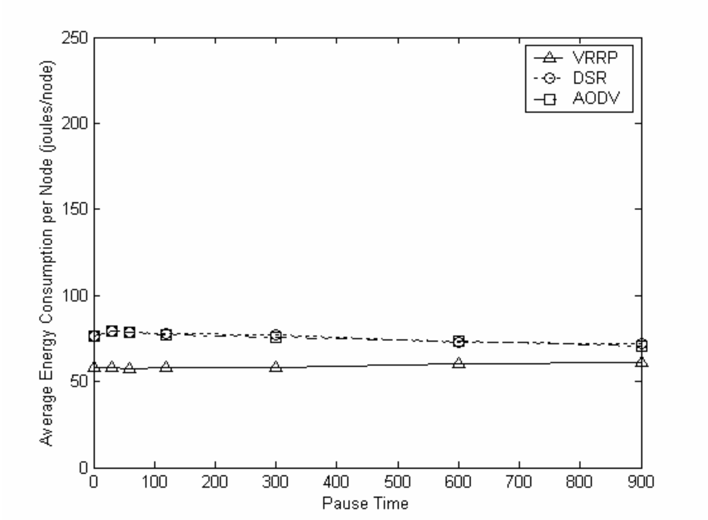


(c) 60 connections

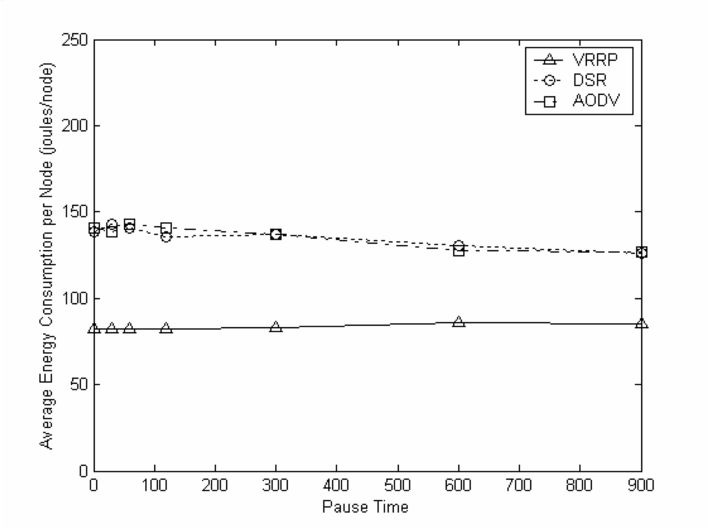
Figure 7.8: Normalized routing message overhead as a function of traffic load in low mobility scenarios.

Figure 7.9 shows the average energy consumption per node as a function of pause time with varying numbers of CBR traffics in low mobility scenarios, and averaged over 70 trials. Note that the smaller this value is, the more energy efficient the routing protocol is, and vice versa. The energy consumption of VRRP at 10 connections is about three-quarters that of AODV and DSR, around three-fifths that of AODV and DSR at 30 connections, and about half that of AODV and DSR at 60 connections. From the results, we can see that VRRP exhibits significant advantage over AODV and DSR in terms of energy consumption, and can provide a considerable amount of energy saving over AODV and DSR. There are mainly two reasons: (1) VRRP does not introduce any new control messages and uses data packet directly in route discovery, thus it incurs less routing overhead and less energy consumption than AODV and DSR; (2) In our design, we turn off the radio when the node is idle, which saves significant amount of energy. We have implemented the radio switch-off process at the TDMA-based MAC layer where it can be efficiently coordinated with the channel access algorithm. However, in DSR and AODV, the idle nodes are the most significant power consumers, thus their energy efficiency is lower than VRRP. VRRP always consumes less energy than AODV and DSR, that is, VRRP is more energy-efficient than both AODV and DSR.

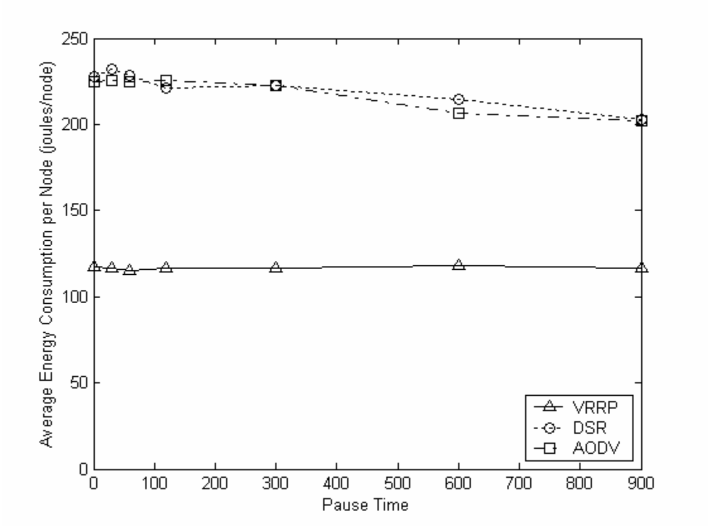
The energy consumption of all protocols increases with growing amount of traffic. The energy consumption of VRRP shows a significant two-fold rise as the number of connections increases from 10 to 60, and continues to increase from hereon. Both AODV and DSR show approximately a three-fold increase as the number of connections increases from 10 to 60. These results imply that VRRP scales better than AODV and DSR to increasing number of traffic. VRRP exhibits the lowest increase of energy consumption, thus, achieves the highest benefit in terms of energy efficiency when the number of traffic increases. The results are in accordance with previous results that VRRP incurs a smaller routing overhead increase than AODV and DSR, which results in a smaller energy consumption rise with increasing number of traffic.



(a) 10 connections



(b) 30 connections



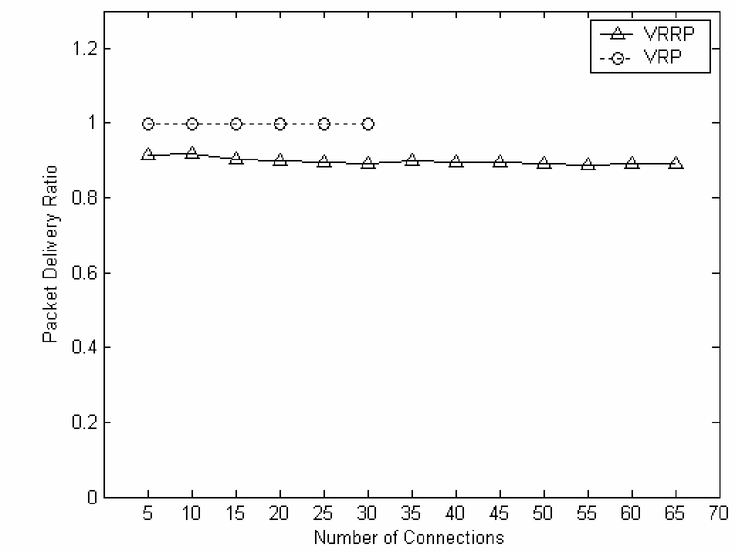
(c) 60 connections

Figure 7.9: Average energy consumption per node as a function of traffic load in low mobility scenarios.

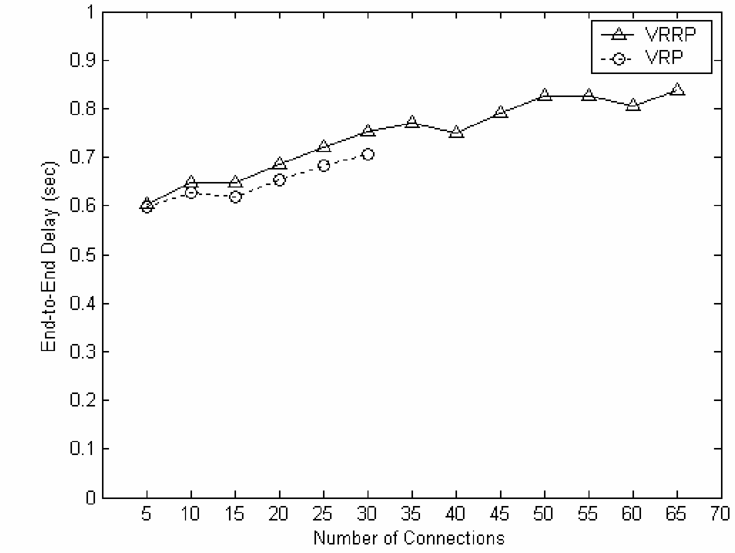
7.3.3 Performance Evaluation in High Mobility Scenarios

In this section, the simulation network is the same as the previous multi-hop scenarios with the assumption that the maximum speed of each node is 30 m/s. The impact of high mobility is illustrated in Figure 7.10. Figure 7.10 shows the performance of VRP and VRRP as a function of traffic load in high mobility scenarios. The simulation results here are averaged over 910 different runs for all the 13 distinct traffic patterns, 70 runs for each traffic pattern. These scenarios of different traffic patterns were simulated with the purpose of evaluating the behavior of the protocols as the number of traffic connections increases. As illustrated in Figure 7.10 (a), the packet delivery ratio of VRRP decreases slightly by 2% from 91% (at 5 connections) to 89% (at 65 connections) as the number of traffic connections increase. In other words, VRRP scales well to increasing traffic load in high mobility scenarios, which is a significant advantage over VRP. VRRP exhibit only a slightly higher end-to-end delay than that of VRP at all connections. Moreover, the delay of VRRP is not very sensitive to increasing number of connections. At 50 and 55 connections, the delay of VRRP is almost the same, and the delay at 65 connections amounts to 0.836s, an increase of 38%, from 0.604s at 5 connections.

Like in the low mobility scenarios, when the nodes do not execute any routing algorithm, close to 100% packet delivery is achievable in these high mobility scenarios. These results validate that the MAC protocol VRP works well in a relatively large size network (50 nodes) with moderate traffic load in high mobility scenarios. The simulation results also show that VRP cannot scale well under heavy connection load in high mobility scenarios. When workload in the network exceeds 30 connections, VRP fails to function due to heavy congestion in the network. However, VRRP can perform well under heavy traffic load (65 connections or more). VRRP has doubled the network capacity at a small price of slightly lower packet delivery ratio and higher end-to-end delay, exhibiting a significant advantage over VRP. Furthermore, VRRP accommodates traffic growth well: as the number of connections increases from 30 to 65 connections, the packet delivery ratio decreases by only 0.2% from 89.3% to 89.1%, and the end-to-end delay increases by merely 11% from 0.753 to 0.837 second.



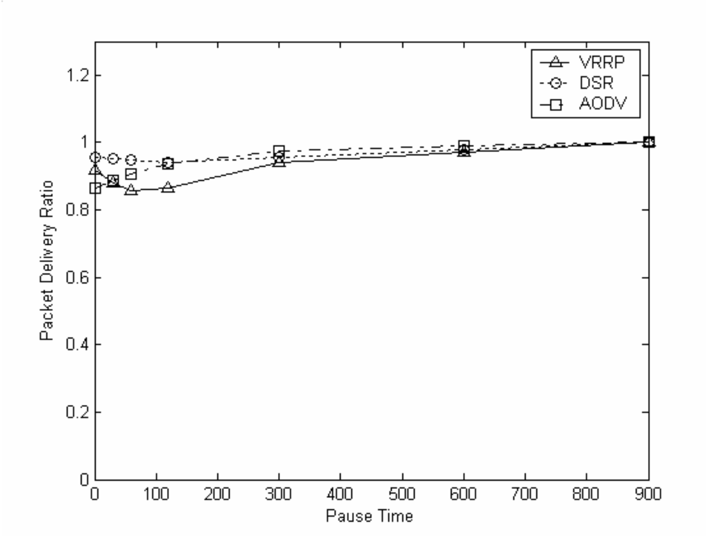
(a) Packet delivery ratio



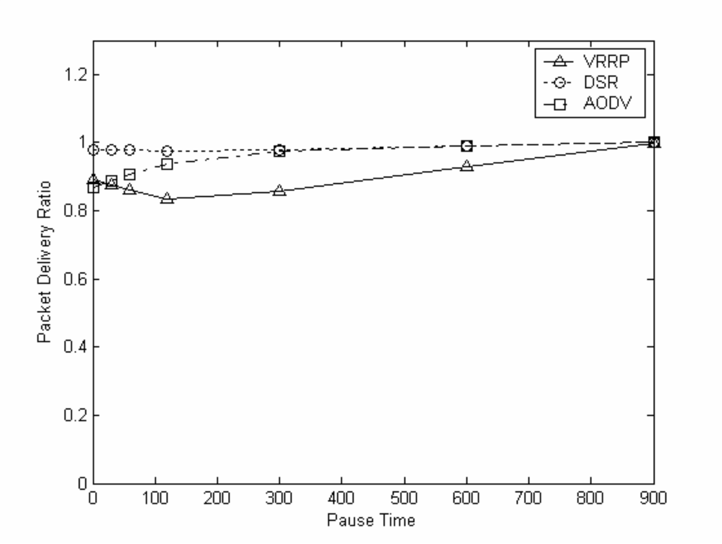
(b) End-to-end delay

Figure 7.10: Performance of VRP and VRRP as a function of traffic load in high mobility scenarios

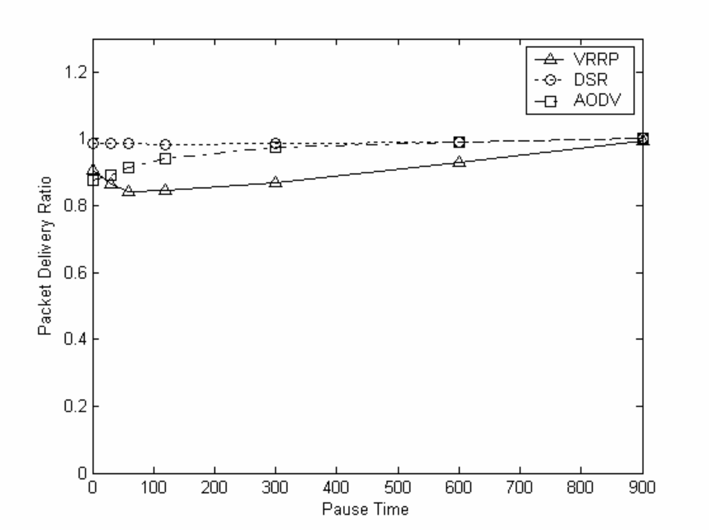
Figure 7.11 shows the packet delivery ratio as a function of pause time with varying numbers of CBR traffics in high mobility scenarios. Like in the low mobility scenarios, DSR and AODV show only a slightly higher packet delivery ratio over VRRP. In higher load scenarios with 60 connections at 0 pause time, AODV exhibits the worst performance (dropping by 12%), followed by VRRP (dropping by 9%). DSR shows the best performance among the three (dropping by 1%), leading VRRP by 8%, while VRRP leads AODV by 3%. The packet delivery ratio for all the protocols decreases as the rate of mobility increases but the decrease in this metric has not been influenced by traffic load very much. In 10-, 30-, and 60-connection scenarios, the packet delivery ratio of VRRP incurs a drop of around 10% from 900s pause time to 0s pause time.



(a) 10 connections



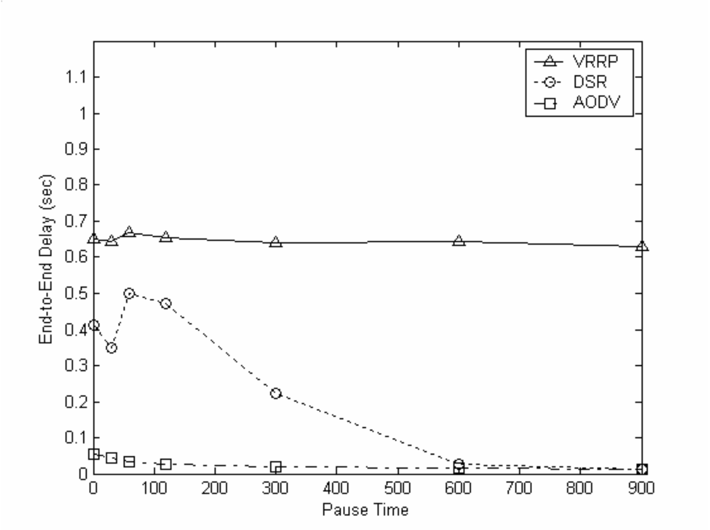
(b) 30 connections



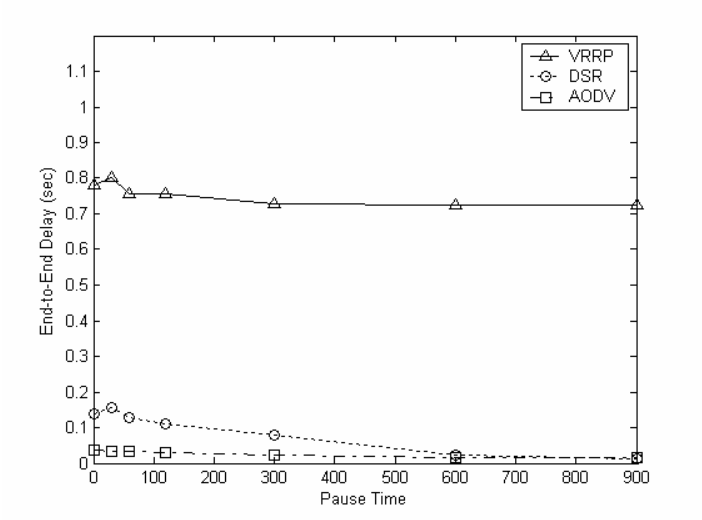
(c) 60 connections

Figure 7.11: Fraction of successfully delivered data packets as a function of traffic load in high mobility scenarios.

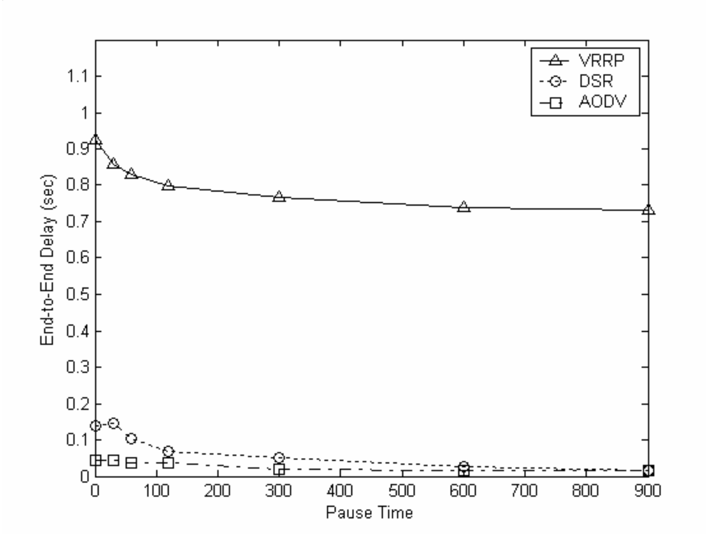
Figure 7.12 shows the end-to-end delay as a function of pause time with varying numbers of CBR traffics in high mobility scenarios, and averaged over 70 trials. VRRP exhibits a larger end-to-end delay than DSR and AODV. Like in the low mobility scenarios, the worse delay of VRRP is expected. This is because the TDMA-based MAC protocol we used for the simulation of VRRP can incur large end-to-end delay, as each node has to wait for its scheduled time slots to transmit a packet. Furthermore, the delay of VRRP is affected by mobility rate. VRRP shows an increase of 4% from 0.629s to 0.652s in terms of delay as mobility rate increase from 900s pause time to 0s pause time at 10 connections, an increase of 8% from 0.724s to 0.780s at 30 connections, and a quarter increase from 0.732s to 0.924s at 60 connections.



(a) 10 connections



(b) 30 connections



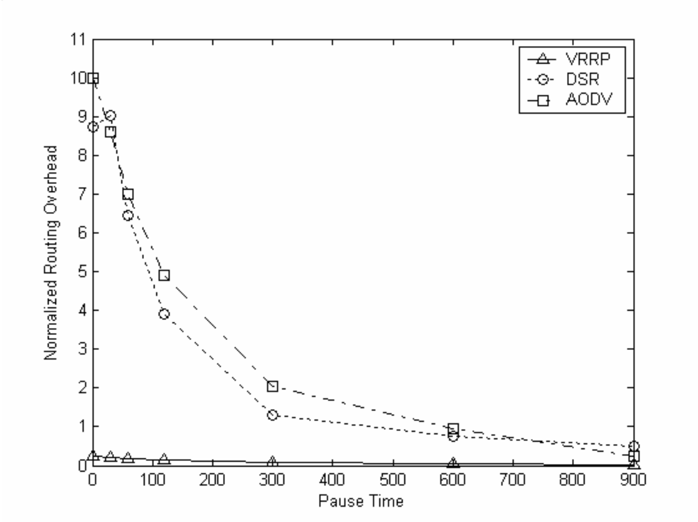
(c) 60 connections

Figure 7.12: End-to-end delay as a function of traffic load in high mobility scenarios.

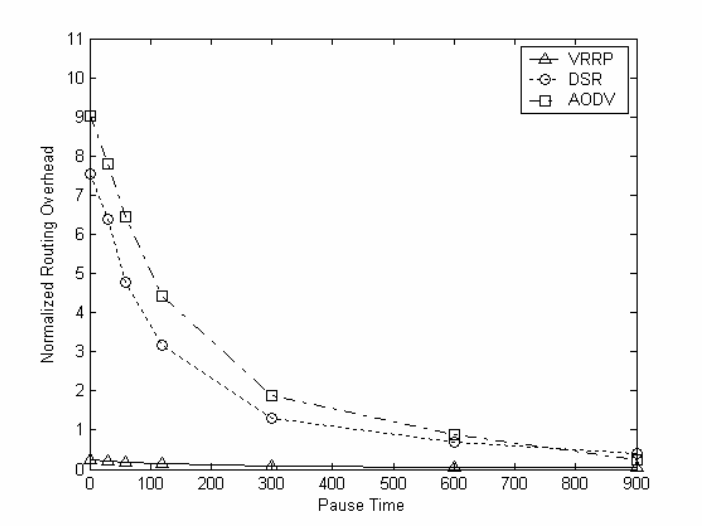
Figure 7.13 shows the normalized routing overhead as a function of pause time with varying numbers of CBR traffics in high mobility scenarios, and averaged over 70 trials. Like in the low mobility scenarios, AODV shows the largest routing overhead at all mobility rates (pause times of 0, 30, 60, 120, 300 and 600 seconds), while DSR shows the largest routing overhead when the nodes remain stationary. VRRP outperforms AODV and DSR at any mobility rates, always showing the least routing overhead. At 10 connections and 0s pause time, DSR and AODV generate the normalized routing overhead of 8.37 and 10.0, respectively, while VRRP generates only 0.242. At 30 connections and 0s pause time, DSR and AODV generate the normalized routing overhead of 7.54 and 9.01, respectively, while VRRP generates only 0.244. At 60 connections and 0 pause time, DSR and AODV generate the normalized routing overhead of 5.85 and 7.84, respectively, while VRRP generates only 0.266. Note that VRRP's overhead is 3% that of DSR and 2% that of AODV at 10 connections and 0s pause time; 3% that of DSR and 3% that of AODV at 30 connections and 0s pause time; and 5% that of DSR and 3% that of AODV at 60 connections and 0s pause time. VRRP's significant advantage over DSR and AODV in terms of normalized routing overhead is expected since no route request packet is generated in route discovery, a node only processes the route reply packet and sets up a path to its corresponding next hop according to the information in the route reply. This leads to small routing overhead and savings in energy consumption. Consequently, mobile nodes can last longer, which is a big advantage of VRRP. In summary, VRRP greatly outperforms DSR and AODV in terms of routing overhead in both high and low mobility scenarios.

Like in the low mobility scenarios, the normalized routing overhead of VRRP is not very sensitive to the increasing number of traffic. While the normalized routing overhead increases as the number of traffic increases, the rise is only around 10% (from 0.242 to 0.266), when the number of traffic changes from 10 to 60.

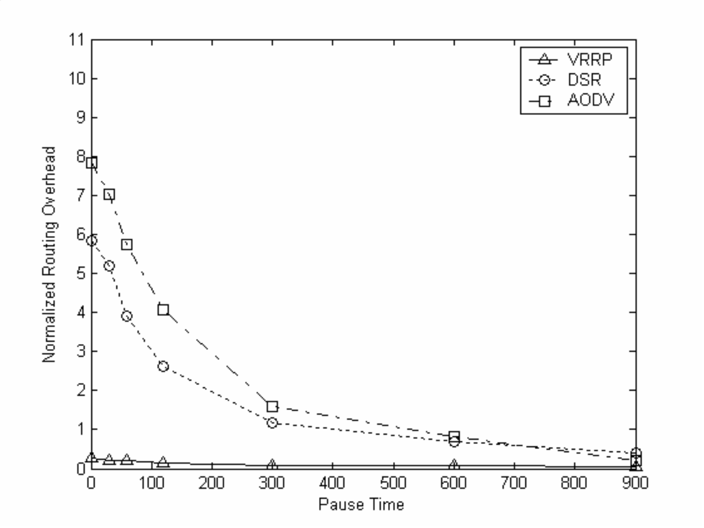
The routing overhead of the protocols is also affected by node mobility. The observable trend is for the routing overhead to rise as the rate of mobility rises. At 60 connections, AODV shows the biggest change as its routing overhead increases thirty-seven-fold from 0.21 to 7.8, DSR shows a more than fifteen-fold increase from 0.40 to 5.8, while VRRP shows the smallest change as its routing overhead increases five-fold from 0.05 to 0.27. This result suggests that VRRP is the least sensitive to mobility, which is another significant advantage over AODV and DSR. Moreover, routing packet overhead has an effect on the congestion seen in the network and also helps evaluate the efficiency of a protocol. Low routing overhead is desirable in a low-bandwidth MANET where node mobility is high and battery power is limited.



(a) 10 connections



(b) 30 connections

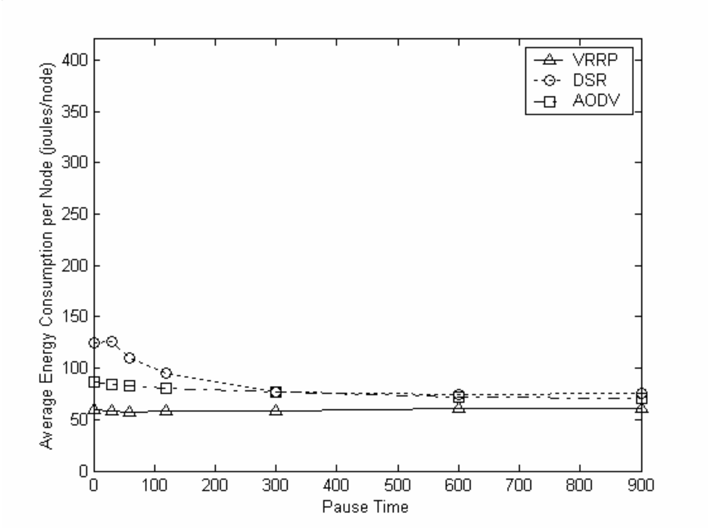


(c) 60 connections

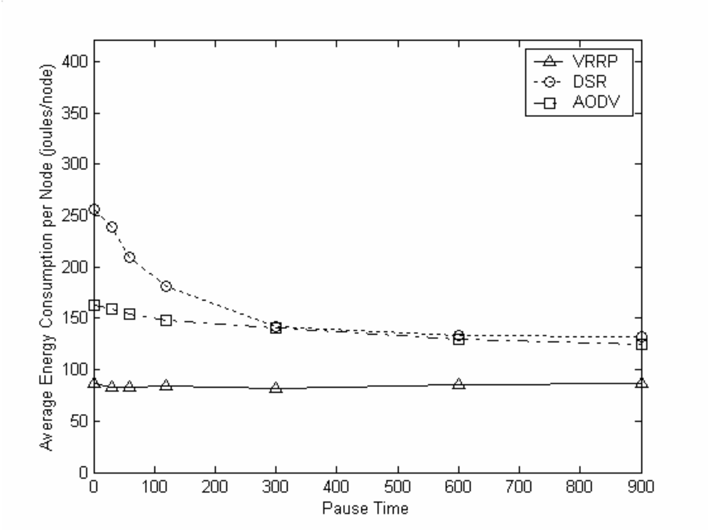
Figure 7.13: Normalized routing message overhead as a function of traffic load in high mobility scenarios.

Figure 7.14 shows the average energy consumption per node as a function of pause time with varying numbers of CBR traffics in high mobility scenarios, and averaged over 70 trials. At constant high mobility (zero pause time), the energy consumption of VRRP at 10 connections is 70% that of AODV and 48% that of DSR, around half that of AODV and one-third that of DSR at 30 connections, and even less than half that of AODV and one-third that of DSR at 60 connections. Like in the low mobility scenarios, VRRP exhibits significant advantage over AODV and DSR in terms of energy consumption, and can provide a considerable amount of energy saving over AODV and DSR. The results are expected, since VRRP generates a less routing overhead than AODV and DSR, which results in less energy consumption. Another reason is in our design we turn off the radio when the node is idle, which saves significant amount of energy. We have implemented the radio switch-off process at the TDMA-based MAC layer where it can be efficiently coordinated with the channel access algorithm. However, in DSR and AODV, the idle nodes are the most significant power consumers, thus their energy efficiency is lower than VRRP. VRRP always consumes less energy than AODV and DSR, that is, VRRP is more energy-efficient than both AODV and DSR.

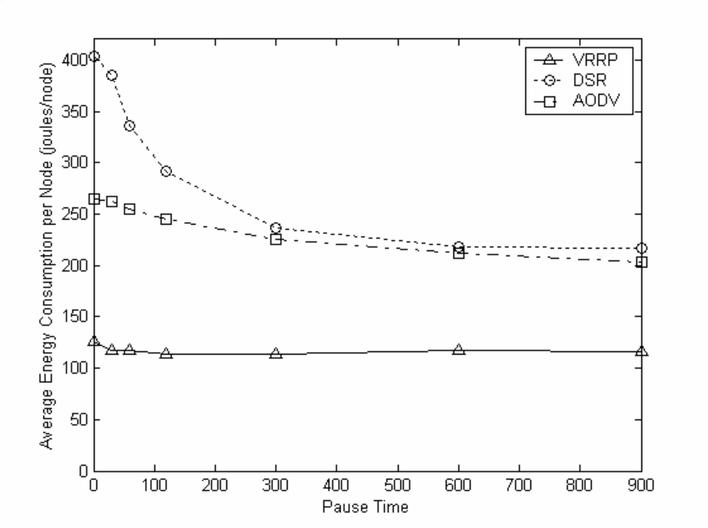
The energy consumption of all protocols increases with growing amount of traffic. The energy consumption of VRRP shows a significant two-fold rise as the number of connections increases from 10 to 60, and continues to increase from hereon. Both AODV and DSR show approximately a three-fold increase as the number of connections increases from 10 to 60. These results imply that VRRP has better scalability to growing traffic load than AODV and DSR. VRRP exhibits the lowest increase of energy consumption, thus, achieves the highest benefit in terms of energy efficiency when the number of traffic increases. The results are in accordance with the previous results that VRRP incurs a smaller routing overhead increase than AODV and DSR, which results in a smaller energy consumption rise with increasing number of traffic. Thus, we can draw the same conclusion as we did with the simulation results from low mobility scenarios in section 7.3.2. In brief, VRRP turns out to be the most energy efficient protocol, and most scalable to increasing number of traffic in both high and low mobility scenarios.



(a) 10 connections



(b) 30 connections



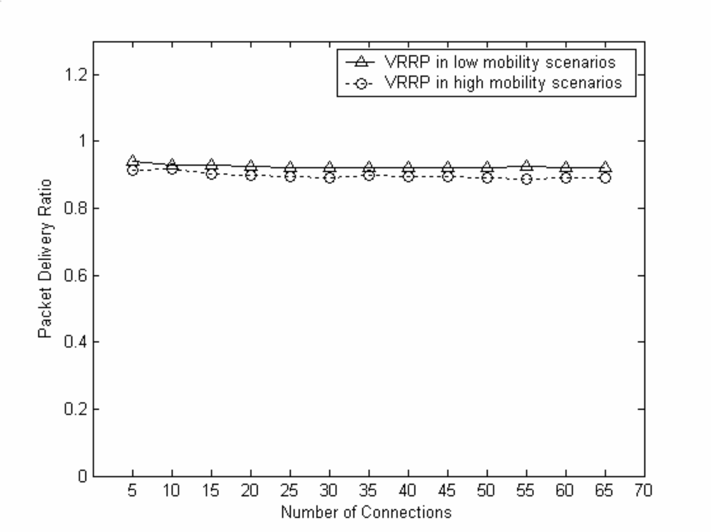
(c) 60 connections

Figure 7.14: Average energy consumption per node as a function of traffic load in high mobility scenarios.

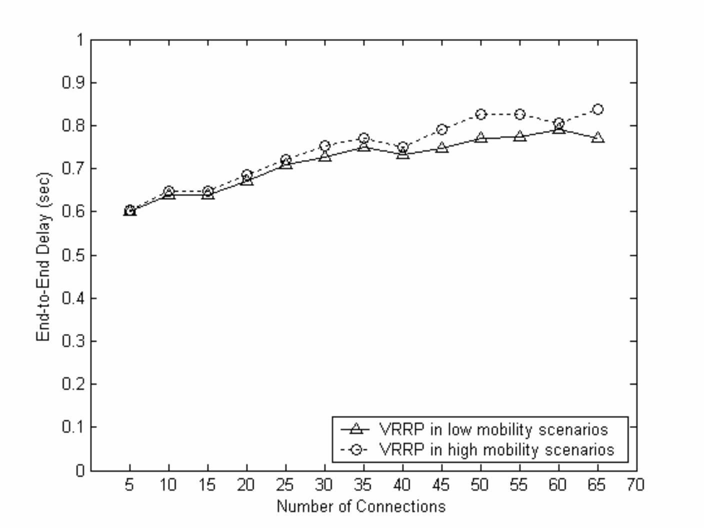
7.3.4 Comparison and Summary

To summarize the simulation study II, we present comparisons of the performances of VRRP in low and high mobility scenarios in Figure 7.15 . Figure 7.15 (a) shows the packet delivery ratio with varying number of CBR traffic and averaged over 70 runs for each traffic pattern. Figure 7.15 (b) shows the end-to-end delay with varying number of CBR traffic and averaged over 70 runs for each traffic pattern. Figure 7.15 (c), (d) show the normalized routing overhead, and the average energy consumption per node respectively with varying number of CBR traffic and averaged over 70 runs for each traffic pattern.

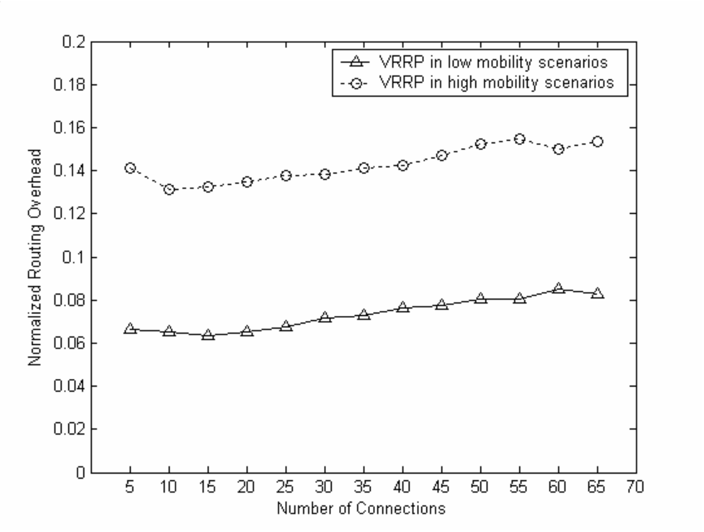
VRRP always shows a better performance in low mobility scenarios than in high mobility scenarios, that is, a higher packet delivery ratio, lower end-to-end delay, lower routing overhead, lower energy consumption, and higher energy efficiency. VRRP exhibits the largest difference in terms of packet delivery ratio (3.7%) between high and low mobility scenarios at 55 connections, and shows an 8% (0.0656s) decrease of end-to-end delay in low mobility at 65 connections. The noteworthy difference between VRRP's performances in low and high mobility scenarios is in the normalized routing overhead. The routing overhead generated throughout the entire simulations in high mobility scenarios is twice as much as in low mobility scenarios. VRRP consumes slightly more energy and is less energy efficient in high mobility scenarios, but the degradation of performance is far less than significant. The energy consumption of VRRP in high mobility scenarios is only 1.4% higher than in low mobility scenarios on average.



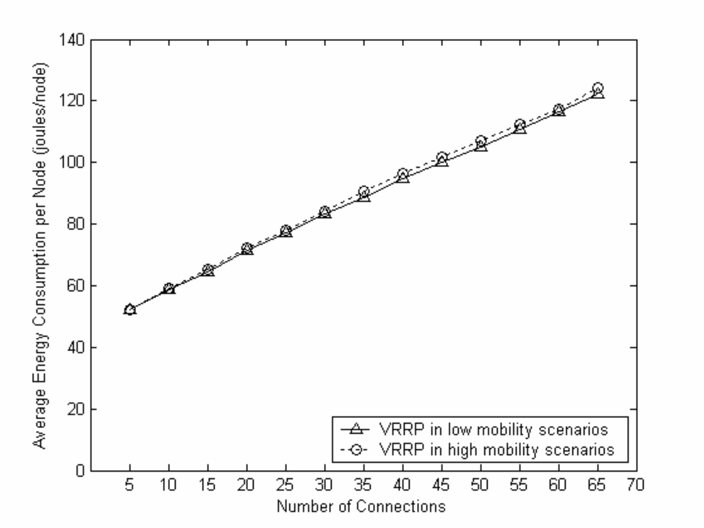
(a) Packet delivery ratio



(b) End-to-end delay



(c) Normalized routing overhead



(d) Average energy consumption per node (joules/node)

Figure 7.15: Comparisons of the performances of VRRP in low and high mobility scenarios as a function of traffic load

CHAPTER 8 CONCLUSION AND FUTURE WORK

This chapter presents some of the conclusions of the work carried out as part of this thesis. It also provides some guidelines for the future work.

8.1 Conclusion

Village radio network is a self-organizing radio network where ad hoc routing can be applied to reduce energy consumption. This thesis presents the design of VRRP, a power-saving protocol for ad hoc networks. VRRP is designed chiefly to work for village radio network, but not limited to village radio network, it can be applied to mobile ad hoc networks in general.

We have described the design of the VRRP in chapter 5, and the detailed design of the multi-hop TDMA-based MAC protocol that uniquely supports our routing protocol in chapter 4. We have also described the simulation of VRRP and VRP in Network simulator (*ns-2*), a discrete event simulator developed for networking research by the University of California at Berkeley and the VINT project [21]. Our simulation is highly meticulous: we evaluate our design in two steps. First in simulation study I, we evaluate the MAC protocol and routing protocol design in a serial of small scale networks, where node mobility is very high, and traffic load is moderate. Then in study II, we simulate our protocols design in a relatively large-scale network, where node mobility can be either very high or low, and traffic load varies from light to heavy. Our simulation is also highly-comprehensive: the second part of the two-step simulation study enables us to make a comprehensive measurement of our energy-efficient routing protocol's performances under various traffic loads and different node motilities. We have reported some initial results to show that VRRP saves the energy resources of the ad hoc network as a whole. We have also obtained more comprehensive results from simulation II to compare VRRP's performance with DSR and AODV in terms of packet delivery ratio, end-to-end delay, normalized routing overhead, and energy consumption. Finally, we have presented comparisons of the performances of VRRP in low and high mobility scenarios, and concluded that VRRP performs better in low mobility scenarios than in high mobility scenarios.

This thesis makes three important contributions. First, as presented in [27], a novel routing protocol, *Village Radio Routing Protocol* (VRRP), that fits well for village radio network is proposed. In addition, by implementing the MAC protocol, *Village Radio Protocol* (VRP) [1], routing-layer design complexity and energy wastage are reduced.

Second, the new *Village Radio Routing Protocol* (VRRP), as presented in [27] and further in chapter 5, is one of the first attempts to not introduce any new messages in route discovery.

Third, as presented in [27], a simulation model has been set up, and simulation studies have been performed to gauge the performance of the new routing protocol. It shows that VRRP has greatly improved energy efficiency at a small price of slightly lower packet delivery ratio and higher end-to-end delay. In addition, by using implicit route discovery, the routing overhead in the network is substantially reduced.

Moreover, our work is a first step towards the cross-layer design for wireless mobile ad hoc networks. We introduced a new on-demand routing protocol VRRP together with a multi-hop TDMA-based MAC protocol to improve the village radio system. And we used this as an example that designing the layers of the network jointly can be more efficient in certain ad-hoc networks. The interaction of VRRP with MAC VRP behaved better than both DSR and AODV, which are efficient on-demand routing protocols, in terms of end-to-end delay, normalized routing overhead and energy consumption, irrespective of the amount of traffic. VRRP had far less control overhead than DSR and AODV. This is because the protocol has intentionally reduced routing messages by using implicit route discovery.

In this study, routing protocol performance is linked very closely to the type of MAC protocol used in wireless ad hoc networks. Simulations also showed that the performance of VRRP over the IEEE 802.11 WLANs is not good.

8.2 Future Work

Although the new routing protocol is developed on the basis of the village radio network, it can be used in other MANET scenarios. Future work includes fully implementing VRRP on a testbed and testing whether the implementation of VRRP can function in a real ad hoc network, as well as determining the protocol's scalability.

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