

LEARNING-BASED ROUTE MANAGEMENT IN WIRELESS AD HOC NETWORKS

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ABSTRACT OF THE DISSERTATION

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The nodes in a wireless ad hoc network must act as routers in a self-configuring network without infrastructure. An application running on nodes in the ad hoc network may require that intermediate nodes act as routers, receiving and forwarding data packets to other nodes to overcome limitations of noise, router congestion and limited transmission power. In existing routing protocols, the “self-configuring” aspect of network construction has generally been limited to route selection using a shortest-path routing metric as a predictor of routing efficiency. This limited, network-layer predictor fails to consider the effects of existing traffic on router loads and fails to consider the effects of noise experienced at the MAC layer. Not all network topologies are suited to efficient routing using a shortest-path metric. The location of the nodes and physical characteristics of the network environment can create topologies where shortest-path routing overloads some routers and underutilizes others. Similarly, noise sources can undermine the quality of wireless links depending on the relative distance between the noise sources and the receiving nodes. This dissertation presents a cross-layer predictor that combines the effects of noise and router congestion into a single time-based routing metric based on statistical estimation from recent experience. Also presented is a new cross-layer, adaptive routing protocol, called Warp-5, that not only uses the new routing metric to make better initial routing decisions in a noisy or congested network, but can also adjust previously existing routes as new routes or new noise sources are added to the network. Simulation results for Warp-5 are presented and compared to the existing shortest-path routing protocol AODV. The results show the cross-layer approach of Warp-5 to be superior to shortest-path routing protocols for managing router congestion and noise in wireless ad hoc networks.

Dedication

This dissertation is dedicated to my wife,

Susan,

who never did get used to the mess.

And to

Irv

I came back, just like I promised.

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Chapter 1

Introduction

Establishing and maintaining routes in a wireless ad hoc network is an essential component to supporting communications across a broad geographical area when individual nodes have limited communication range. Although many wireless routing protocols exist, the problem of supporting efficient and effective communication by establishing appropriate routes is a challenging task for which there is no completely adequate protocol in the literature. This dissertation seeks to address this problem by applying machine-learning techniques to wireless ad hoc routing. In particular, this dissertation shows that machine learning is feasible and useful in managing noise and router congestion in wireless ad hoc networks to improve distributed application throughput.

1.1 Wireless Ad Hoc Networks

A wireless ad hoc network is a collection of nodes exchanging information through radio or infrared wireless adapters. Such a network functions without an established infrastructure. In infrastructure-based wireless networks, there is no direct peer-to-peer communication between nodes; all communication between nodes is managed by the network infrastructure. One example of an infrastructure-based network is the wireless local area network, or wireless LAN. The infrastructure of a wireless LAN consists of access points connected by the Internet. Wireless nodes communicate with the access points and the access points provide networking functionality to the wireless nodes. Another example of an infrastructure-based network is the cellular system. In cellular systems, a geographical area is divided into *cells*, each with a *base station* at the center of the cell. The base stations are connected to a backbone wired network. The base stations and the backbone wired network form the infrastructure for the cellular system. Wireless nodes communicate with the base stations, and the base stations in combination with

the backbone wired network perform the networking functions and direct communication to other wireless nodes.

Nodes in an ad hoc wireless network, on the other hand, communicate with each other on a peer-to-peer basis, and the networking functions are distributed among the nodes in the ad hoc network. Without an infrastructure, the nodes in a wireless ad hoc network must act as routers in a self-configuring network. A distributed application running on nodes in the wireless ad hoc network, such as a video feed between two parties separated by a large distance, may require that intermediate nodes act as routers, receiving and forwarding data packets to other nodes as needed.

The use of radio or infrared adapters as links in wireless ad hoc networks introduces characteristics that are not present in wired networks. Given a powerful enough transmission, any two nodes in a wireless ad hoc network can communicate directly. However, for a fixed transmit power, the received signal power decreases rapidly as the distance between sender node and receiver node increases. When sender and receiver nodes are separated by a large distance, the high-powered transmissions required for direct wireless communication can cause interference in other links in the network, degrading their performance or breaking the other links altogether. Using intermediate nodes with limited communication range as forwarding relays can reduce the sum of transmit power at the source and intermediate nodes needed for source-to-destination communication. Routing using intermediate nodes allows geographically dispersed nodes to communicate with less power expenditure and less interference with other links in the wireless ad hoc network.

1.2 Routing Protocols

The need for routing protocols in wireless ad hoc networks is prompted by the limited communication range used by radio and infrared wireless adapters. Limitations on the direct communication range between nodes and the need for many nodes to cover an area much larger than the limited direct communication range means that nodes in an ad hoc network have to act as intermediaries, forwarding information to destination nodes that could not be reached directly

by the original sending nodes. The purpose of a routing protocol is to find a sequence of intermediate nodes from a source node to a destination node. A sequence of nodes from source to destination is called a *route*.

Previous routing protocols such as DSDV use frequent system-wide broadcasts of global routing information to maintain current connectivity between all nodes in the ad hoc network [46]. A complete global picture held by all nodes almost always exceeds the needs of the application in the ad hoc network. Further, with each node having to send and maintain routing information for the entire network, the amount of routing overhead grows in proportion to the square of the number of nodes in the network, which limits the scalability of the approach. Later approaches to route construction, such as AODV [47] and DSR [30], employed an on-demand approach in response to scalability issues, where routes are constructed as needed, and eliminated the need for maintaining and broadcasting global connectivity information. Both AODV and DSR are distance-vector protocols [36] that seek to find the best routes from the source to a destination, where “best route” is generally defined to be the route with the fewest intermediate nodes (“hops”) between source and destination.

Each route consumes some of the finite forwarding capacity of the routers it uses as packets are sent from source to destination, reducing the speed at which all traffic moves through the routers. Using the minimal hop count as a routing metric ignores the effects of existing routes on router forwarding. The same metric also does not consider the quality of links connecting neighbors, which may be affected by packet collisions on crowded links or noise. Congested routers drop packets, reducing the number of application data packets that reach their intended destination. Transmission of packets over lossy links forces either retransmission of packets with concomitant loss of time, or loss of data packets altogether. In order to support better communication, what is needed is a routing metric that considers router loading and link quality. Such a routing metric would make it possible to avoid bottlenecks caused by forcing too many routes through too few routers and increase overall application data throughput.

1.3 Coordinating Communication in Wireless Networks

This section discusses the mechanics of how wireless nodes share a single communication channel for data packet transfer in wireless networks.

Routers in wired networks have multiple adapters, one for each neighboring node. A wired router receives a data packet for a remote destination through one adapter, extracts the final destination of the data packet from the IP address in the packet network header, consults a routing table to determine the appropriate outgoing adapter and then transmits the data packet through the outgoing adapter. With the proper internal switching fabric, a wired router can receive and forward data packets through different adapters simultaneously.

Routers in wireless networks forward data packets in a different fashion. The wireless router has a single adapter for all incoming and outgoing data packet transmissions. All wireless routers in the wireless network exchange data packets through the same communication channel. An incoming data packet is received on the adapter, which determines that the receiving neighbor is the intended intermediate destination from the destination address in the Medium Access Control (MAC) header. The wireless router then extracts the final destination of the data packet from the IP address in the packet network header, and consults a routing table to determine the appropriate next hop for the packet and then transmits the data packet through the wireless adapter to the next hop node.

The difference between the router in the wired network and the router in the wireless network is while the router in the wired network can receive and forward data packets through each of its multiple adapters simultaneously, the router in the wireless network can only receive or transmit one data packet at a time through a single wireless adapter. Worse still, the data packets in the wireless network are communicated through omnidirectional transmissions received by all nodes within communication range. Multiple overlapping transmissions render themselves unintelligible to the receivers, so the nodes in a wireless network have to cooperatively coordinate which node can transmit and when that node can transmit on the communication channel shared by all the nodes in the wireless network. The coordination of communication in 802.11 wireless networks is performed by the 802.11 Distributed Coordination Function (DCF), originally defined in the IEEE 802.11 standard [24]. The DCF uses carrier sensing multiple access

with collision avoidance (CSMA/CA). There are two protocols in the DCF: the basic access method and the RTS/CTS protocol. This dissertation focuses on wireless ad hoc networks built on the 802.11 MAC layer.

1.3.1 Basic Access Method

A node with a packet to transmit must monitor the communication medium to ensure that it has been idle for a period of at least DIFS (DCF InterFrame Space). If the medium has been idle for DIFS or longer, the node is free to transmit the packet immediately. If the medium is not idle or has been idle for a period less than DIFS, the node must wait until the medium has been idle for at least DIFS time. The node then selects a discrete random backoff counter before transmitting the packet. The underlying assumption here is that there may be multiple nodes in the same area waiting to transmit. Once the nodes detect the medium becoming idle after a transmission, independently selected random backoff period will minimize the chance of overlapping transmissions. The backoff counter is uniformly selected from a contention window value initially set by a value specific to the individual PHY layer implementation.

The backoff counter is decremented at the end of a discrete time slot if the communication medium is still idle. The duration of the slot is the time required for the node to sense the medium to determine if it is still idle. The backoff counter is not decremented when the node determines that the medium is busy. When the backoff counter is decremented to zero, the node transmits the packet.

In this dissertation, a packet transmission intended for a single receiver is called a *unicast*¹. Unicast packets must be acknowledged by the receiver. To do so, the receiver sends a small (14 byte) acknowledgement (ACK) packet to the sender after an interval SIFS (Short InterFrame Space), which must be smaller than DIFS to ensure that the ACK packet can be transmitted before another node attempts to transmit a packet. If the sending node receives the ACK packet, then the unicast is considered successful and no further action is taken by the sender for that packet. If the sender does not receive an ACK packet within a fixed timeout interval, it doubles the value of the contention window and selects a new random backoff value,

¹The term *unicast* also refers to any communication from a source to a single receiver.

at the end of which, it will retransmit the unicast packet. This retransmission procedure is repeated, doubling the contention window each time until either the sending node receives an ACK packet from the receiver or the contention window reaches some maximum size specific to the individual PHY layer implementation. In the latter event, the packet is dropped and the unicast is considered a failure.

The wireless network simulations documented in Chapter 6 use a simulation of the 802.11 MAC layer based on Direct Sequence Spread Spectrum (DSSS) with a SIFS of 10 microseconds, a DIFS of 50 microseconds, an initial contention window size of 32 and a maximum contention window size of 1024. The slot size used for random backoff is 20 microseconds. The timeout for ACK packet return is 300 microseconds.

The random binary exponential backoff mechanism described in the 802.11 standard is an effective means of managing contention for the communication medium [3]. The algorithm self-adjusts to small or large numbers of contending nodes in a few steps. The same algorithm is less applicable for responding to noise. While some sort of distributed randomized waiting is an effective means of sharing the communication medium, the same waiting response to noise when there is little contention leads to stretches where no node is transmitting, even when there are multiple nodes with packets to transmit. A more effective response to noise is the immediate retransmission of the failed unicast to increase the likelihood of correct reception of the packet.

1.3.2 RTS/CTS Protocol

A node with a packet to transmit must monitor the communication medium to ensure that it has been idle for at least DIFS time, and after that choose a random backoff counter, just as it would for the basic access method. When the backoff counter is decremented to zero, the transmitting node sends a 20 byte Request To Send (RTS) packet to the receiver. The RTS packet contains the duration that the sender wants for exclusive access to the communication medium in microseconds. The duration in the RTS packet is the time required to send a data packet, a clear to send (CTS) packet, and an ACK packet plus three SIFS intervals. The receiver of the RTS packet responds to the RTS packet after a SIFS interval by transmitting a CTS packet containing a duration to the sender. The duration in the CTS packet is the time required to send the data packet, and an ACK packet plus two SIFS intervals, in microseconds. When the sender

receives the CTS packet, it transmits its packet after a SIFS interval.

Any node in communication range of the RTS and CTS transmissions will also receive the RTS or CTS packets. Nodes other than the receiver that overhear only the RTS packet will not transmit during the duration specified in the RTS packet. Nodes other than the sender or receiver that overhear the CTS packet will not transmit during the duration specified in the CTS packet.

The RTS/CTS protocol is an effective means of dealing with *hidden nodes*, where there may be other nodes within communication range of the receiver, but not the sender. The RTS/CTS protocol also reduces the chances of packet collisions, since the only potential for collision is during the transmission of the short RTS packet.

1.4 Wireless Transmission Rates and Packet Forwarding Capacity

There are three different 802.11 PHY layers currently available, designated 802.11b, 802.11a and 802.11g. Each layer offers multiple transmission rates. The maximum packet transfer capacity for each transmission rate for all three 802.11 PHY layers is shown in Table 1.1. The first and second column identify a specific PHY layer and transmission rate, the transmission rate expressed in megabits per second. The next five columns shown different packet sizes, with 50 bytes being considered a small packet and 1500 bytes a large packet. Individual entries under each of the packet size columns is the maximum number of packets per second that can be sent for that PHY/transmission rate combination for that packet size given the overhead required by the DCF for that PHY implementation. The individual rates for maximum number of packets per second transfer are based on a 50 microsecond DIFS, an initial contention window size of 32, a maximum contention window size of 1024, a 20 microsecond slot size and an average random backoff time of 320 microseconds.

The fastest 802.11b transmission rate is eleven times faster than the slowest 802.11b transmission rate. However, the communication medium coordination overhead imposed by the DCF reduces the potential packet transfer rate for the 11 Mbits/sec transmission rate to less than twice the potential packet transfer rate for the 1 Mbits/sec transmission rate for 50 byte packets and a little over eight-fold for 1500 byte packets. The increase in bandwidth for packets

Protocol	Rate	50 bytes	100 bytes	500 bytes	1000 bytes	1500 bytes
802.11b	1 Mbits/sec	1265.80	840.33	227.79	119.19	80.71
802.11b	2 Mbits/sec	1694.90	1265.80	418.41	227.79	156.49
802.11b	5.5 Mbits/sec	2161.10	1867.60	895.04	542.14	388.83
802.11b	11 Mbits/sec	2345.40	2161.10	1326.90	895.04	675.26
802.11a/g	6 Mbits/sec	2189.78	1910.80	946.40	580.27	418.41
802.11a/g	9 Mbits/sec	2301.79	2088.20	1198.40	781.93	580.27
802.11a/g	12 Mbits/sec	2362.20	2189.78	1382.59	946.37	719.40
802.11a/g	18 Mbits/sec	2425.88	2301.79	1633.39	1198.40	946.37
802.11a/g	24 Mbits/sec	2459.02	2362.20	1796.41	1382.49	1123.60
802.11a/g	36 Mbits/sec	2493.07	2425.80	1995.57	1633.39	1382.49
802.11a/g	48 Mbits/sec	2510.46	2459.02	2112.68	1796.41	1562.50
802.11a/g	54 Mbits/sec	2516.31	2470.27	2154.83	1858.22	1633.39

Table 1.1: Maximum packet forwarding rate (in packets per second) for 802.11 a/b/g transmission rates for packet sizes 50, 100, 500, 100 and 1500 bytes.

of a particular size is not directly proportional to the increase in transmission rate due to the overhead imposed by the 802.11 DCF.

The fastest 802.11a transmission rate is nine times faster than the slowest 802.11a transmission rate. Increasing the transmission rate for 50 byte packets from 6 Mbits/sec to 54 Mbits/sec results in only a 14.91 percent increase in data transfer speed, again due to overhead imposed by the 802.11 DCF. Increasing the transmission rate for 1500 byte packets from 6 Mbits/sec to 54 Mbits/sec results in a 290.38 percent increase in data transfer speed, much greater than the increase gained for 50 byte packets. Although the contention control overhead imposed by the 802.11 DCF does reduce data transfer rates regardless of transmission rate, larger packets get greater benefits from faster transmission rates than smaller packets.

The slowest 802.11b wireless transmission rate provides a link capacity of approximately 0.6 Mbits/sec for 1500 byte packets after correcting for overhead required by the 802.11 Distributed Coordination Function. The fastest 802.11g wireless transmission rate provides a link capacity of approximately 20 Mbits/sec for 1500 byte packets after correcting for DCF overhead. In contrast, a wired 802.3z Ethernet link has a capacity of 1 gigabit/sec and a wired 802.3ae Ethernet link has a capacity of 10 gigabits/sec [15], [25]. The 10 gigabit 802.3ae wired Ethernet link provides 500 times the capacity of the fastest 802.11 wireless link. The magnitude of the disparity between wired and wireless links, and the wide variety of current and developing applications for wireless ad hoc networks in different areas underscores the

importance of using the limited bandwidth of wireless links effectively. The effective use of wireless links in ad hoc networks is the motivation for the research in this dissertation.

1.5 Applications of Wireless Ad Hoc Networks

The self-configuring capabilities of wireless ad hoc networks coupled with the lack of costly infrastructure, makes them appealing for many applications in a variety of circumstances. The success of wireless ad hoc networks comes from their flexibility, making them useful for new circumstances as the need arises. The lack of infrastructure and ease of reconfigurability must be balanced against the performance penalties inherent to wireless ad hoc networks including wireless communication, multi-hop routing and distributed routing control. The very flexibility means that research into wireless ad hoc networks must balance flexibility of design against varying application needs. A network designed to meet a wide variety of circumstances may not be able to meet stringent performance requirements for some distributed applications. Conversely, a network designed to meet specific stringent requirements may be less useful in general. The ideal wireless ad hoc network design would be flexible enough to support a variety of distributed applications while being capable of meeting high performance requirements when needed.

This section describes some of the common applications for wireless ad hoc networks. There are distributed applications on the battlefield, in industry and in the home.

1.5.1 Military Applications

The inherent lack of infrastructure makes wireless ad hoc networks desirable for military situations where networks must be dropped (literally) into remote and often hostile areas where network infrastructure is nonexistent and cannot be developed. Such networks have to be built, configured and torn down quickly. Military scenarios require sensor networks and intelligence gathering mechanisms placed close to potential targets. A sensor network consists of small nodes with sensing, computation and wireless networking capabilities. The nodes in the sensor network could contain passive optical, electromagnetic, audio, chemical, or biological sensors. Optical sensors could be used to coordinate unmanned aircraft in flight, or provide networked

navigation on the ground by routing vehicles effectively through complex terrain and constantly changing hazards. Electromagnetic sensors could be used to monitor hostile communications as well as detect military hazards like land mines and active radar signals. Chemical and biological sensors can be used to monitor the presence of chemical and biological warfare agents to provide vital information necessary to the planning of troop movement on the battlefield. The potential threat to the network devices is quite high, and the network must be robust to hazardous conditions and loss of nodes with minimal human intervention.

The United States military plans to use networked communication on a grand scale. The Department of Defense wants to assign a unique IP address to every piece of equipment and every soldier on the electronic battlefield [53]. The Defense Advanced Research Project Agency (DARPA) project GLOMO (GLObal MObile information system), intended to develop high-speed metropolitan area networks for multimedia communication, has met with limited success [40], [51].

1.5.2 Industrial Applications

Networking without the overhead of infrastructure installation and maintenance costs makes wireless ad hoc networks attractive in the industrial world. Wireless ad hoc networks can support distributed control applications with sensors and actuators connected with wireless networks. Wireless sensor networks can be deployed in mines, nuclear power plants and other hazardous industrial environments. In less dangerous industrial environments, analog control systems for heating, ventilation and cooling (HVAC) systems can be replaced with more energy efficient digital controls that communicate through wireless ad hoc networks. Similarly, large-scale lighting systems and motor controls could also be made more energy efficient by replacing the analog control systems with digital controls that communicate through wireless ad hoc networks [21].

Wireless ad hoc networks can be used to coordinate automated vehicles in industrial environments and the control of industrial and manufacturing processes. Wireless ad hoc networks could provide the coordination, sensing and control of industrial processes while the lack of infrastructure provides reconfigurability and scalability on an economical basis as the industrial environment changes and expands.

1.5.3 Wireless Ad Hoc Networks At Home

Wireless ad hoc networks can be employed in the day-to-day operation of individual homes. Sensor networks using metering devices can regulate residential appliances that consume large amounts of energy like hot-water heaters, air conditioners, furnaces and refrigerators [29]. Individual appliances could be monitored through wireless metering devices attached to power outlets. Information on residential energy consumption could be monitored through the home computer. The home computer could also monitor the state of the family automobile that would have its own IP address [42]. The residential network could include intelligent appliances that coordinate with each other and the Internet for software upgrades and maintenance scheduling, again under the supervision of the owner through the home computer [54].

Wireless ad hoc networks can also be used to detect and manage abnormal residential situations. A home-based sensor network utilizing video, thermal sensors or motion detectors could coordinate and interpret sensor data to detect abnormal or potentially dangerous situations including intruder detection, property damage or fire in the earliest stages. The result of such detection could be alerting the home owner, the police or the fire department as appropriate for the specific situation. Information relevant to the emergency situation including location relative to the home blueprints could be conveyed as part of the automated response [43], [23].

One design challenge for wireless ad hoc networks in the home is the need for standardization, since all of the networking devices in the home must be able to communicate in accord with the same standards. Another challenge is the ability to provide the desired functionality in a cost-efficient fashion. A third challenge is the need to support different Quality of Service (QoS) requirements for different home networking applications, including delay constraints and data throughput rates. Another challenge is power management. Some devices will have an external power source and have no real power constraints, while other devices will have to conserve limited battery power. Effective power management would place the heaviest power demands on the devices with the external power sources and minimize the demands placed on the battery-powered components of the home network.

1.6 Thesis Statement

Noise and router congestion can affect application data throughput in wireless ad hoc networks. Noise can corrupt packets transmitted between wireless nodes, resulting in loss of data. The location of a noise source tends to be beyond the control of the applications running on a wireless ad hoc network. The timing and strength of the noise transmissions, whether accidental or deliberately hostile, are also likely to be beyond the control of the applications running on the ad hoc network. The location of nodes in the network and the timing of when any node chooses to send data to a possibly distant node affects the router congestion of the intermediate nodes in ways that could not always have been predicted beforehand. The dynamic and unpredictable nature of noise and congestion suggests the need to adapt to changing noise and congestion conditions as they arise. Mechanically observable factors related to wireless ad hoc networks can provide enough information to machine-learning mechanisms to allow nodes to automatically manage noise and router congestion. Such machine learning is possible and can be used to improve the throughput of distributed applications. The thesis of this dissertation is:

Machine learning is feasible and useful in managing noise and router congestion in wireless ad hoc networks to improve application throughput for distributed applications.

There are two contributions of this dissertation. The first is a new time-based, cross-layer routing metric that takes recent learned experience from the network and MAC layers into consideration when making routing decisions in wireless ad hoc networks. The second contribution is a new cross-layer wireless routing protocol, called Warp-5, that uses the new routing metric and other machine-learning mechanisms to establish new routes and to adjust existing routes when they overload routers. The new routing metric and routing protocol are significant for commercial or military distributed applications that exchange large amounts of audio, video or sensor data between nodes or where there is a need to make the best use of available router capabilities. The exchange of large amounts of data through wireless links underscores the importance of well-constructed routes in a wireless ad hoc network.

1.7 Organization of Dissertation

Chapter 1 has introduced the ideas of wireless ad hoc networks, routing protocols, applications of wireless ad hoc networks, how communication is coordinated in wireless networks, wireless transmission rates in relation to communication capacity and the thesis statement. Chapter 2 covers previous work in the areas of link-level transmission rate selection, routing protocols and routing protocols that use machine learning. Chapter 3 presents mathematical models for noise and packet loss, the machine-learning based routing metric and a discussion of how noise sources are calibrated for specific noise loss effects in simulated wireless ad hoc networks. Chapter 4 describes the Warp-5 routing protocol, including route requests, route construction and route management in response to noise and congestion. Chapter 5 describes the machine learning mechanisms used by Warp-5 and where those mechanisms are used. Chapter 6 contains simulation results for noise and congestion problems, which show improvements in distributed application throughput in noisy and congested environments, thus proving the thesis. Chapter 7 presents the current status and future work done for this research area along with the conclusion.

Chapter 2

Previous Work

Nodes in a wireless network communicate digital data through radio signals. Digital data bits and extra error detection and recovery bits are encoded into a radio signal waveform by the transmitter in one node, and decoded back into digital data by receiver nodes within communication range of the transmitter. How many data bits and how many error detection and recovery bits are encoded per unit time determines the *transmission rate*. Faster transmission rates encode more data bits and fewer error detection and recovery bits into a signal waveform, resulting in a trade-off between speed of data communication and robustness to noise. Faster transmission rates carry more data, but are more susceptible to noise. Lower transmission rates carry less data, but are more resilient to noise.

Digital communication between nodes in a wireless network may take the form of a *broadcast* or a *unicast*. A broadcast is an omnidirectional radio transmission from one node to all nodes within communication range, where all the receiving nodes are the intended recipients. A unicast is an omnidirectional radio transmission from one node to all nodes within communication range, where only one node is the intended recipient. After receiving a unicast, the intended receiver must acknowledge the unicast by transmitting an acknowledgement packet (ACK) back to the sender. The unicast is complete when the sender receives the ACK packet. Some wireless communication protocols, including 802.11, will retransmit a unicast packet if the sending node does not receive an ACK packet within a specific time limit [24]. The 802.11 MAC layer will retransmit a unicast packet some maximum number of times before abandoning the unicast attempt. Broadcast packets do not require acknowledgement from the receiver nodes.

The challenge of transmission rate selection is to find a transmission rate that maximizes data communication speeds by balancing the trade-off between maximizing how many data

bits are transmitted per unit time and minimizing the probability of data corruption and loss in digital transmissions due to noise in the radio communication environment. Noise sources may be anywhere in the network environment and affect each node differently due to individual proximity to the noise sources. Each node has to find a transmission rate that most efficiently communicates unicast packets given the noise characteristics of the environment local to the sender and receiver nodes.

The purpose of a routing protocol is to find a sequence of intermediate nodes from a source node to a destination node. Nodes are selected or rejected to be part of the sequence of intermediate nodes according to a *routing metric* communicated between nodes as part of the routing protocol. The routing metric used by many of the routing protocols described in Section 2.2 is the number of intermediate nodes (called “hops”) between the source and destination nodes. The objective of the routing protocols using this metric is to find the sequence with the fewest hops between the source and destination nodes. Other routing metrics exist, such as length of router input queues, total data packet arrival rate in the network and source-to-destination transit time for data packets. Regardless of the routing metric used, the goal of the routing protocol is to find routes that best fit the routing metric.

Multiple routes in the same wireless network contend for routers using whatever metrics are defined by the routing protocol in use. The intermediate nodes forwarding data packets for currently existing routes are that much less able to handle the data traffic for later routes, should they occur. Network topologies can exist where multiple routes forward data traffic through intermediate nodes whose routing capacity is exceeded by the levels of incoming traffic (see the example “castle” topology described in Chapter 6). Data traffic levels that exceed the ability of the intermediate nodes to forward data packets result in loss of data packets when incoming packets are dropped from router input queues. Noise levels along the shortest route may cause significant corruption and loss of data packets transmitted from node to node. The combined problems of noise and router congestion in wireless ad hoc networks emphasize that shortest path between source and destination is not always the best route.

The first section in this chapter discusses previous work in the area of transmission rate selection. The second section in this chapter discusses previous work in wireless routing protocols

that are not based on machine learning. The third section covers previous work in machine-learning based routing protocols and how these protocols attempt to address router congestion. The effects of noise are not considered in either the non-machine-learning based routing protocols or the machine-learning based routing protocols.

2.1 Transmission Rate Selection

There are currently three different 802.11 PHY layers available, designated 802.11b, 802.11a and 802.11g [24]. Each layer offers the ability to transmit packets at multiple rates. Under ideal (and physically unattainable) noiseless conditions [49], all unicasts between neighboring nodes would be completed in a single transmission and the fastest available transmission rate would always provide superior performance in terms of application throughput. In the real world, background noise exists and can be augmented by artificially generated noise, either accidental or deliberate. The problem is that the higher the transmission rates, the more susceptible the transmission is to corruption and loss from noise. Unicast packets lost in this fashion have to be retransmitted to ensure correct reception, but the retransmission takes time that reduces application throughput.

Transmission rates are either chosen automatically at the PHY level to reflect current noise conditions or are set manually at a higher level in the protocol stack [22]. The individual PHY layer hardware determines how the transmission rate is set and varies according to the hardware implementation, but higher levels of the protocol stack could determine the quality of the unicast link. When the PHY layer selects the transmission rate, the wireless card would have to provide the total number of transmission attempts, the transmission rate selected and whether the unicast was successful or not as feedback to the higher levels of the protocol stack. In hardware situations where the transmission rate is set manually, the wireless card would have to provide the number of transmission attempts and whether the unicast was successful or not as feedback.

Previous work in the area of transmission rate selection addresses adjustments of link-level transmission rates in response to changing environmental noise conditions. The individual merits of the transmission rate selection algorithms are judged by the responsiveness to changing

conditions and relative efficiency in stable environmental conditions.

2.1.1 Automatic Rate Fallback (ARF)

The Automatic Rate Fallback (ARF) algorithm was one of the first published rate adaptation algorithms [33]. It was originally developed for WaveLAN-II 802.11 network cards, which were one of the earliest multi-rate 802.11 cards, capable of transmitting at 1 and 2 Mbits/sec. ARF also worked on later WaveLAN cards with more than two transmission rates. The algorithm on the sending node initially selects the highest available transmission rate. If a unicast transmitted at the selected rate is not acknowledged, the algorithm drops to the next lower transmission rate. If ten successive unicasts are successful, the algorithm selects the next higher transmission rate. If the first unicast at the higher transmission rate is not successful, then the algorithm returns to the previous lower transmission rate.

The algorithm does not adapt to rapidly changing conditions and the first packet transmitted at a higher transmission rate (called the *probing packet*) will require more retransmissions than packets sent at a lower rate if the environmental conditions change slowly or are stable. The failed retransmissions at the higher transmission rate reduce application throughput.

2.1.2 Receiver-Based AutoRate (RBAR)

The Receiver-Based AutoRate (RBAR) transmission rate selection algorithm shifts responsibility for selecting the appropriate transmission rate from the sender to the receiver of the unicast [22]. The sender is required to use a modified RTS/CTS protocol to unicast a data packet of any size, even in the absence of hidden nodes. Instead of containing the length of the data transmission in microseconds, the RBAR RTS packet contains the length of the data in bytes and a candidate transmission rate. The receiver must then use the signal-to-noise ratio of the RTS packet to select the appropriate transmission rate from pre-calculated tables. The selected transmission rate is returned to the sender as part of the RBAR CTS packet. Upon receipt of the CTS packet, the sender transmits the data packet at the transmission rate specified in the CTS packet.

Nodes that overhear only the RTS packet do not transmit for a duration calculated from

the data length and candidate transmission rate in the RTS packet. Nodes that overhear the CTS packet do not transmit for a duration calculated from the data length and the selected transmission rate in the CTS packet.

RBAR performs well, but it does present some problems. The first is that the RTC/CTS packet formats must be changed to contain data that is not compatible with the 802.11 standard, which means that RBAR cannot be used with existing 802.11 systems. The second is that SNR information may not always be available in all PHY hardware. The third is that the RTS/CTS protocol must be used for all unicasts, regardless of size, which is inefficient when data packets are small. The fourth problem is that SNR information, even when it is available, is not a good predictor of packet delivery probability over some SNR ranges [4].

2.1.3 Adaptive Automatic Rate Fallback (AARF)

The Adaptive Automatic Rate Fallback (AARF) algorithm addresses the inefficiency of the ARF algorithm by doubling the number of consecutive unicasts before attempting to increase the transmission rate if the attempted rate increase proves unsuccessful [37]. The exponential increase in the number of consecutive successful unicasts at the same transmission rate before attempting a higher rate reduces the frequency of unicast retransmissions under stable or slowly changing noise conditions and improves overall application throughput.

2.1.4 SampleRate

The SampleRate algorithm selects the transmission rate that will minimize the expected unicast transmission time, including the time used in detecting failed transmissions and subsequent retransmissions in noisy environments [4]. After every ten consecutive successful unicasts, the SampleRate algorithm randomly selects an alternative transmission rate whose lossless expected transmission time is less than the current (and possibly lossy) transmission rate. A lossless transmission will complete a unicast in a single transmission. The SampleRate algorithm directly tries to minimize MAC-to-MAC unicast transmission time.

The SampleRate algorithm will not use transmission rates whose lossless transmission time is greater than the transmission time of the current transmission rate, since doing so would only

increase the expected transmission time. It will also not use an alternate transmission rate that has experienced four successive failed unicasts. Bicket [4] does not state whether SampleRate ever tries the transmission rates excluded under this later condition. The excluded transmission rates might provide better throughput under different conditions, which is especially relevant if the noise conditions change.

2.1.5 Discussion

ARF rigidly attempts to send at a higher transmission rate after every ten consecutive successful unicasts. AARF does better, but still sends a packet at a higher transmission rate even when environmental conditions change more slowly than AARF increases its threshold for a new transmission rate change. The tables used by RBAR may be poorly constructed and lead to the selection of the wrong transmission rate from an observed SNR. SampleRate tries randomly selected transmission rates that may reduce application throughput in the wireless ad hoc network. The evolutionary pattern of these transmission rate selection algorithms shows a greater tendency to use information gained from recent experience in making better decisions about selecting transmission rates for a given link. What is missing is the use of link-quality information to choose among different neighbors in trying to forward packets from a source to a destination when multiple neighbors are available. The new machine-learning based routing protocol introduced in Chapter 4 makes use of link-quality information to select and maintain efficient routes in wireless ad hoc networks operating in noisy environments. The simulations in Chapter 6 comparing this new routing protocol to previously existing routing protocols will demonstrate the basic statement of this thesis—that machine learning is feasible and useful in managing noise in wireless ad hoc networks to improve application throughput.

2.2 Routing Protocols For Wireless Ad Hoc Networks

Routing protocols fall into two categories based on how routing information is made available to nodes in a network. *Proactive* protocols attempt to continuously maintain routes for all nodes in the network by regularly disseminating routing information between nodes. When a node needs to send data to a destination, the route is immediately available and ready for

use. *Reactive* protocols will *discover* a route only when it is needed. Proactive protocols entail high overhead in communicating routing information, but offer low latency in providing routing information. Reactive protocols have lower routing overhead, since they communicate information only for routes that are actually needed, but suffer higher latency in providing routing information.

There are three kinds of routing algorithms. In *link-state* algorithms, each node in the network knows the entire network topology and the cost of every link in the network. Nodes share routing information by broadcasting the topology and link-cost information to their neighbors. Neighbors receiving these broadcasts update their own network topology and link-cost information and then perform a shortest-path algorithm to select the next hop for each destination. In *distance-vector* algorithms, each node in the network knows the cost of every neighbor for each destination. When a node receives routing information for a specific destination from a neighbor, the receiving node updates its own cost to the destination using that neighbor as a link. If the cost to the destination for that neighbor is now smaller than the previous smallest cost to that destination, the receiving node broadcasts its new estimate of the smallest cost to the destination to its neighbors. In *path-vector* algorithms, each node maintains routing information that consists of a list of one or more *paths* to each destination. A path defines a sequence of intermediate nodes to the destination node. The paths to a specific destination are ordered by a routing metric, with one path designated as the “best” path. Nodes share information by broadcasting routing tables to their neighbors. Neighbors that receive routing table information add their own address to the paths, discard paths with loops, add the remaining paths to their own routing tables and sort the paths by the routing metric.

Previous work in wireless routing protocols shows an evolution toward balancing a reduction in the amount of routing information communicated through the wireless ad hoc network and an increased responsiveness to changing conditions.

2.2.1 Destination-Sequenced Distance Vector (DSDV) Routing Protocol

The Destination-Sequenced Distance Vector routing protocol is a proactive distance-vector routing protocol designed specifically for wireless ad hoc networks [46]. The DSDV protocol requires each node to periodically broadcast its own routing information to ensure that

every node in the ad hoc network always has a route to every other node in the network in light of potentially changing network topology. Each entry in the routing table of each node is tagged with a sequence number set by the destination node. Nodes use the sequence numbers to quickly distinguish new routing information and older routing information, and thus prevent the formation of routing loops. The requirement that each node carry routing information for every other node means the size of each routing information broadcast is $O(n)$ where n is the number of nodes in the ad hoc network. With every node periodically transmitting its own routing information, the routing information message overhead is $O(n^2)$. The high routing information overhead limits the usefulness of DSDV to small networks, where even the authors of the DSDV paper acknowledge that the communication bandwidth is the most precious and scarce resource in the wireless medium [46]. An important contribution of DSDV is the use of sequence numbers to express relative freshness of routing information. The routing metric is the number of intermediate nodes (“hops”) between source and destination nodes. The objective of DSDV is to find the shortest path between source and destination nodes.

2.2.2 Ad-hoc On-Demand Distance Vector (AODV) Routing Protocol

AODV is a reactive routing protocol that builds routes as needed [45], [47]. Nodes in the wireless ad hoc network are assumed to have no initial routing information. A node that needs to communicate with a destination node for which it has no routing information initiates a broadcast flood of route request packets in an expanding ring search algorithm. The request packet contains a sequence number that is used by intermediate nodes to compare relative freshness of routing information. Routing decisions by intermediate nodes will always reflect a preference for newer routing information over older routing information, even when the newer information defines a longer path to the destination. A destination node or other node with a higher sequence number than the one in the received route request unicast reply packets upstream toward the source node. Other recipients of the route request build the shortest route back to the source node (for bidirectional routes) as well as propagating the route request within the constraints of the expanding ring. Recipients of the route reply packets select the route that either has the larger (and thus later) sequence number or the shorter path from multiple neighbors when the

sequence numbers are equal. Routing information for neighbors with older routing information or longer paths is discarded. AODV also has an aging algorithm that discards forwarding information for neighboring nodes that are not selected to receive forwarded data packets. The routing metric is the number of hops between source and destination nodes. The objective of AODV is to find the shortest path between source and destination nodes.

2.2.3 Dynamic Source Routing (DSR) Protocol

DSR is a reactive path-vector protocol that builds routes as needed [30], [31]. Nodes in the wireless ad hoc network are assumed to have no initial routing information. A node that needs to communicate with a destination node for which it has no routing information initiates a broadcast flood of route request packets. The route request packet contains path information, initially empty. Intermediate nodes without routing information for the requested destination that receive the request propagate the request if the request does not contain the address of the intermediate node, otherwise the intermediate node drops the request. The intermediate node adds its own address to the path in the propagated request packet. Destination nodes or nodes with routing information to the destination node unicast reply packets to the source node. The reply packets contain a complete path to the destination, built from the path in the route request packets. Routing loops are prevented by disallowing the same node from appearing in a path more than once.

The source node receives reply packets containing a complete path from source to destination. The extended IP header of each data packet sent from the source node contains the complete source to destination path, which is used by the intermediate nodes to make forwarding decisions. The source node has the ability to cache multiple routes to the same destination, giving it the ability to send data packets to the same destination using different routes. The source nodes have no information regarding how other routes are moving packets through the ad hoc network, so the source nodes have no basis for making useful route selections other than finding the shortest path between source and destination nodes. The length of the alternative routes is determined from the number of node addresses in the route reply packet.

2.2.4 Optimized Link State Routing (OLSR) Protocol

OLSR is a proactive routing protocol that propagates route request broadcasts through a subset of the neighbors of each node [28], [12]. These nodes are called the *multipoint relays*. The multipoint relays for a given node are the minimal set of neighbors that can reach all nodes two hops away from the given node. Other neighbors that are not part of the multipoint relay set do not participate in route request propagation. Limiting route request propagation to multipoint relays reduces duplicate retransmissions of the route request packets. All routes resulting from the route request are paths through the multipoint relays from source to destination. Expressing paths in terms of the multipoint relays also reduces the amount of routing information transmitted in the periodic route exchange broadcasts, and reduces the demand on network capacity used to maintain current routing information. The routing metric is the number of hops between source and destination nodes. The objective of OLSR is to find the shortest path between source and destination nodes.

2.2.5 Zone Routing Protocol (ZRP)

ZRP is a hybrid routing protocol that is proactive in localized *zones* and reactive between zones in wireless ad hoc networks [20]. The zone for a given node in the network consists of the nodes that are at most some fixed number of hops away from the given node. Routing changes are proactively propagated with the zone for each node and each node is required to know the network topology within its zone. Route requests with a zone are handled by the proactively available routing information. Route requests between zones are reactively handled by multicasting the route request directly to the nodes on the periphery of the zone, where the request then propagates through the network to nodes at the periphery of the zone of the destination node. The nodes at the periphery of the zone of the destination node then send the reply packets back to the sender node. Proactive zones are maintained for all nodes in the network.

The protocol requires the MAC layer provide immediate neighbor connectivity information. The routing metric is the number of hops between source and destination nodes. The objective of ZRP is to find the shortest path between source and destination nodes.

2.2.6 Sharp Hybrid Adaptive Routing Protocol (SHARP)

SHARP is another hybrid routing protocol that is proactive in localized zones and reactive between zones in wireless ad hoc networks [52]. In contrast to ZRP, only the destination nodes have proactive routing zones, other nodes do not have zones. The proactive routing protocol with a zone maintains only routes to the central destination node. The zone radius is the number of hops away from the central node. The zone radius is automatically increased in response to link failures or increases in the amount of data traffic for the destination node. The increase in zone radius increases the packet overhead to maintain the larger zone. Reductions in zone radius decrease proactive routing overhead. The routing metric is the number of hops between source and destination nodes. The objective of SHARP is to find the shortest path between source and destination nodes.

2.2.7 Discussion and Other Previous Work

All of the routing protocols described in this section select routes that minimize the number of intermediate nodes between source and destination nodes, using path length as a routing metric. Gelenbe, Liu and Laine [16] present a generic basis for other routing metrics by defining a *goal function* for different paths between a given source and destination node. Example goal functions for a given path include number of packets lost, delay in packet delivery, variance in packet delay, power consumed in forwarding a packet, or overall security level. Router congestion in wireless networks is not addressed. Noise is not explicitly addressed, although it does affect packet delay as shown in Chapter 3.

Legendre, de Amorim and Fdida present possible requirements for how initially separate wireless ad hoc networks using different routing protocols could merge [39]. Physically merging wireless ad hoc networks using heterogeneous routing protocols would still be able to provide loop-free routing through the use of a *Neighborhood Routing Protocol Discovery Protocol* (NRPDP). Nodes at the periphery of the merging networks would use an NRPDP to determine the routing protocol used by the other network and translate routing messages from one protocol to another as routing protocol control messages pass from one network to the other. The operational assumption is that the routing protocols use the same routing metric in different

forms (e.g. hop count), and does not address how heterogeneous routing metrics like those enumerated by Gelenbe, et al. could be translated.

2.3 Machine-Learning Based Routing Protocols

The problem of routing in a wireless ad hoc network is one of finding and selecting a sequence of intermediate nodes from source node to destination node. The sequence of intermediate nodes from the source node to the destination node is called a *path*. There may be many paths between the source and destination nodes and the selection of a route is determined by a routing metric. The most common routing metric is the number of intermediate nodes (“hops”) between the source and destination nodes, as discussed in the previous section. When the routing metric is the number of hops, the most common objective of the routing protocol is to find the shortest path between source and destination nodes. Other routing metrics exist, such as length of router input queues, total data packet arrival rate in the network and source-to-destination transit time for data packets. Chapter 3 introduces a new routing metric combining the effects of noise and router congestion into a single value for nodes with heterogeneous forwarding capacities in wireless ad hoc networks. Regardless of the routing metric used, the routing problem is one of finding routes that best fit the routing metric.

Previous work in the application of machine learning to routing in wireless networks has treated the problem as a kind of Markov Decision Process (MDP). The subfield of machine learning that deals with sequential control problems is called reinforcement learning [57]. In reinforcement learning, the control mechanism is called the *agent* with an explicit goal it can achieve by taking a variety of *actions*. The agent is also capable of perceiving its environment in some means relevant to the goal and from these perceptions the agent determines the *state* of the system. The *state transition model*, denoted by $T(s, a, s')$, defines the probability of entering state s' after taking action a in state s . The *reward* is a quantification of the result of an action a taken from state s as it relates to the goal, denoted by $R(s, a)$. The result of an action can also be represented as a *cost*, denoted by $C(s, a)$ for the action a taken from state s . The difference between reward and cost is that the agent wants to maximize reward and minimize cost. The state transition model and reward functions depend only on the current

state and not on any preceding state. The total reward an agent can acquire in the long run when taking action a in state s is denoted by the Q-value $Q(s, a)$.

The goal of solving an MDP is to find a decision rule, called an *optimal policy*, that determines which action to take in each state to maximize the total reward (or minimize the total cost) as the agent progresses from state to state in the system. The *Q-learning* algorithm [62] iteratively improves the $Q(s, a)$ estimates as the agent gains experience after taking each action in the system. The Q-learning algorithm begins with the agent in state s . The $Q(s, a)$ values are initially set to arbitrary values. The agent in state s selects the action a that maximizes $Q(s, a)$ over all actions in state s :

$$a \leftarrow \underset{a'}{\operatorname{argmax}} Q(s, a').$$

From the action a , the agent gains experience in the form of an immediate reward, $R(s, a)$, received after taking action a when the agent is in state s . The agent uses the immediate reward and the expected maximum long-term reward to update the $Q(s, a)$ estimate. The Q-learning update used after obtaining each reward is:

$$Q(s, a) \leftarrow (1 - \alpha)Q(s, a) + \alpha(R(s, a) + \gamma \max_{a'} Q(s', a')),$$

where $\alpha \in (0, 1]$ is a learning rate and $\gamma \in (0, 1]$ is a discount factor that makes immediate reward more desirable than later rewards. The updated $Q(s, a)$ estimate influences future action selections made by the agent. The state-transition and reward functions are underlying parts of the system environment and are not necessarily known to the agent. The ability of the Q-learning agent to discover its reward and new state from the environment after taking each action makes Q-learning applicable to the problem of finding routes in wireless ad hoc networks.

All of the Q-routing based protocols described in the following subsections use $Q(s, a)$ as a routing table. The state s is the current node and the action a is the downstream neighbor. The state transition functions are deterministic in that forwarding a packet to a specific neighbor y always forwards the packet to y and not some other node. The reward functions will vary for each Q-learning based protocol and can be stochastic.

2.3.1 Q-Routing

Littman and Boyan [41], [6] introduced the Q-routing routing algorithm based on Q-learning [62]. The distributed Q-routing algorithm treats the nodes in a network as a collection of learners, each responsible for learning part of the routing problem. The routing problem is treated as a Markov decision process (MDP). The goal of Q-routing is to minimize the time-to-destination cost of routing data packets. Each node x in the network keeps an estimated time-to-destination value $Q_x(d, y)$ for each of its neighbors. The Q-learning protocol is reactive. In response to a route request, each Q-learning node x sets the initial value of $Q_x(d, y)$ to an arbitrary value for each neighbor y of node x for the destination d . The Q-routing state is the intermediate node x forwarding the packet to destination d . The action is the selection of a neighbor y with the lowest estimated time to destination d and the link-level unicast of a data packet to y :

$$y \leftarrow \underset{y' \in \text{neighbors of } x}{\operatorname{argmin}} Q_x(d, y').$$

The downstream neighbor y returns its best time-to-destination estimate for the destination d to x :

$$\min_{z \in \text{neighbors of } y} Q_y(d, z).$$

The node x uses the received estimate from y as a Q-value estimate to update its own $Q_x(d, y)$ estimate

$$Q_x(d, y) \leftarrow (1 - \alpha)Q_x(d, y) + \alpha \left(\min_{z \in \text{neighbors of } y} Q_y(d, z) + T_{xy} + W_x \right)$$

where α is a learning rate, T_{xy} is the link-level transmission time from x to y and W_x is the time the packet spent waiting in x 's input queue.

The time-to-destination estimates are transmitted backward from downstream neighbor to upstream neighbor after every link-level unicast. The effect of the link-level time-to-destination transmissions is the propagation of time-to-destination estimates backward from the destination node toward the originator of the data packet.

The Q-routing algorithm proved similar to the Bellman-Ford shortest path algorithm [1], [14] under low-load conditions where many routes could share the shortest paths without router congestion. Under high-load conditions where the use of the shortest path metric resulted in router congestion and packet loss, the Q-routing algorithm adapted to the increased routing

times by selecting paths around congested routers and demonstrated better performance than pure shortest-path routing algorithms.

The $Q_x(d, y)$ values were initially implemented as a lookup table [6] and later as a neural network [41], but the neural network implementation did not provide consistent results.

2.3.2 Predictive Q-Routing

Choi and Yeung presented a modification of Q-routing called Predictive Q-routing [11] to address two shortcomings of the original Q-routing algorithm. The first shortcoming is that Q-routing does not always find the shortest path under low-load conditions. If one path has a Q-value less than the Q-value of a shorter path, the Q-routing algorithm will select the path with the smaller Q-value, with resulting updates to the Q-value of the selected path. The Q-value of the unexplored shorter path will not be selected and its Q-value will not be updated until the Q-value of other selected paths grow larger than the Q-value of the shorter path. The second shortcoming is the inability of the Q-routing algorithm to adapt to shorter paths when the offered load is lowered. When the Q-value of a path increases because of an increased queue waiting time, the Q-value of an alternate, longer path may become preferable. Unicasts on the longer path result in updates on that path, while the Q-value of the shorter path remains unchanged, even after reductions in offered load on the shorter path.

The Predictive Q-routing (PQ-routing) algorithm remembers the smallest Q-values of each neighbor. When the Q-value of these neighbors later increases, the algorithm occasionally sends data packets to the shortest paths (identified by the remembered small Q-value) in an exploratory activity Choi and Yeung call *probing*. The goal of probing is to reduce the average delivery time in a changing environment. If the updated Q-value of the probed path remains high, then PQ-routing behaves like Q-routing. If the updated Q-value of the probed path decreases, PQ-routing adapts by selecting the shorter path.

Frequent probing increases offered load to routers on congested paths and infrequent routing provides performance no different from Q-routing. The PQ-routing algorithm attempts to balance these extremes by predicting when probing should occur as a function of current offered load, the probability of link failure and the magnitude of the downward trend in Q-value from recent probes. By exploring paths that have been inactive, PQ-routing can recover from

reductions in offered load.

2.3.3 Dual Reinforcement Q-Routing

Kumar and Miikkulainen [35] proposed Dual Reinforcement Q-routing (DRQ-routing) as a modification to Q-routing. DRQ-routing does not address any potential shortcoming of Q-routing. DRQ-routing is based on Dual Reinforcement Learning, which was initially developed for adaptive signal equalizers in satellite communications [17]. Both ends of a satellite communication system have equalizers that change signals prior to transmission to cancel out atmospheric distortion. The receiver evaluates the performance of the sender's equalizer to modify its own equalizer. The equalizers at both ends of the communication system learn on-line.

The DRQ-routing algorithm uses the same $Q_x(d, y)$ time-to-destination estimates as in Q-routing. The $Q_x(d, y)$ estimates are updated with a new estimate from the downstream neighbor after each data packet is unicast. The novel contribution of DRQ-routing is that information about the time to the source node is carried on the data packets. The downstream neighbor receiving the data packets updates its knowledge about the path already traversed. The update information carried downstream is

$$\min_{z \in \text{neighbors of } x} Q_x(s, z).$$

The downstream neighbor y updates its own estimate $Q_y(s, x)$ for the time needed to send a packet to node S through the neighbor x :

$$Q_y(s, x) \leftarrow (1 - \alpha)Q_y(s, x) + \alpha \left(\min_{z \in \text{neighbors of } x} Q_x(s, z) + W_y \right),$$

where α is a learning rate, and W_y is the time the packet spent waiting in y 's input queue.

The experiments run by Kumar and Miikkulainen showed that DRQ-routing adapted to routes almost twice as fast as Q-routing in handling low offered loads and found better routes twice as fast as Q-routing under high offered loads. These increases are attributed to the enhanced exploration in DRQ-routing.

2.3.4 Policy-Gradient Q-Routing

Tao, Baxter and Weaver proposed the use of stochastic gradient ascent as an enhancement to Q-routing [60]. The goal of the enhancement is to balance offered load and minimize source-to-destination trip time for all routes in a wireless ad hoc network. Where Q-routing treats routing as a distributed Markov Decision Process (MDP), Tao et al. treat routing as a partially observable Markov Decision Process (POMDP). Each node is an independent agent that sees only some of the packets moving through the network, making the decision problem partially observable. The forwarding decision facing each intermediate node is unaffected by the previous path the packets have taken, making the problem a POMDP.

In Q-routing, the reward signal was the estimated time-to-destination from the downstream neighbor. The proposed enhancement uses the negative source-to-destination trip time for all packets in the network as the reward signal sent from downstream neighbor y to upstream neighbor x for destination d . Upstream node x uses policy-gradient reinforcement learning to adjust the $Q_x(d, y)$ value in the direction of the gradient of the average reward. The authors acknowledge that it is unrealistic to instantly communicate the sum of the packet trip times from the unconnected destination nodes as a reward signal to all the nodes in a wireless ad hoc network. They offer the alternative of having the destination nodes periodically broadcast their component of the reward signal throughout the network. Routers take the sum of the values from the received broadcasts as the reward signal. The reward signals sent as broadcasts are not instantaneous, but the long-term average reward can still be calculated.

The gradient-ascent modification is intended to speed up convergence of routes in a stationary routing environment, but provides no added value in non-stationary routing environments where offered load or noise conditions vary. The dependence on continual network-wide broadcasts of reward signal information increases contention for the limited communication bandwidth of wireless network communication, which distorts the source-to-destination trip time used to formulate the reward signal. The source-to-destination calculation itself assumes completely synchronized clocks in all nodes in the network, which is an impossibility given that there is no guarantee that all clock oscillators will run at exactly the same frequency [58].

2.3.5 Gradient Ascent Q-Routing

Peshkin and Savova [48] proposed the use of a stochastic gradient ascent policy search as an enhancement to Q-routing. The goal of the enhancement was to balance offered load and maximize the total data packet arrival rate for all routes in a wireless ad hoc network. Like the work of Tao et al. [60], Peshkin and Savova treat the routing problem as a partially observable Markov Decision Process. Each node in the wireless network is an independent agent that sees only some of the packets moving through the network, making the decision problem partially observable.

The reward signal is the total data packet arrival rate. The reward signal is propagated throughout the wireless network by broadcasting an acknowledgement packet when a data packet reaches its intended destination node. Nodes that receive the reward signal update their $Q(d, y)$ values in the direction of the empirically estimated gradient of the aggregate data packet arrival rate. The authors acknowledge some of the unrealistic assumptions used in their experiments, including fixed unit cost of unicast transmission from neighbor to neighbor and routing time as fixed unit cost equivalent to neighbor-to-neighbor unicast cost.

The gradient-ascent modification is intended to speed up convergence of routes in a stationary routing environment, but provides no added value in non-stationary routing environments where offered load or noise conditions vary. The dependence on continual network-wide broadcasts of reward signal information increases contention for the limited communication bandwidth of wireless network communication, which distorts the total packet arrival rate calculation used to formulate the reward signal. The packet arrival rate reward signal information can be calculated by independent clocks in the destination nodes, avoiding the need for synchronized clocks to compute the source-to-destination time metric used by Tao et al.

2.3.6 Least Squares Policy Iteration Q-Routing

Wang and Wang [61] used a least-squares policy iteration (LSPI) [38] enhancement to Q-routing. The least-squares policy iteration algorithm uses a weighted linear combination of numerical features to approximate Q-values using a fixed policy. The features represent known information about the $Q(s, a)$ action pairs. The LSPI algorithm uses the known information to

estimate the unknown $Q(s, a)$ information, and in so doing makes better policy improvement decisions after collecting several actual reward signals.

There are two goals of using LSPI as an enhancement to Q-routing. The first goal is to reduce the number of iterations before converging to an optimal solution. The time lost in learning may outweigh the benefits of finding optimal routes. The second goal is to reduce the sensitivity to differences in how the learning rate parameter is set.

The reward signal is a weighted linear combination of hop count, remaining battery power in the downstream node, the number of routes sending data packets through the downstream node, and the reliability of the link to the downstream node. The weights are updated by a central base station using the LSPI algorithm. The updated weights are broadcast through the ad hoc network. The requirement of a central base station to calculate and propagate updated weight information violates the basic concept of an infrastructure-free ad hoc network. Nodes receiving the weight update broadcasts will update their own $Q(s, a)$ estimates and make routing decisions by selecting the neighbor with the highest $Q(s, a)$ value.

The LSPI modification is intended to speed up convergence of routes in a stationary routing environment, but provides no added value in non-stationary routing environments where offered load or noise conditions vary. The dependence on continual network-wide broadcasts of weight update information increases contention for the limited communication bandwidth of wireless network communication, and further reduces battery power levels in the nodes, distorting the calculations used to create the reward signal.

2.3.7 CMAC-Based Q-Routing

Chetret, Tham and Wong proposed the use of neural networks as an enhancement for Q-routing [10]. The authors used a neural network variation called a Cerebellar Model Articulation Controller (CMAC) in a modified AODV implementation. The motivating advantage was that a neural network stores data in a constant-size memory block rather than a block whose size is linearly proportional to the number of entries in a table. Instead of storing values, neural networks reconstruct values as needed. Routes are discovered as needed with AODV Route Request (RREQ) and Route Reply (RREP) packets.

The reward signal consists of the time used to unicast the data packet to the downstream

neighbor and the time to destination from the downstream neighbor. The authors do not state how the downstream neighbors calculate the unicast time, especially when the upstream neighbor can calculate the unicast time from the ACK packet required under 802.11. The reward is communicated with a new reward packet, called QREP, sent to the upstream sender node from the downstream receiver node. The QREP packet contains an estimate of the delay from the downstream neighbor to the destination, based on the Q-values held by the downstream neighbor. The upstream sender updates its $Q(s, a)$ estimate, which represents the estimated time to destination for the downstream neighbor. A node that sends or forwards a data packet selects a neighbor stochastically according to a Boltzmann distribution

$$p(a) \leftarrow \frac{e^{\beta Q(s,a)}}{\sum_{a' \in ACTIONS} e^{\beta Q(s,a')}} \quad (1)$$

to balance exploration and exploitation. β is a parameter that controls the exploration of alternative paths.

The AODV route discovery algorithm sets up initial routes faster than the random trial-and-error exploration used by Q-routing. The CMAC enhancement is a means of dealing with routing metrics other than hop count, but does not speed up convergence of routes in a stationary routing environment. The dependence on unicasts of reward signal information after every link-level unicast increases contention for the limited communication bandwidth of wireless network communications, which distorts the time-to-destination calculation used to formulate the reward signal.

2.3.8 Ant-Based Q-Routing

Subramanian, Druschel and Chen [56] proposed an approach inspired by ant colonies to address some of the shortcomings of Q-routing. The primary shortcoming is that Q-routing does not always find the shortest path. Assume that the Q-routing metric is estimated time to destination and the goal is to minimize the time required to deliver data packets to their destination. If one path has a Q-value less than the Q-value of a shorter path, the Q-routing algorithm will select the path with the smaller Q-value, with resulting updates to the Q-value of the selected path. The Q-value of the unexplored shorter path will not be selected and its Q-value will not be updated until the Q-value of other selected paths grows larger than the Q-value of the

shorter path. A secondary shortcoming is the number of reward signal packets. Unicasting a reward signal packet from receiver to sender after every link-level unicast increases contention for the limited communication bandwidth of wireless network communications, which distorts the time-to-destination estimates used to formulate the reward signal.

The proposed solution to these shortcomings is to send small messages called *ants* through the wireless network to provide reinforcement of network conditions. Instead of each node sending a reward signal after every link-level unicast, ant messages are sent periodically from source to destination. The purpose of the ant message is to assess the cost of traversing links between nodes. The ant message contains the identity of the source and destination nodes, and path cost information. Nodes receiving an ant message use the cost information to update the weights associated with different neighbors. The weights are used in the stochastic selection of neighbors for routing data packets.

There are two kinds of ant messages. The *regular ant* messages are forwarded through the network from source to destination probabilistically according to the routing tables in each intermediate node. The paths traveled by the regular ants converge to the best path in the network, assuming stable network conditions. The *uniform ant* messages are forwarded to any neighbor with equal probability. The uniform ants continue to explore the network to find better routing alternatives under changing network conditions.

The Q-routing algorithm requires a receiver node to send a reward signal packet to the sender node after every link-level unicast. Subramaniam et al. replace the frequent transmission of reward signal packets with a less-frequent periodic propagation of ant packets through the network. The lower number of ant packets reduces the contention for the limited communication bandwidth of wireless network communication, but does not eliminate it.

2.3.9 Q-Routing in Mobilized Ad hoc Networks

Chang, Ho and Kaelbling [8] presented the idea of the *mobilized ad hoc network*. In the more generally known *mobile ad hoc network*, the nodes move with a purpose beyond the control of the routing mechanisms. In mobilized ad hoc networks, some nodes move solely to maintain network connectivity. There are therefore two learning problems: routing data packets through the ad hoc network, and movement of nodes to support network connectivity.

The node movement problem is treated as a partially observable Markov decision process (POMDP). Nodes can only observe the local conditions of the overall network state. The length of the training phase led the authors to solve the problem of finding a motion policy for the node motion as an off-line policy done in simulation before the nodes are actually deployed. The mobilized agent node can perceive its neighbors by “sniffing” packet transmissions sent by neighbor nodes, and from the sniffed packets determine the routes passing through the neighbor nodes. The mobilized node determines its local state from the perceived neighbors and perceived routes. The reward signal is the percentage of successful transmissions during each time period. In a real-world situation, information on successful transmissions is not available, but the information can be supplied during the training simulation.

The Q-routing algorithm retains the original goal of minimizing estimated packet delivery time. Node mobility is handled with two modifications to the Q-routing algorithm. When node y moves out of direct communication range of node x , node x sets the time-to-destination estimate $Q_x(d, y)$ to ∞ to suppress use of that link in neighbor selection. When a previously unknown neighbor z moves into direct communication range of node x , node x sets the time-to-destination estimate $Q_x(d, z)$ to 0 to encourage exploration through the new neighbor z . If forwarding data packets through node z results in long estimated delivery time, node x reverts to its previous routing policy. If forwarding data packets through node z results in short estimated delivery time, node x will continue to forward data packets through the new neighbor z .

Simulations run by the authors showed that the modified Q-routing algorithm performed satisfactorily in mobilized ad hoc networks. Potential future work stated that a learning algorithm could manage both routing and node movement.

2.3.10 Discussion

The purpose of a routing protocol is to find a sequence of intermediate nodes from a source node to a destination node. The objective of routing protocols using the number of intermediate nodes as a routing metric is to find the sequence with the smallest number of intermediate nodes between source and destination nodes. The shortest path metric is not always the best routing metric. In some network topologies, multiple routes forward data traffic through intermediate nodes whose routing capacity is exceeded by the levels of incoming data traffic, resulting in

router congestion and loss of data packets. Noise sources can affect data packet transmission between nodes, resulting in corrupted data and lost data packets.

The previous work in this section covers routing protocols that used machine learning to deal with router congestion in limited-bandwidth wireless ad hoc networks. The initial Q-routing algorithm is an adaptation of Q-learning to network routing problems. The Q-routing algorithm, like the underlying Q-learning algorithm, requires a great deal of data and is slow to arrive at a stable solution for routing. Data packets get lost while the Q-routing algorithm tries to arrive at stable routes, reducing application throughput. Subsequent modifications to Q-routing included stochastic gradient ascent, least-squares policy iteration and neural networks, all with the goal of improving convergence speed with less acquired data. Another Q-routing modification was the ability to build bidirectional routes between the source and destination nodes.

Another limitation of Q-routing is the reliance on Q-values to represent the estimated time to destination. A high offered load through a node increases the Q-value used by the upstream neighbor, who will choose a different downstream neighbor that has a lower Q-value for data packet forwarding. A later reduction in the offered load through the now-unused neighbor does not result in a reduction of the Q-value held by the upstream neighbor and less than optimal forwarding decisions continue. Subsequent routing protocols either retained small Q-values from the past to select unused paths, forwarded data packets stochastically to different neighbors or introduced ant-like reconnaissance packets that explored unused paths to detect and respond to changing congestion conditions in wireless networks.

The dependency on reward signal packets is another limitation of Q-routing and the routing protocols based on Q-routing. The radio communication bandwidth between nodes in a wireless network is limited. Sending a reward packet from downstream receiver node to an upstream sender node after every link-level unicast reduces the bandwidth available for data packets and reduces data packet throughput in high offered load situations. The inherent variability in unicast packet transmission time due to the random exponential backoff algorithm in 802.11 MAC layer can result in an occasional long wait time to complete a unicast. The long wait time is an artifact of the 802.11 MAC protocol and does not reflect a change in network conditions. Communicating a long unicast completion time in a reward signal increases the

Q-value estimate in the upstream node, which can distort the forwarding selections made by the upstream node. These transient extended wait times to complete the occasional unicast can be seen in the noise simulation results documented in Chapter 6.

The previous work in Q-routing and the routing protocols based on Q-routing consider the effects of router congestion, but do not adequately address the effects of noise in the wireless network environment. In a noisy environment, a link-level unicast packet sent by a node may not reach its intended downstream neighbor. The downstream neighbor fails to send a reward signal packet back to the sender. Even if the data packet does arrive at the downstream neighbor, the corresponding reward signal packet may be lost and not reach the upstream neighbor. The inability to complete the feedback loop after each link-level unicast undermines the efficacy of the Q-routing algorithms in noisy environments.

Taking the prior work into consideration, what is needed is a routing protocol that manages both noise and router congestion in wireless ad hoc networks. This dissertation focuses on this problem. A new routing protocol introduced in Chapter 4 uses machine learning mechanisms to manage noise and router congestion. The design of this new protocol and the results of noise and congestion simulations in Chapter 6 will prove the basic thesis of this dissertation—that machine learning is feasible and useful in managing noise and router congestion in wireless ad hoc networks.

Chapter 3

Mathematical Models For Communication and Routing

There are many factors that affect the performance of routing schemes for wireless ad hoc networks. Noise undermines the quality of transmitted signals and corrupts packets transmitted between wireless nodes. Corrupted packets are detected and dropped by the receiving node, resulting in the loss of application data packets. A router becomes congested when packets are sent to a node faster than the router on the node can forward them. Congested routers drop packets, reducing the number of application data packets that reach their intended destinations.

This chapter defines a model for noise and its effect on packet transmissions. It also presents a time-based routing metric that combines the effects of noise and congestion to make routing decisions that reflect previously existing routes and noise in the communications medium. A final section is devoted to calibrating noise sources to achieve specific packet loss rates, which will play an essential part in setting up noise sources in the simulation environments in Chapter 6.

3.1 A Mathematical Model For Noise And Packet Loss

Radio transceivers communicate through electromagnetic signals. An analog version of a signal is defined by the three characteristics of amplitude, frequency and phase. The transmission of digital data requires that the signal be *modulated* over an analog bandpass channel by appropriately modifying the characteristics of the analog carrier signal. The binary data is translated into a sequence of *symbols* for transmission by appropriately modifying amplitude, frequency or phase of the carrier signal to convey these symbols. The number of bits encoded into the symbol is determined by the *modulation scheme*. The symbols are transmitted at the *symbol rate* and the *data rate* is determined by how many data bits are encoded in each symbol. Higher data rates are achieved by encoding more data bits in each transmitted symbol [50].

The quality of the transmitted signal can be reduced at the receiver by signal attenuation, fading and interference in the form of noise from other sources. The lower the signal-to-noise ratio (SNR), the more difficult it is for the receiver to decode the received signal. Forward error correction (FEC) protects the transmitted data from the effects of noise by inserting controlled redundant bits into the data stream, making it possible for the receiver to detect and correct bit errors [63]. Higher data rate modulation schemes encode more data bits into a signal waveform and use fewer error detection and error recovery bits in the transmitted symbols, resulting in a trade-off between the data rate and robustness to noise in preserving the integrity of the encoded data. Higher data rate modulation schemes carry more data, but are less resilient to noise. Conversely, lower data rate modulation schemes are more resilient to noise. The performance of the modulation scheme is determined by the strength of the received signal and the noise experienced by the receiver.

Noise is present in the real world at levels directly proportional to the ambient temperature of the communication environment. Interference may also be viewed as a transmitted signal, sharing the same characteristics of amplitude, frequency and phase. In practical terms, a transmitted interference signal is subject to the same behaviors as any other transmitted signal, including the constructive and destructive effects of multipath fading. The effects of an interference signal affected by multipath fading or transmission from multiple sources can range from complete cancellation by half-cycle out-of-phase reception to reinforced in-phase reception at the receiver. The interference capacity of time-varying fading is unknown in general [18]. An additive white Gaussian noise (AWGN) channel is time-invariant and the level of noise can be calculated by summing the noise from the various transmission sources at the receiver disregarding fading or phase-shifting effects. The virtue of AWGN noise modeling is that appropriately defined, AWGN modeling can capture a worst-case situation, representing an upper bound on noise effects in real-world situations.

The IEEE 802.11 wireless standard uses a variety of different modulation schemes, all based on modulating the phase of the signal carrier wave. The 802.11b LAN standard [26] uses differentially encoded binary phase-shift keying (DBPSK) at the lowest rate of 1 Mbit/sec with one bit per symbol. For higher data rates, differentially encoded quadrature phase-shift keying (DQPSK) is used with two bits encoded per symbol. The higher speed 802.11a and

802.11g standards [27] use binary phase-shift keying (BPSK) for 6 and 9 Mbits/sec. The 12 and 18 Mbits/sec rates use quadrature phase-shift keying (QPSK) and the remaining rates use quadrature amplitude modulation (QAM) as the modulation scheme.

There are other coherent modulation schemes, including BFSK, QPSK, 4-QAM, MPAM, MPSK and MQAM [18]. The focus of the work in this dissertation was to show the efficacy of machine learning approaches in managing noise and router congestion in wireless ad hoc networks. This work assumes the use of the BPSK modulation scheme, but the choice of modulation scheme should not affect the overall behavior of the machine learning mechanisms.

The transmission of digital packets is subject to loss from signal attenuation, noise, collisions with other packet transmissions and multipath fading. The likelihood of collisions is managed and minimized by random exponential backoff at the Medium Access Control (MAC) layer [24]. Bit errors in packets are detected by receiving nodes through the use of Cyclic Redundancy Check (CRC) codes [55]. Any received packet failing CRC is considered lost at the MAC layer and is not delivered to the higher levels of the protocol stack. Multipath fading may preclude direct wireless communication between nodes that are otherwise within normal communication range. The effects of multipath fading are similar to those of noise—the receiver cannot receive the transmitted packet.

The model for packet loss in this dissertation assumes that the signal-to-noise ratio is constant over the transmission of each bit in the packet and that each bit is affected by noise independently of the other bits in the packet. With a probability of bit error P_b , the probability that a packet of length n bits is successfully transmitted is the probability that every bit in the packet is transmitted successfully:

$$(1 - P_b)^n,$$

where n is the number of bits in the packet. From this, the probability of packet error, PPE, is

$$\text{PPE} = 1 - (1 - P_b)^n.$$

For coherent modulation schemes, the probability of bit error takes the form $P_b = Q(z)$. The $Q(z)$ function¹ is defined to be the probability that a Gaussian random variable x with mean 0

¹The Q function as it appears here is taken from the literature of wireless communications, notably Goldsmith [18], and is unrelated to Q -learning in the area of artificial intelligence.

and variance 1 is greater than z :

$$Q(z) = \int_z^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx = \frac{1}{2} \operatorname{erfc} \left(\frac{z}{\sqrt{2}} \right).$$

The signal-to-noise ratio for digital transmissions is E_b/N_0 , where E_b is the energy per bit at the receiver and N_0 is the total noise [50]. For the BPSK modulation scheme,

$$P_b = Q \left(\sqrt{\frac{2E_b}{N_0}} \right).$$

By substituting the complimentary error function, we get:

$$P_b = \frac{1}{2} \operatorname{erfc} \left(\frac{\sqrt{\frac{2E_b}{N_0}}}{\sqrt{2}} \right) = \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{E_b}{N_0}} \right),$$

for the probability of bit error expressed as a function of energy per bit at the receiver and total noise. A final substitution back into the earlier packet loss formula gives the probability of packet loss in terms of energy per bit and total additive white Gaussian noise at the receiver:

$$\text{PPE} = 1 - \left(1 - \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{E_b}{N_0}} \right) \right)^n.$$

The probability of packet error is a real value between 0.0 and 1.0. Chapter 6 documents network simulations based on these models for noise and packet loss. The simulator architecture uses a real-valued random number generator (drand48() on Linux/UNIX systems) to make random success/failure decisions using this model for probability of packet error at the receiver of each simulated transmission.

3.2 A Time-Based Routing Metric

A route consists of a sequence of nodes from a source node sending data to the intended destination node. A unicast along one link is actually an omnidirectional radio transmission from one node to all its neighboring nodes, where only one node is the intended recipient. Upon receipt of the unicast packet, the recipient must transmit an ACK packet back to the sender. The unicast is complete when the sender receives the ACK packet. The 802.11 a/b/g MAC layer automatically retransmits a unicast packet if the sending node does not receive an ACK within a specific time limit [24]. The 802.11 MAC layer will retransmit a unicast packet a maximum number of times before dropping the packet. The unicast *succeeds* when the sender receives

an ACK packet, otherwise the unicast *fails*. The finite time from the first unicast transmission to the determination of success or failure is called the *unicast time*. The nodes along the route incur a time penalty as forwarding decisions are made for each packet received. The time a packet takes to travel from source to destination is the sum of routing time in the nodes and unicast time of the links. Throughput is the measure of how many packets are successfully delivered to their destination per unit time.

Routing time is affected by the router load (the packet arrival rate relative to the routers' packet forwarding capability). Unicast time is affected by packet transmission collisions and the level of noise in the packet communication channel. Packet collisions occur due to the hidden terminal problem [36], [59]. The combination of time spent in the router, the time required to complete the unicast and the time effects of packet loss due to noise comprise a time-based routing metric.

Router congestion increases as the packet arrival rate increases, thus increasing the delay time packets spend in router input queues. The factors affecting router congestion are the mean packet forwarding rate μ and the rate that packets enter the router input queue λ_q . A router follows a *work-conserving* queueing discipline, where the router is not idle when there are packets in the input queue and the time required to process each incoming packet is not affected by the queueing discipline [34]. The component of the routing metric that represents the mean time a packet spends in the router before it is forwarded is $1/(\mu - \lambda_q)$ under a work-conserving queueing discipline [7].

Unicasts along a link may not always succeed, so the probability of unicast failure P_f and the mean time to complete a unicast T_m are factors in determining the estimated time required to complete a link-level unicast. The higher the probability of unicast failure, the less desirable the link becomes. The time-based metric used here treats link time as if each unicast was repeated until it succeeded before starting the next unicast.

A unicast will succeed without retransmissions with probability $(1 - P_f)$ and take T_m time. A unicast that succeeded after one retransmission would occur with probability $(1 - P_f)P_f$ and take T_m time for the initial failed unicast and T_m for the second successful unicast. More generally, a unicast that succeeds after n (where $n = 0, 1, \dots$) retransmissions occurs with probability $(1 - P_f)(P_f)^n$ and takes $(n + 1)T_m$ time.

The routing metric is the expected time x required to move a packet through a router to the next hop, which combines the expected time y to complete a unicast and the expected routing overhead $1/(\mu - \lambda_q)$. The number of unicast attempts is a discrete random variable. In general terms, the expected value for the time to complete a unicast is:

$$E[y] = \sum_{i=0}^{\infty} y_i P(y_i).$$

Applying the general formula for the expected value to the time required to complete a unicast when multiple link-level retransmissions are required yields:

$$E[y] = (1 - P_f)T_m \sum_{i=0}^{\infty} i(P_f)^i + (1 - P_f)T_m \sum_{i=0}^{\infty} (P_f)^i.$$

Calculating the values of the sums yields:

$$E[y] = (1 - P_f)T_m \frac{P_f}{(1 - P_f)^2} + (1 - P_f)T_m \frac{1}{(1 - P_f)}$$

and algebraic simplification and the addition of the expected routing overhead time results in the routing metric for the expected time x to move a packet through a router to the next hop:

$$E[x] = T_m \frac{P_f}{1 - P_f} + T_m + \frac{1}{\mu - \lambda_q}.$$

The probability of unicast failure P_f and the mean time required to complete a unicast T_m are both learned values calculated from link-level feedback from recent unicast attempts to the next hop. The current packet arrival rate λ_q is calculated from network-level observations of recent packet arrivals at the router. Chapter 5 describes the exponential weighted average mechanism used to calculate P_f as well as the sliding window mechanisms used to calculate T_m and λ_q .

3.3 Calibrating Noise Sources for Specific Packet Loss Effects

Before discussing the calibration of noise to disrupt data packet transmissions, it is first necessary to discuss how wireless communication can be modeled.

One model for wireless communication between nodes assumes that signals transmitted from the sender travel through free space to a receiver at distance d from the sender. The signal propagates unobstructed in a straight line to the receiver. The *free-space* attenuation model defines the power of the received signal, P_r , as a function of the transmission power,

P_t . Received signal power is inversely proportional to the square of the distance from the transmitter with the following formula:

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2},$$

where G_t and G_r are the gain of the transmitting and receiving antennas, respectively [44]. The wavelength of the transmitted signal in meters is also part of the formula. The higher the frequency (and the shorter the wavelength), the greater signal attenuation. In this work, the antenna gain values G_t and G_r have been treated as 1 assuming omnidirectional transmit and receive antennas, without loss of generality to different antenna configurations. The same formula that determines the power of received data signals is also applicable in determining the power of transmitted interference noise.

The free-space attenuation model is only one of many analytical signal attenuation models for wireless networks. The analytical models define signal attenuation as a function of the distance d between transmitter and receiver with the general formula

$$P_r = P_t \frac{K}{d^\alpha},$$

where P_r is the power of the received signal, P_t is the power of the transmitted signal, K is a constant that depends on antenna characteristics and signal frequency, and α is an exponent. The choice of α is determined by factors in the communication environment. The free-space attenuation model is based on the inverse-square relationship of radiated power in an unobstructed environment and uses an exponent $\alpha = 2$. The *two-ray* signal attenuation model places transmitters and receivers on a simulated ground, rather than floating in space. The received signal in the two-ray model consists of two components, called *rays*. The first ray is the signal transmitted directly through free space to the receiver, and the second is the transmitted signal reflected off the ground. The exponent α for the two-ray model is 4 [18]. Indoor corridor and urban environment models use $\alpha \leq 2$ as a result of wave-guide effects when antenna heights are significantly less than building heights in the surrounding environment [19].

The wireless ad hoc networks simulations in Chapter 6 use the free-space attenuation model for radio communication between nodes. The use of other attenuation models does not invalidate the simulation results.

One factor relevant to the ability of a wireless node to actually decode a transmitted signal is the signal-to-noise ratio. If noise power at the receiver is greater than the received signal power, then no transmission can be successfully received. Near the opposite extreme, if the noise level is too low, communication in the wireless network will not be significantly affected. Both extremes are uninteresting with regard to managing routes and responding to noise in an ad hoc wireless network. Investigation and experimentation with the effects of noise on wireless ad hoc networks requires the ability to create noise sources that can disrupt link-level unicasts by causing target levels of the probability of packet error at the receiver.

The calibration of a noise source is based on controlling the probability of packet error between a specific sender and a specific receiver. This calibration requires knowing the transmitter power P_t from the sender, the distance from the sender to the receiver, and the signal wavelength λ so that the received signal power, P_r , can be computed. From P_r , the energy per bit E_b is calculated by dividing P_r by the transmission rate, expressed in bits per second.

At the MAC layer, each unicast transmission requires the receipt of an ACK signal from the intended receiver node. Failure to receive an ACK signal causes the sender MAC layer to repeat the transmission some small number of times before concluding that the unicast has failed. Given that the MAC layer in use by the nodes in the wireless network retransmits a unicast k times before giving up, the k th root of the desired probability of packet error should be calculated to ensure that the unicast fails the desired proportion of the time over k retransmissions at the MAC layer.

Given a desired probability of packet error and a packet size expressed as n bits, the goal is to calculate the proper transmission power at the noise source transmitter. The first task is to calculate the necessary noise power at the receiver N_0 .

The initial formula for the probability of packet error is the starting point:

$$\sqrt[k]{\text{PPE}} = 1 - \left(1 - \frac{1}{2} \text{erfc} \left(\sqrt{\frac{E_b}{N_0}} \right) \right)^n.$$

Some algebraic rearrangement yields:

$$1 - \sqrt[k]{\text{PPE}} = \left(1 - \frac{1}{2} \text{erfc} \left(\sqrt{\frac{E_b}{N_0}} \right) \right)^n.$$

Taking the n th root of both sides (where n is the packet size in bits) yields:

$$\sqrt[n]{1 - \sqrt[k]{\text{PPE}}} = 1 - \frac{1}{2} \text{erfc} \left(\sqrt{\frac{E_b}{N_0}} \right).$$

Algebraic rearrangement and multiplying both sides of the equation by 2 yields:

$$2 - 2 \sqrt[n]{1 - \sqrt[k]{\text{PPE}}} = \text{erfc} \left(\sqrt{\frac{E_b}{N_0}} \right).$$

The $\text{inverfc}()$ function is defined as the inverse complimentary error function:

$$\text{inverfc} \left(2 - 2 \sqrt[n]{1 - \sqrt[k]{\text{PPE}}} \right) = \sqrt{\frac{E_b}{N_0}}.$$

Squaring both sides removes the square root:

$$\text{inverfc}^2 \left(2 - 2 \sqrt[n]{1 - \sqrt[k]{\text{PPE}}} \right) = \frac{E_b}{N_0}.$$

Rearranging to solve for N_0 yields:

$$N_0 = \frac{E_b}{\text{inverfc}^2 \left(2 - 2 \sqrt[n]{1 - \sqrt[k]{\text{PPE}}} \right)}.$$

The calculated N_0 value is the noise power at the receiver. For a noise source at distance d from the receiver, the noise source should be transmitting at the following power level:

$$P_t = N_0 \frac{(4\pi d)^2}{\lambda^2},$$

again assuming omnidirectional antennas for both the receiver and the noise transmitter.

The design of the wireless network simulator used to run the noise and congestion simulations documented in Chapter 6 incorporates these mathematical models for noise and packet loss along with the model for calibrated noise sources to cause predetermined, targeted packet loss effects in simulated wireless networks. A targeted stochastic packet loss effect is set for the unicast packets sent from a specific sender node to a specific receiver node. Given the location of the sender and receiver nodes, the data transmission frequency and the transmission power from the sender node, it is possible to calculate the received signal power, P_r . Dividing received signal power by the number of bits transmitted per second gives energy per bit, E_b . Taking the maximum number of transmissions the MAC layer will attempt to complete a single link-level unicast, k , the length of the transmitted packet in bits, n , and the probability of packet

loss, PPE, it is possible to determine the noise power required at the receiver node, N_0 that will cause the desired rate of packet loss. The noise transmitter can then be placed anywhere in the simulated topology and its transmit power set as a function of the distance from the noise source to the receiver node.

Chapter 4

The Warp-5 Routing Algorithm

This chapter introduces a new on-demand route acquisition algorithm, called Warp-5 (wireless adaptive routing protocol, version 5). In Warp-5, nodes in the ad hoc networks start with no knowledge of neighbors or any pre-existing routing information. Further, nodes do not hold or transmit complete path information for any route. Each node performs all route discovery, packet forwarding and route management functions knowing only the upstream and downstream neighbors for established routes.

The design goals of the Warp-5 protocol are intended to maximize application data throughput. Specifically, the objectives of Warp-5 involve:

1. Selection of routes that minimize source-to-destination packet travel time based on link-level unicast transmission time and router load.
2. Modification of established routes to maximize distributed application data throughput as new routes are added to the ad-hoc network.
3. Minimize the transmission of routing control packets consistent with efficient application data routing.

The goal of improving and adjusting routes in a network is accomplished by having the network act as a distributed agent to discover the best routes as needed and to improve the routes used in the ad hoc network.

The Warp-5 route discovery mechanism uses route request broadcasts, similar to the Ad-hoc On-Demand Distance Vector protocol (AODV) [47] and the Dynamic Source Routing protocol (DSR) [30]. Instead of selecting routes that have the smallest hop count and ignoring existing traffic on those routes, Warp-5 selects routes that have the smallest expected time to move a

packet through a router based on experience gained from previous recent traffic through the nodes themselves. During the route discovery, the nodes learn the cost of forwarding to each neighbor to reach a specific destination. Packet forwarding is accomplished by selecting the neighbor that is currently expected to reach the destination in the least amount of time.

Warp-5 also supports route freshness. Each node uses a monotonically increasing sequence number to maintain the most recent routing information. Route discoveries use larger sequence numbers to supercede routing information associated with lower sequence numbers and to prevent routing loops.

4.1 Route Requests

A node that needs to communicate with a destination for which it does not have routing information will initiate a route discovery by broadcasting a route request (RREQ) packet to its neighbors:

$$S \rightarrow \text{all neighbors}, [S, D, \text{Seqnum}, \text{hopCount}, F]$$

where S is the source IP address, D is the destination IP address, Seqnum is a sequence number, hopCount is a hopcount and F is a set of flags. The sequence number is incremented before each new route discovery. The hop count is incremented by each recipient and is used to control the propagation of route reply (RREP) packets.

The recipient of a RREQ packet either is the desired destination, an intermediate node that has route information that is not earlier than the route request, an intermediate node that does not have route information that is earlier than the route request, an intermediate node that does not have route information for the desired destination, or is the original sender of the RREQ packet. Whether or not route information is older than the request is determined by comparing the sequence number in the RREQ packet to the sequence number associated with the route information held by the intermediate node.

If an intermediate node does not have routing information for the destination in the RREQ packet or the routing information it does have is from an earlier time than the RREQ packet, the intermediate node propagates the request by broadcasting the RREQ packet to its neighbors. If the recipient of the RREQ packet is either the destination or is an intermediate node that

has routing information to the destination that is not earlier than the request, then the node broadcasts a route reply (RREP) packet. If the originator receives its own RREQ packet, it drops it.

A node may receive the same RREQ packet from different neighbors. Nodes that propagate RREQ packets are required to limit rebroadcasts of the same RREQ packet to a parameterized value. A node that receives any more than the parameterized number of identical RREQ packets would drop the extra RREQ packets. This parameter is set by the network designer and is intended to assure reasonable propagation of RREQ packets in noisy or collision-prone environments. For example, in the experiments documented in Chapter 6, the parameter is set to 2. The hop count value is incremented by one when the RREQ packet is propagated by an intermediate node.

4.2 Route Construction

A RREQ packet will eventually reach either the desired destination node or an intermediate node that contains current routing information to the desired destination. Under these conditions, the node broadcasts a route reply packet (RREP):

$$D \rightarrow \text{all neighbors}, [S, D, \text{Seqnum}, \text{TTD}, F]$$

where S is the source IP address, D is the destination IP address, Seqnum is a sequence number greater than the sequence number in the RREQ packet, TTD is an estimated time-to-destination value and F is a set of flags. The TTD value in a RREP packet broadcast from a destination node is always zero. The TTD value in a RREP packet broadcast from an intermediate node is the sum of its own overhead (routing time and unicast time) and the TTD of its least expensive next hop to the destination.

The recipient of a RREP packet may be an intermediate node, the node that sent the original request or the desired destination node. The destination node always ignores the RREP packet and drops it. A source or intermediate node uses the received RREP packet to update its own routing table. A node that has no routing entry for the desired destination adds a routing entry that contains the sender of the RREP packet as next hop and the TTD from the RREQ packet. A node that already has routing information for the desired destination from the sender of the

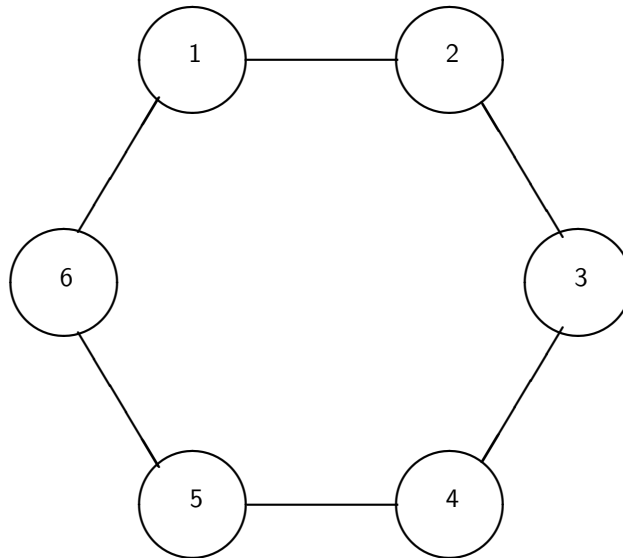


Figure 4.1: Topology for Route Construction Example With Links Between Adjacent Nodes.

RREP packet updates the TTD value if either the RREP contains a higher sequence number than the existing entry or the TTD from the RREP packet is less than the TTD in the existing entry. The hop count value from the RREQ packet is used to determine a time-to-live value in the broadcast RREP packet to control its propagation through the network.

An intermediate node propagates the first RREP it receives for a given destination. Later RREP packets are propagated if the RREP packet contains either a larger sequence number or the same sequence number with a lower TTD. This design ensures propagation of the least expensive and most recent routing information while preventing the transmission of unnecessary RREP packets.

An originating node that receives a RREP packet may start sending packets immediately. Subsequent RREP packets may change the route to the destination without affecting packets already sent.

4.2.1 Route Construction Example

To illustrate how Warp-5 works, consider the example topology of Figure 4.1. In this example, the nodes are far enough apart so that only the two nodes that numerically precede and follow that node are its neighbors. Nodes 1 and 6 are also neighbors. Initially, no nodes have any routing information. At time 0, node 1 requests a route to Node 3 by broadcasting a RREQ packet. The neighbors receive the RREQ, and having no routing information to the destination node, re-broadcast the RREQ. When node 1 receives a re-broadcast RREQ, it recognizes itself as the source and ignores the packet. Intermediate nodes receiving a re-broadcast, will propagate the re-broadcast a small number of times, afterward ignoring the packet. The RREQ propagates through the topology until it reaches the destination, Node 3.

Node 3 recognizes itself as the requested destination and broadcasts a RREP with a cost field of 0. Neighboring nodes that receive the RREP may or may not propagate the RREP by adding their own routing and unicast transmission time to the cost field from the RREP and re-broadcasting the RREP. Nodes that receive the RREP for the first time always add the sender of the RREP as a possible next hop and associate the cost field from the RREP with the next hop and re-broadcast a RREP with the larger time cost. Nodes that receive a RREP for the same destination update their list of next hops and destination costs and propagate the RREP only if it offers a lower time cost to the destination. Since there are no routes in use initially, only the time cost is added to propagated RREP packets. This cost would be 0.0203916 seconds per hop in the simulated runs from Chapter 6. The 0.0203916 second cost is the minimum possible time required to forward and successfully complete the unicast of a 500-byte packet. The minimum time cost is attained when the unicast is completed in a single transmission at the fastest 802.11g transmission rate of 54 Mbits/sec.

Shortly, the originating node, Node 1 receives a RREP packet with a cost of 0.0407832 seconds from Node 2 and a RREP from Node 6 with a cost of 0.0611748 seconds. Node 1 selects Node 2 as the neighbor with the lowest time cost to the destination and starts sending data packets to Node 2. The data traffic on the Node 1 → Node 2 → Node 3 route takes half of the forwarding capacity of the routers, which increases the time cost along that route. If the router forwarding capacity were 50 packets per second, the traffic load of 25 packets per second

would result in an expected time to get a packet through a router of 0.4 seconds.

Suppose that Node 6 also wants to send data to Node 3. The RREQ for this request propagates to the destination as before and the destination again broadcasts a RREP with a cost field of 0. From the picture, Node 6 would seem to have two routes of equal length to Node 3 available. However, the RREP packets that propagate back through Nodes 2 and 1 show a cost of 0.8407832 seconds (reflecting the routing cost through the previous route), while the RREP packet that propagates back through Nodes 4 and 5 would show a cost of 0.0407832 seconds because of the lack of router overhead. When Node 6 receives the RREP packets from Nodes 4 and 5, Node 5 will offer a lower time cost than Node 1, and Node 5 will be selected as the next hop.

4.3 Route Table Management in Routers

Each router is required to track recent packet arrival rate information for all routes sending application data packets through that node. The sum of the packet arrival rates is the λ_q component of the dynamic calculation of the expected time to move a packet through the router to the next hop. This aggregate packet arrival rate may fluctuate due to variations in the packet transmission patterns and packet loss due to noise or collisions. The router samples the aggregate data packet arrival rate every 0.1 seconds and calculates an average arrival rate over the ten most recent sampled arrival rates. Averaging the ten most recent sampled rates smooths out transient bursts of data packets that do not actually overflow the router input queue. Limiting the averaging window to the most recent ten samples also provides reasonable responsiveness to sustained overloads when they occur. An average data packet arrival rate equal to or greater than the router forwarding capacity is a trigger for the route detangling algorithm described in Section 4.4.

The router maintains packet forwarding information for each destination from received RREP packets. This information consists of entries containing a time-to-destination value and a sequence number for each neighbor. A new entry is for a particular neighbor added the first time a node receives a RREP packet from that neighbor. The TTD information is updated when the node receives a RREP packet from the neighbor that has either a later sequence number or

when the RREP packet has same sequence number with a lower TTD.

The router also dynamically tracks recent mean time to complete a unicast (successful and unsuccessful) and recent unicast failure probability for all neighbors being sent forwarded packets. These values are estimated from experience with recent unicasts. The mean time to complete a unicast is the T_m component of the expected time to move a packet through a router to the next hop used as a routing metric. The probability of unicast failure is the P_f component of the same metric expression. These quantities are estimated using the methods described in Sections 5.1 and 5.2.

Holding forwarding information for all neighbors gives a node the ability to select new forwarding neighbors dynamically as link conditions change without a rediscovery process. A formerly inexpensive link could become undesirable as the neighbor moves out of communication range, suffers increasing noise or packet transmission collisions.

Routers also keep track of the order in which routes are created, by observing incoming RREP packets. The order in which routes are created is useful in the detangling of existing routes, as described in the next subsection.

4.4 Route Improvement and Detangling

Routes contend for routers in the network using whatever metrics are defined by the routing protocol in use. Using the expected time to move a packet through a router as a metric gives the protocol the ability to make routing decisions based on the forwarding overhead created by previously existing routes currently using the network. Route discovery is an inherently selfish process, with each discovery trying to find the best route from source to destination and consuming the forwarding resources of whatever routers are selected. The effect of route selection is that the traffic forwarding through intermediate routers selected makes those routers that much less able to handle the traffic for later routes, should they occur. The process of route discovery is therefore chronological and sequential. A route discovery that occurs before another route exists may select a different route than if the same route discovery had occurred after the other route had existed with potentially different effects on overall application throughput.

The effects on application throughput are apparent when two or more routes actively send

traffic through the same intermediate nodes. The forwarding rate of the intersecting routers is slowed down as the combined rate of incoming packets increases. When the combined rate of incoming packets exceeds the forwarding capacity of an intersecting router, the result is packet loss and reduction in overall application throughput. The term “tangled route” refers to one of the multiple routes actively sending traffic through some set of intermediate nodes. The term “detangling” refers to the act of improving or separating overlapping routes in a network.

Each node monitors the rate at which packets enter its routing queue. Any router R that has traffic for two or more routes and experiences an aggregate packet arrival rate that exceeds its routing capacity can act to detangle overlapping routes in the network. The router R increments its sequence number, selects a route in reverse order of creation and broadcasts a RREQ packet with the new sequence number and a “detangling” flag.

$R \rightarrow \text{all neighbors}, [S, D, \text{Seqnum}, \text{hopCount}, F, \text{routeList}]$

where S is the source IP address of the selected route, D is the destination IP address of the selected route and routeList is a list of routes, each consisting of a [source IP address, destination IP address] pair. Note that any router can broadcast such a request for any source or destination sending packets through that node. The detangling RREQ packets propagate like regular RREQ packets during a regular route discovery until they reach the destination node. The destination node broadcasts a RREP packet also flagged “detangling”:

$D \rightarrow \text{all neighbors}, [S, D, \text{Seqnum}, \text{hopCount}, F, \text{routeList}]$.

The routeList contains a list of the routes that were created after the source and destination IP addresses specified in the detangling RREQ packet. Routers that receive the “detangling” RREQ packet remember which route has been selected and will try another route to detangle should conditions warrant further detangling efforts.

The receiver of a detangling RREP packet recalculates the expected time to move a packet through its router to the next hop considering only the forwarding overhead of the newer routes listed in the detangling RREP packet. The detangling RREP packet for the most recently created route would have an empty list of newer routes and the route calculation would act as if there were no other active routes in the network. Making routing decisions for a particular route in this fashion forces route selection that accommodates more recently created routes while ignoring routes older than the route being detangled. As a result, the detangled route

may intersect routes older than itself, which may result in the selection from the older set of routes for the broadcast of another detangling RREQ packet. The detangling ends when either all tangled routes cease to overlap or the detangling RREQ packet broadcasts do not result in further route changes.

The result of the detangling algorithm is not necessarily the elimination of multiple routes sharing intermediate nodes. The new detangled route may still share intermediate nodes with other routes if such a decision is best for the route being detangled. The routing decisions of the newer routes were made considering the effects of the older route and this detangling causes routing decisions for an older route that are reciprocally affected by the routes newer than itself. Allowing each routing decision to selfishly act for its own benefit by considering the effects of routes both older and newer than itself, the result is maximized throughput for the distributed application.

4.4.1 Route Detangling Example

To illustrate how Warp-5 manages router congestion, consider a single example taken from the congestion simulations documented in Chapter 6. The example uses the *castle* topology where the shortest path is not always the best path for three routes. The effective communication radius for all nodes is 10 meters, while the nodes were placed 9 meters apart, limiting direct communication between nodes to the neighbors above, below, left and right of the transmitting node. The nodes are numbered left-to-right, top-to-bottom as shown in the topology. In the castle topology example, Node 3 wants a route to Node 4, Node 1 wants a route to Node 6 and Node 2 wants a route to Node 5, in that order. Each of the three routes requires two-thirds of the forwarding capacity of each router, so the greatest application throughput is achieved when no routes share any routers. The nodes in the topology use one radio for data communication and a separate radio for routing information. Further information on single- and dual-radio nodes appears in Chapter 6.

In the initial topology, nodes have no routing information and no awareness of their neighbors. The example begins with the initial topology.

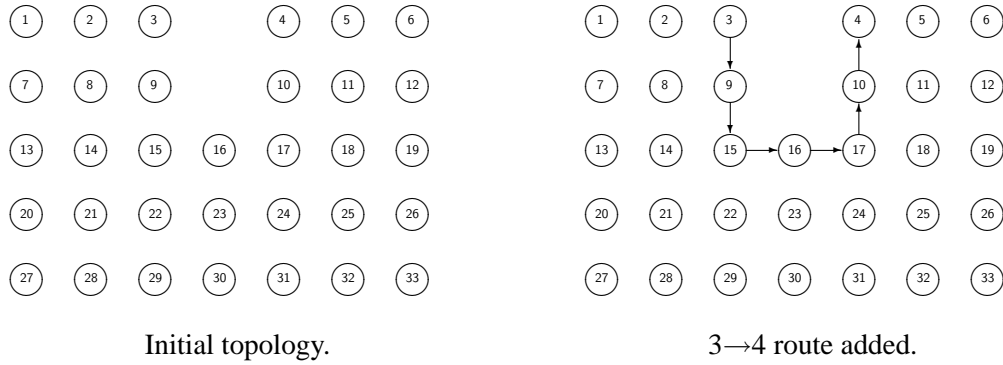


Figure 4.2: The first route request is a route from Node 3 to Node 4, called the 3→4 route. In a topology with no pre-existing routes, Warp-5 simply finds the shortest path, as shown in the right side topology. Routers in the network have seen the RREP packets for the 3→4 route and know that the 3→4 route is the first route created.

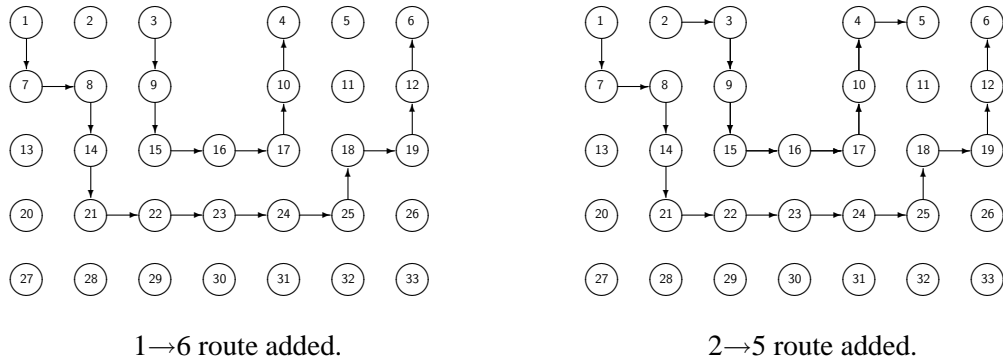
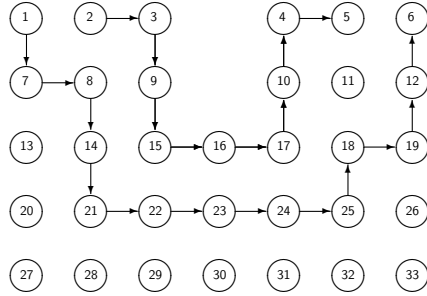
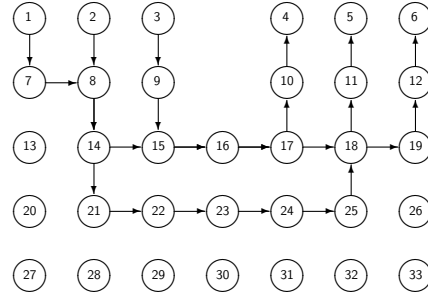


Figure 4.3: The second route request is a 1→6 route. The nodes on the 3→4 route have established traffic, so Warp-5 finds a 1→6 route that avoids nodes used by the previous route. The 1→6 and 3→4 routes do not overlap, no routers are overloaded, so no router takes any corrective action. Routers in the network know that 1→6 is the second route created. The right side topology shows the least expensive 2→5 route, which overlaps the 3→4 route at nodes 3, 9, 15, 16, 17, 10 and 4. Routers in the network know that 2→5 is the third route created. Given the existing 3→4 and 1→6 routes, it is impossible to create a 2→5 route without overloading some router in the network.

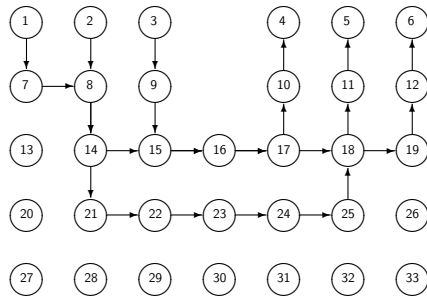


Node 3 modifies 2→5 route.

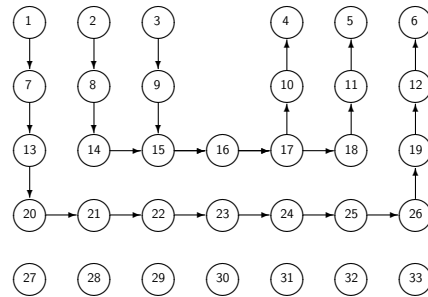


Modified 2→5 route.

Figure 4.4: The left side topology shows Node 3 is overloaded as both a source of traffic for the 3→4 route and an intermediate node for the 2→5 route. In response to the overload, Node 3 modifies the 2→5 route. The modified 2→5 route will ignore the other routes in the network. The right side topology shows the modified 2→5 route. By ignoring the other routes, the modified 2→5 route is a shortest path between Node 2 and Node 5.

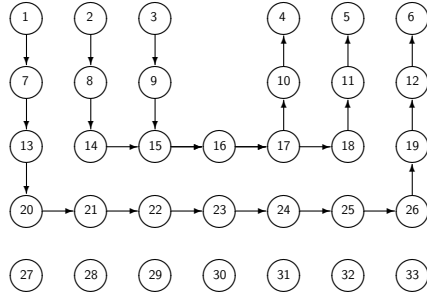


Node 8 modifies 1→6 route.

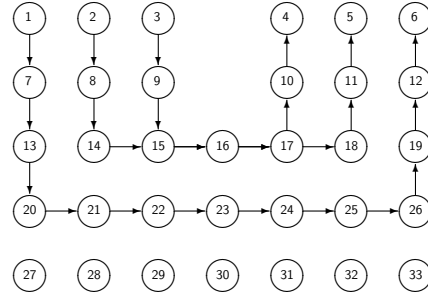


Modified 1→6 route.

Figure 4.5: Node 8 responds to overload by modifying the 1→6 route. The modification considers only the 2→5 route. The modified 1→6 route in the left side topology now avoids the 2→5 route.

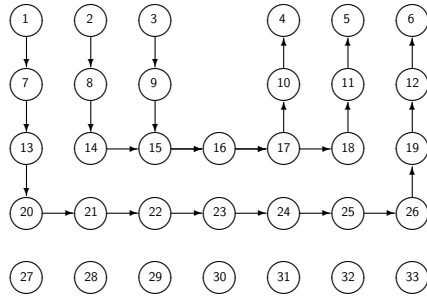


Node 16 modifies 3→4 route.

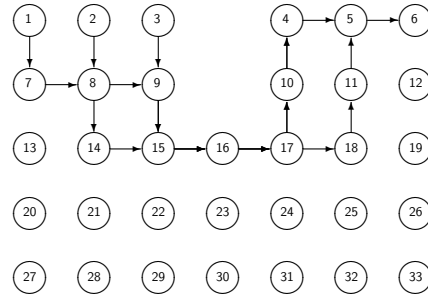


Modified 3→4 route.

Figure 4.6: Node 16 is overloaded and responds by modifying the 3→4 route. The modification considers the 2→5 and 1→6 routes. The 3→4 route could not be improved under current circumstances and is shown unchanged in the left side topology.

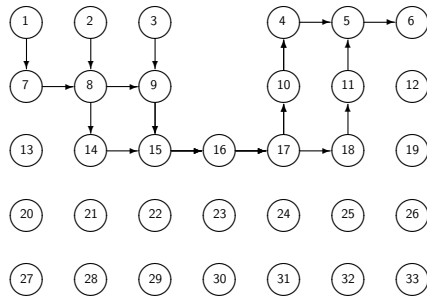


Node 16 modifies 1→6 route.

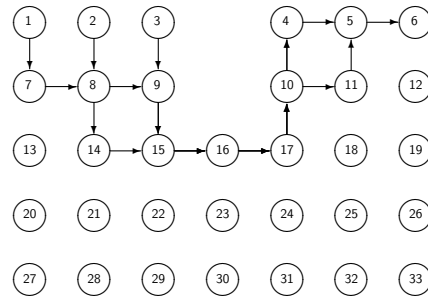


Modified 1→6 route.

Figure 4.7: Node 16 is still overloaded. Node 16 changes the shared routeList to (3→4, 2→5, 1→6) and modifies the 1→6 route, ignoring all other routes. The resulting shortest-path modification is actually worse.

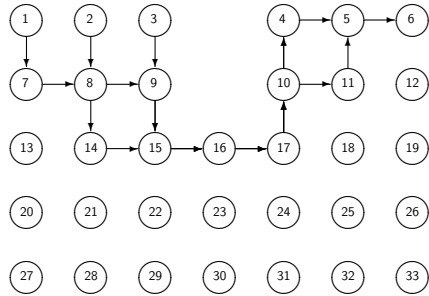


Node 10 modifies 2→5 route.

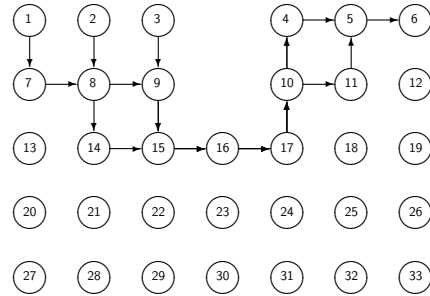


Modified 2→5 route.

Figure 4.8: Node 10 is overloaded and responds by modifying the 2→5 route. The modification considers only the 1→6 route and ignores the 3→4 route. The resulting modification is not an improvement.

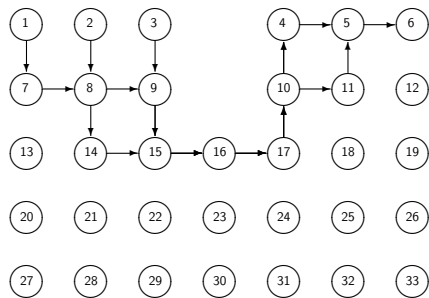


Node 10 modifies 3→4 route.

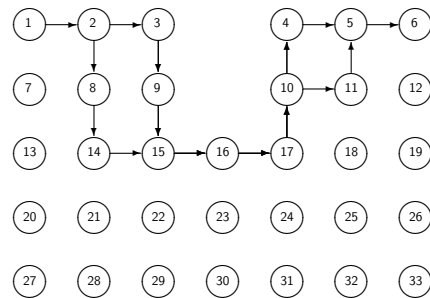


Modified 3→4 route.

Figure 4.9: Node 10 is still overloaded and responds by modifying the 3→4 route. The modification considers the 2→5 and 1→6 routes. The 3→4 route could not be improved under current circumstances and is shown unchanged in the left side topology.

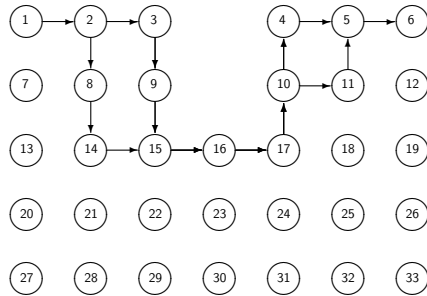


Node 4 modifies 1→6 route.

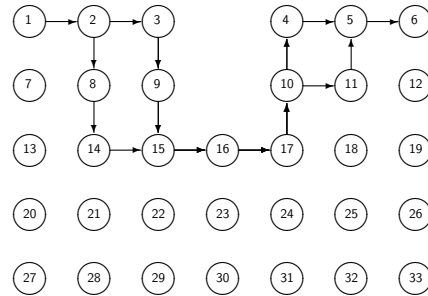


Modified 1→6 route.

Figure 4.10: Node 4 is overloaded. Node 4 changes the shared routeList to (2→5, 3→4, 1→6) and modifies the 1→6 route, ignoring all other routes. The resulting shortest-path modification is not an improvement.

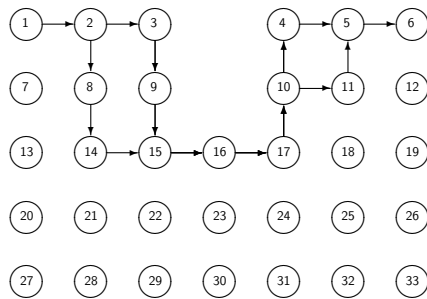


Node 2 modifies 3→4 route.

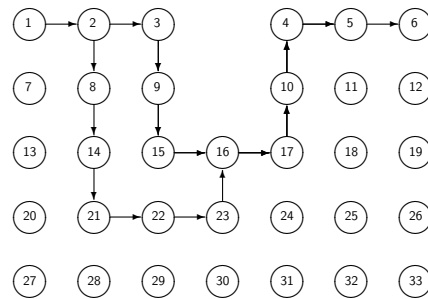


Modified 3→4 route.

Figure 4.11: Node 2 is overloaded and responds by modifying the 3→4 route. The modification considers only the 1→6 route. Note that the 3→4 route was selected from the routeList as the next route to modify and does not directly affect Node 2. No change results from this modification.

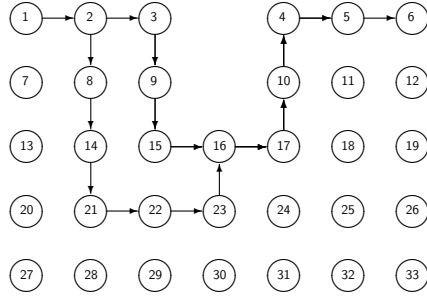


Node 2 modifies 2→5 route.

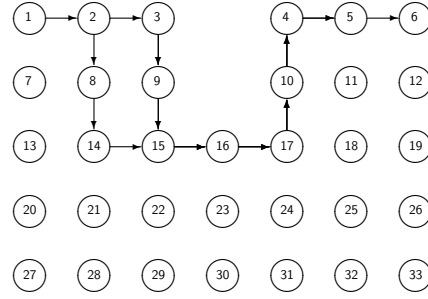


Modified 2→5 route.

Figure 4.12: Node 2 is still overloaded and responds by modifying the 2→5 route. The modification considers the 1→6 and 3→4 routes. The modified route is shown in the left side topology.

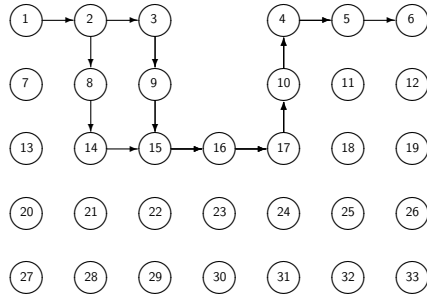


Node 2 modifies 2→5 route.

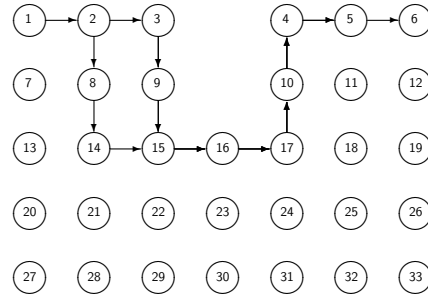


Modified 2→5 route.

Figure 4.13: Node 2 is still overloaded. Node 2 changes the shared routeList to (1→6,3→4,2→5) and modifies the 2→5 route, ignoring all other routes. The resulting shortest-path modification is not an improvement.

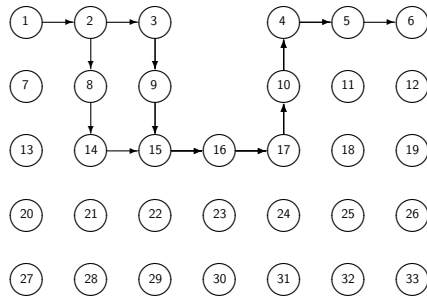


Node 2 modifies 2→5 route.

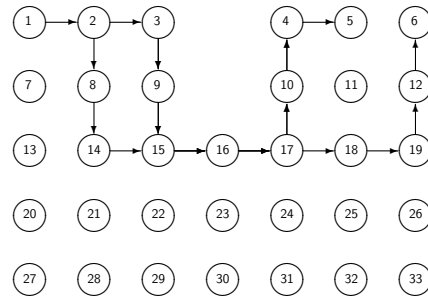


Modified 2→5 route.

Figure 4.14: Node 2 is still overloaded and responds by modifying the 3→4 route. The modification considers only the 2→5 route. The 3→4 route could not be improved under current circumstances and is shown unchanged in the left side topology.

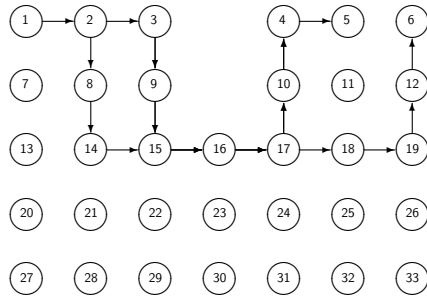


Node 2 modifies 1→6 route.

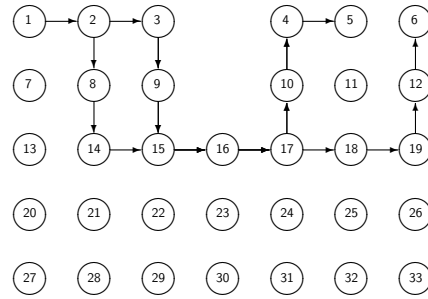


Modified 1→6 route.

Figure 4.15: Node 2 is still overloaded and responds by modifying the 1→6 route. The modification considers the 2→5 and 3→4 routes. The modification is premature, and the modified route does not change significantly.

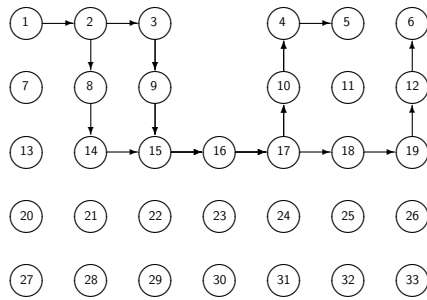


Node 2 modifies 3→4 route.

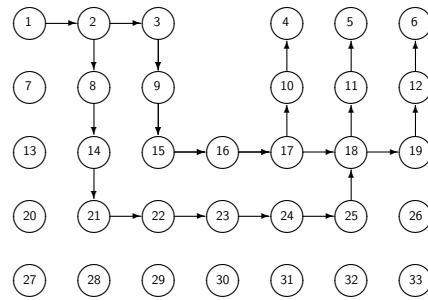


Modified 3→4 route.

Figure 4.16: Node 2 is still overloaded. Node 2 changes the shared routeList to (1→6, 2→5, 3→4) and modifies the 3→4 route, ignoring all other routes. The resulting shortest-path modification is not an improvement.

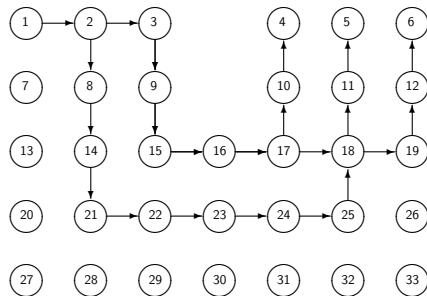


Node 2 modifies 2→5 route.

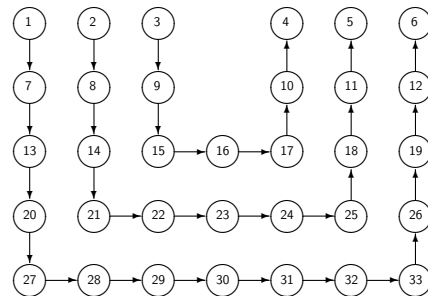


Modified 2→5 route.

Figure 4.17: Node 2 is still overloaded and responds by modifying the 2→5 route. The modification considers only the 3→4 route. The resulting modification is an improvement.



Node 15 modifies 1→6 route.



Modified 1→6 route.

Figure 4.18: Node 15 is overloaded and responds by modifying the 1→6 route. The modification considers the 2→5 and 3→4 routes. The result is a stable detangled network with no overloaded nodes.

4.4.2 Discussion

The nodes in the example network detangled the initially very tangled routes using only local information. No node ever had complete or even partial source-to-destination path information about any route. The nodes acted as sensors, detecting their own overloaded routers and responding by modifying individual routes. Each route modification selectively considered the effects of some routes while deliberately ignoring the effects of other routes. The occasional result of deliberately ignoring some routes was that some routes caused overloads in other nodes after the modification, leading to new situations after each route was modified. The nodes shared information about what routes to consider and what routes to ignore by modifying and sharing an ordered list of routes. The route an overloaded node chose to modify was determined by the shared ordered list of routes. Overloaded nodes modified the next route in the shared list, sometimes modifying routes that did not directly overload them, thus seeming to act altruistically.

The example also showed some nodes occasionally acting prematurely, with ineffectual results. Learning how long changes in the network take to stabilize is one of the learning tasks described in greater detail in Chapter 5. Even when some nodes do not have enough experience to learn an accurate estimate of how long a route change takes to stabilize, the Warp-5 detangling algorithm has proven robust and consistently able to successfully detangle the congestion problems documented in Chapter 6.

Chapter 5

Machine Learning in Warp-5

There are many challenges in wireless ad hoc networking that are well-suited to machine learning algorithms. New routes may be introduced into the network as needed in response to external circumstances, and the routing metric used in route discovery requires information based on the existing offered load of previously existing routes. The timing and level of offered load on those routes may be determined by circumstances that could not have been predicted beforehand, but may be consistent over time. Noise sources may be present or be introduced into the communication environment at times and intensities that are beyond the control of the distributed applications running on the wireless ad hoc network. The unpredictability and dynamism of circumstances that can affect traffic in a wireless ad hoc network are what makes them appropriate control problems for machine learning techniques.

The subfield of machine learning that deals with adaptation and control is called reinforcement learning. In the world of reinforcement learning, the control mechanism is called the *agent*, with an explicit goal it can achieve by taking a variety of *actions*. The agent is also capable of perceiving its environment in some means relevant to the goal and from these perceptions the agent determines the *state* of the system. The *policy* is the decision rule that determines the action the agent will take as a function of its state. The *reward* is a quantification of the result of an action as it relates to the goal. The *value* of a state is the total reward an agent can acquire in the long run starting from that state. The agent can learn these values and compare them to decide which actions better achieve the goal. Some situations require that an agent maximize the total acquired reward. Other situations require that the agent minimize some aspect of the situation to best achieve the goal. Most work in reinforcement learning adopts a Markov decision process view of the problem [57], [32]. This work takes a broader view that defines as reinforcement learning any task that can be seen as learning from experience combined with

optimization of behavior based on what is learned.

In systems where the effects of actions are not known beforehand or where circumstances change in unpredictable ways, the learning agent has to find a policy that best achieves the desired goal. Two classes of approaches to learning an effective policy are *on-policy* and *off-policy* methods. On-policy methods use experience gained from the agents' actions to evaluate and modify the policy it is currently using to make decisions. Off-policy methods use experience gained from one policy to evaluate and modify a separate policy for later use. The advantage of off-policy methods is that the exploration policy used to gain experience may randomly sample all possible actions while generating a separate exploitation policy [57]. The advantage of a fixed exploitation policy can be realized only in stable environments. In dynamic environments, on-policy methods allow the agent to learn from recent experience to better respond to changing circumstances.

The learning agent may start out knowing little or nothing about the effects of its actions. It will take an action, observe an effect and make a decision about the next action to take. By selecting different actions, the agent learns that some actions achieve a better result than others. If an agent is to do the best possible job, it must explore the effects of all available actions and be reasonably sure of the effects of those actions. This exploration conflicts with exploiting the knowledge it has already acquired to select the action that is expected to produce the best results in achieving its explicit goal. The trade-off between exploration and exploitation is a central challenge in reinforcement-learning systems. Neither pure exploration nor pure exploitation are useful in effectively achieving the goal. An agent that only explores alternative actions that result in poor results underachieves by failing to use the knowledge it has gained to make more effective choices. Conversely, an agent that sticks rigidly to a limited set of actions underachieves by failing to find better options, especially in a dynamic or stochastic environment. The learning agent is most effective when it can balance exploration and exploitation by preferring the actions with better results, but trying other actions that might achieve even better results when appropriate.

In a deterministic environment, the results of a single specific action would provide useful information to a learning agent. In stochastic environments, the results of a specific action would be affected by some unknown probability distribution that represents external behaviors

that are not directly observable. It could take many repetitions of the same action before the agent would have a reasonable expectation of what the action accomplishes (or how potentially counterproductive the action is). The time spent on the exploration of less productive actions is wasted in comparison to taking actions known to produce better results.

In stationary environments, the information gained at some early point in the process may be applied to the same problem at any later point with equally good results. In non-stationary environments, what worked well in the past may not work well under current circumstances. A learning agent can manage changing circumstances by using what it has learned from its most recent experience and discarding conflicting experience from the distant past. In environments that are both stochastic and non-stationary, the learning agent must make predictions based on multiple previous experiences that are sufficient to accurately reflect current conditions while not reflecting the now out-of-date conditions. This work uses learning agents that give greater consideration to more recent experiences, either by discarding or discounting data gathered from earlier experiences.

In the context of the work presented in this dissertation, the Warp-5 protocol seeks to minimize the time data packets spend between source and destination in wireless ad hoc networks. To do so effectively, it decomposes the task into a set of learning problems and corresponding optimization algorithms. Each node uses its experience to estimate the time it takes to complete a link-level unicast from the number of retransmissions done by the MAC layer at different transmission rates. Each node also learns the probability of unicast failure from its experience sending unicast packets to specific neighbors. The time to complete a unicast and the probability of unicast failure are necessary inputs to the Warp-5 routing metric. Each node has to track data packet arrival rates for different routes to be able to recognize its own congestion and changes in the congestion level for specific routes as the routes are modified. Routers have to learn estimated time-to-destination for different neighbors as part of the route discovery process. The time-to-destination estimates are based on current offered loads, the time required to complete unicasts and the probability of unicast failure as used in the Warp-5 routing metric. Routers also have to estimate the time between cause events and later effects on route modifications as part of the route detangling algorithm to alleviate router congestion. The methods used for all of these cope with the uncertain and changing network conditions.

The remaining sections in this chapter describe how Warp-5 performs each of these duties and how the relevant machine learning mechanisms are applied.

5.1 Selecting Link-level Transmission Rates

Each of the 802.11 a/b/g MAC protocols offer a fixed number of link-level transmission rates. The experiments documented in Chapter 6 modeled the 802.11g protocol that offered eight different transmission rates all expressed in Mbits/sec: 6, 9, 12, 18, 24, 36, 48 and 54. The faster rates take less time to transmit a packet, but the faster the rate, the greater the susceptibility to noise and loss of the packet in a single transmission. In practice, the network interface card (NIC) has a MAC layer that automatically retransmits a unicast packet if the sending node does not receive an ACK within a specific time limit as part of the 802.11 Distributed Coordination Function (DCF) [3]. The number of MAC-level unicast transmission attempts with delays between attempts required by the DCF means that the fastest transmission rate is not always the rate that takes the least amount of time to complete a unicast. A mechanism has to learn which transmission rate takes the shortest time.

Warp-5 uses an ϵ -greedy mechanism to control transmission rate selection. The transmission rate selection problem is a case of the “n-armed bandit” problem, where an agent with an explicit goal is repeatedly faced with n different choices to achieve that goal [57]. Each action results in a different result, evaluated by the agent. The agent has to do its best to meet the long-term goal by making the choices that get the best immediate results. What the agent doesn’t initially know is what result to associate with each available choice. For an ϵ -greedy control mechanism, the action that is currently known to produce the best results is called the “greedy” action. Initially, the greedy action may be arbitrary or there may be no greedy action where all actions are equally likely to be chosen. The policy is to select the greedy action with probability $1 - \epsilon$ and with probability ϵ to randomly select one of the other actions with equal likelihood. When ϵ is small, the agent exploits its current knowledge by selecting the best choice known most of the time and exploring for better choices the rest of the time.

The design of the Warp-5 transmission rate selection mechanism takes advantage of some characteristics of the available transmission rates. If a unicast can be successfully completed in

one transmission at the fastest available transmission rate, the mechanism stops exploring and consistently selects that rate. In this case, the combination of one unicast transmission at the fastest rate is known to be the best possible result, making further exploration unnecessary and counterproductive. In other cases, the mechanism randomly selects the rate that it currently knows has completed a unicast in the shortest time with probability of 0.95 and the other rates with probability 0.05. Any transmission rate found to complete a unicast transmission in the least amount of time becomes the new greedy choice. The feedback used to calculate performance measures for any transmission rate is the number of MAC-level transmissions that were performed in completing a link-level unicast and whether or not the unicast was successfully received.

The mechanism also controls the set of transmission rates available for exploration. If a unicast is completed with more than one transmission or if the unicast fails, the set of available rates is extended by the next slower transmission rate. If a unicast is completed in a single transmission, the slower transmission rates are excluded from the exploration set. This mechanism eliminates transmission rates that could not perform as well as current conditions would support, while allowing adaptation to new conditions.

The calculated mean time to complete a unicast component, T_m , of the Warp-5 routing metric used during route discoveries is the average of the time to complete a unicast at each transmission rate currently in the set of rates available for exploration weighted by the probabilities assigned to each rate. The resulting value thus reflects the balance between exploration and exploitation in transmission rate learning.

5.2 Estimating Probability of Unicast Failure

The wireless 802.11 MAC Distributed Coordination Function [24] makes multiple attempts to complete a unicast by repeating the packet transmission until either acknowledgment of the transmission by the receiver or a maximum number of transmission attempts have been made. The network layer considers the unicast a success when the transmitting node receives an ACK packet from the receiving neighbor, regardless of the number of transmissions made at the MAC layer. When the transmitting node fails to receive an ACK packet after the MAC-level timeout,

the unicast is considered a failure.

The result of any single unicast attempt is less significant than knowing the probability that the next unicast to a given neighbor will fail. According to the mathematical model of Section 3.1, the probability of unicast failure increases as the level of noise increases. In simulations using the model of Section 3.1, the routers would not know the underlying mathematical model for noise and packet loss, nor would routers in a real-world situation be able to make *a priori* success/failure predictions for any single unicast. It is possible for a learning mechanism to estimate the probability of packet loss based on recent success/failure experiences in making unicasts.

Warp-5 uses an exponential weighted average update mechanism to estimate the probability of unicast failure using information returned from the MAC layer. The mechanism initially assumes (optimistically) a zero probability of unicast failure and modifies its estimate with the success/failure result obtained after each link-level unicast. The formula used for updating the estimated probability P_f of unicast failure is:

$$P_f \leftarrow (1 - \alpha)P_f + \alpha(R),$$

where R is the outcome of the most recent unicast attempt expressed as 1 for failure, 0 for success. The learning rate α smooths the effect of each success/failure result on the probability estimate and favors more recent experiences over older experiences by exponentially reducing the contribution of the previous estimate of P_f as new results are obtained. The effect of the formula is that many closely occurring failures push the estimated probability of unicast failure toward 1.0, and many closely occurring successes push the estimated probability toward zero. In the Warp-5 experiments documented in Chapter 6, α was set to 0.05, meaning that an occasional success after many failures decreases the probability only slightly, while an occasional failure after many successes increases the probability only slightly. Many failures after a series of failures will quickly increase the estimated probability, and many successes after a series of failures will quickly decrease the estimated probability.

The estimated failure probability is the P_f component of the Warp-5 routing metric used during route discoveries. The P_f estimate could be made to converge to the true value in a stationary environment by making α decay to zero at a rate that makes the sum of the α 's

When a router sees a RREP from some previously unknown neighbor x do:

$$P_{f_x} \leftarrow 0.0$$

$$\alpha \leftarrow 0.05$$

When a link-level unicast to neighbor x succeeds do:

$$P_{f_x} \leftarrow (1 - \alpha)P_{f_x}$$

When a link-level unicast to neighbor x fails do:

$$P_{f_x} \leftarrow (1 - \alpha)P_{f_x} + \alpha$$

Figure 5.1: Warp-5 Estimating Probability of Unicast Failure.

infinite and the sum of the squares of the α 's finite, according to stochastic approximation theory [57], [2]. However, the communication medium is a non-stationary environment with changing noise conditions. In a non-stationary environment, α remains a fixed constant to make the learning responsive to changing noise conditions.

5.3 Learning Data Packet Arrival Rates

Applications running on wireless ad hoc networks may send data packets to distant nodes at any time. A node that needs to send packets to a destination for which it does not have routing information will initiate a route discovery and buffer accumulated packets for that destination until a route is found. Once a route is found, the buffered data packets then travel through the network as fast as they can be individually unicast through the MAC layer. When routes are known and no data packets have been buffered, the 802.11 MAC exponential backoff algorithm introduces variability in traffic levels for data packets generated at a constant rate. Variability in data packet arrival rates is inevitable in wireless ad hoc networks.

Infrequent and short bursts of packets arriving at a high rate that do not overflow the input queue of the affected router requires no action on the part of the router because no packets are lost. A sustained offered load high enough to exceed the router's forwarding capacity and cause loss of data packets is a problem that needs to be corrected. Routers using Warp-5 monitor the arrival rate of all data packets to detect their own congestion and react by detangling the incoming routes. The Warp-5 routers also have to track the arrival rates of individual routes to be able to add the combined arrival rates of selected routes during the detangling process. Warp-5 routers must be able to distinguish between short bursts of packets arriving at a high

rate and sustained periods of high offered load.

Warp-5 routers use a sliding time window containing recent packet arrival times to calculate data packet arrival rates. The calculated arrival rate is the number of packet arrival times divided by the size of the window. The size of the sliding window is a span of time that gets updated every 0.1 seconds of simulated time. Packet arrival times that no longer fit in the updated window are discarded. The window size has to be large enough to smooth infrequent short bursts of arriving packets, but small enough to be responsive to sustained changes in packet arrival rates. A sliding window width of 1.0 seconds proved effective in the experiments documented in Chapter 6.

```

When a router sees a data packet for some previously unknown route  $r$  do:
  Create empty list of data packet arrival times  $rateTracker_r$  for route  $r$ 
  Add time of data packet arrival to  $rateTracker_r$ 

When a router sees a data packet for some known route  $r$  do:
  Add time of data packet arrival to  $rateTracker_r$ 

When a router's timer goes off every 1/10 second do:
   $earliest \leftarrow currenttime - window\ size$ 
  foreach  $rateTracker_r \in All\ active\ routes$  do
    Discard all data packet arrival times prior to  $earliest$  from  $rateTracker_r$ 
  end

```

Figure 5.2: Warp-5 Learning Data Packet Arrival Rates.

Each Warp-5 router uses the sum of the smoothed data packet arrival rates for all active routes in a wireless ad hoc network as the λ_q component of the Warp-5 routing metric used during route discoveries.

5.4 Estimating Time For Route Stabilization

Warp-5 routers make routing decisions using a metric based on multiple learned factors, including the mean time to complete a link-level unicast, the probability of unicast failure and data packet arrival rates. For the routing decisions to be effective, the learned inputs must reflect stable routes in the wireless ad hoc network. Nodes that are heavily used in relation to their forwarding capacity or experiencing trouble forwarding data packets that under-estimate their own routing metric may result in routes that send more traffic through those nodes, not less.

Underutilized nodes that over-estimate their own routing metric may fail to attract traffic that offloads other more heavily loaded nodes in the network.

The addition of new routes or the modification of existing routes requires route discovery in a Warp-5 ad hoc network. A RREQ packet is broadcast from a node and propagates through the network, which is followed by the propagation of RREP packets containing new routing information through the network. Even with Warp-5 propagation rules that force the propagation of newer or better routing information, the RREP packets that first reach individual nodes may not offer the best routing information. Data packets can be forwarded before the route stabilizes, causing transient changes in the packet arrival rates for nodes that will not be part of the stabilized route. As the RREP packets finish propagating through the network, the routes and corresponding data packet arrival rates will stabilize, given constant or close to constant rate data packet generation from the source node. The time required to propagate RREQ and RREP packets through the network, the time required for the route to stabilize and the time the individual routers need to learn the new packet arrival rates are determined by the network topology, router forwarding capacities, the offered load of other routes in the network and ambient noise conditions. The time required to stabilize a new or changed route in a wireless ad hoc network therefore can be estimated, and the time estimate can be used to predict how long it takes a new or modified route to stabilize.

The value of knowing the time required for a new or modified route to stabilize becomes apparent when considering the Warp-5 detangling process. A congested node selects a route and broadcasts a detangling RREQ packet to change the selected route. The selected route may or may not change as a result. If the route does not change, the data packet arrival rates do not change. If the route does change, the congested node may continue to receive data packets forwarded from upstream intermediate nodes that are no longer part of the stabilized route. The data packet arrival rate observed at the congested node changes only after the upstream nodes no longer have packets on the now-changed route to forward. The effect, if any, of any detangling action will not be immediately apparent to the nodes in the network. Any congested node should attempt to change a route only after other routes have stabilized in the network.

Nodes in a wireless ad hoc network can estimate the time it takes new and changed routes

to stabilize with an Expectation-Maximization (EM) algorithm [9]. The term “Expectation-Maximization” does not refer to a single algorithm; it instead defines a class of algorithms that iteratively improve estimated parameters of a probabilistic model. The first step of an EM algorithm assigns arbitrary values to the parameter estimates. The EM algorithm then performs an “expectation” step that calculates the expected value of the parameters from observed data under the assumption that the parameter estimates are accurate. This step is followed by a “maximization” step that calculates new maximum likelihood estimates of the parameters from the values calculated in the expectation step. The expectation step and maximization steps are repeated with the new parameter estimates. The algorithm increases the likelihood at each repetition, thus guaranteeing convergence of the parameter estimates [13], [5].

The Warp-5 EM algorithm calculates Gaussian distribution mean and variance values for the time between cause and effect events. A *cause event* is the first appearance of a specific RREQ packet identified by a route and sequence number. An *effect event* occurs when the data packet arrival rate for that route goes from a positive value to zero. No one-to-one correspondence exists between cause and effect events. A router may attempt to change a route more than once (with other route changes attempted in between) before packets for that route stop coming to that router. Similarly, a router may not receive a RREQ packet for a particular route and still recognize that packets for a route have been diverted away from that router.

Each node using Warp-5 starts with an initial estimate for the mean and variance of 10.0 and 1.0, respectively. The arrival time of each unique RREQ is saved as a cause event. When an effect event occurs, the router performs the expectation and maximization steps to generate new mean and variance estimates. The variance estimate has no utility, but the estimated mean is used when a router detects its own congestion. If the time between the most recent cause event and the current time is greater than the estimated mean, the congested router selects a route and broadcasts a detangling RREQ under the assumption that all routes have stabilized in the network. The congested router does not broadcast a detangling RREQ when the time between the most recent cause event and the current time is less than the estimated mean, under the assumption that some route has not yet stabilized in the network. Routers check the data packet arrival rates for incoming routes every 0.1 seconds, so a router that remains congested after the estimated mean time has passed will then broadcast a detangling RREQ. The Warp-5

expectation maximization algorithm is shown in Figure 5.4.

$$p \leftarrow \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Figure 5.3: Calculation of Gaussian values

```

1 When a router sees a RREQ for some previously unknown route  $r$  do:
2    $\mu_r \leftarrow 10.0$ 
3    $\sigma_r \leftarrow 1.0$ 
4   Create a new  $causeList_r$  for route  $r$ 
5   Add the time RREQ for route  $r$  arrived to  $causeList_r$ 
6   Create a new  $effectList_r$  for route  $r$ 
7 When a router sees a distinct RREQ for some previously known route  $r$  do:
8   Add the time RREQ for route  $r$  arrived to  $causeList_r$ 
9 When a router sees the packet arrival rate for route  $r$  go to zero do:
10  Add the time the arrival rate for route  $r$  went to zero to  $effectList_r$ 
11  foreach  $effect_i \in effectList_r$  do
12     $sum \leftarrow 0.0$ 
13    foreach  $cause_k \in causeList_r$  prior to  $effect_i$  do
14       $cause_k.prob \leftarrow p(effect_i - cause_k.time, \mu_r, \sigma_r)$ 
15       $sum \leftarrow sum + cause_k.prob$ 
16    end
17    if  $sum \geq 1e - 12$  then
18       $estimate \leftarrow 0.0$ 
19      foreach  $cause_k \in causeList_r$  prior to  $effect_i$  do
20         $estimate \leftarrow estimate + (cause_k.prob) / sum * (effect_i - cause_k.time)$ 
21      end
22      Add  $estimate$  to  $estimateList$ 
23    end
24  end
25   $\mu_r \leftarrow \text{mean of } estimateList$ 
26   $\sigma_r \leftarrow \text{standard deviation of } estimateList$ 

```

Figure 5.4: Warp-5 Expectation Management Algorithm.

A Warp-5 router tracks cause/event sequences for multiple routes. The largest estimated mean time was used as the minimum time required to stabilize a new or modified route in the network in the experiments documented in Chapter 6. The largest estimated mean time may shrink as new cause/effect experience is gained.

Chapter 6

Noise and Congestion Simulations

The author implemented an event-driven network simulator to support the evaluation of the Warp-5 protocol. The flexible simulator design supports multiple routing protocols, different ad hoc network topologies and varying traffic generators to model different scenarios. The simulator also supports noise sources at varying operating frequencies and intensity levels.

The objective of the simulations is to show that Warp-5 can effectively prevent and correct noise and router congestion problems in wireless ad hoc networks. For comparison purposes, an implementation of AODV was run on the same simulator to see how it performed in responding to the same routing challenges. The widely-used DSR routing protocol was not used in these simulations because of its similarity to AODV. Both are reactive protocols that use minimal hop count as a routing metric. The two protocols are sufficiently similar that Legendre, et al. [39] gave a partial description of how one protocol can be translated into the other. Thus, any simulation results based on a comparison of Warp-5 to AODV are equally applicable to DSR.

Since routing information is communicated in packets, how the packets are communicated and how the routing control packets are queued on arrival are relevant considerations in dealing with router congestion. If data packets and router control packets share the same communication channel and router input queues, they can have detrimental effects when the routers are congested. Router control packets displace data packets, causing loss of data. Data packets can displace routing control packets, preventing the control packets from reaching all available neighbors possibly resulting in less than ideal routing decisions. Communicating routing control information and application data on separate channels and using separate routing queues can avoid these problems, but the value of the approach needs to be explored with regard to both Warp-5 and AODV. Thus, the simulator design supports both single-radio and dual-radio nodes.

6.1 Simulation Environment

The Warp-5 and AODV simulations were run on static topologies where the nodes are numbered left to right, top to bottom as shown in Figure 6.1 and Figure 6.2. The effective communication radius for all nodes was 10 meters, while the nodes were placed so that the nearest neighbors were 9 meters away. The effect is that the transmission from a node would reach the neighbors above, below, left and right of the transmitting node.

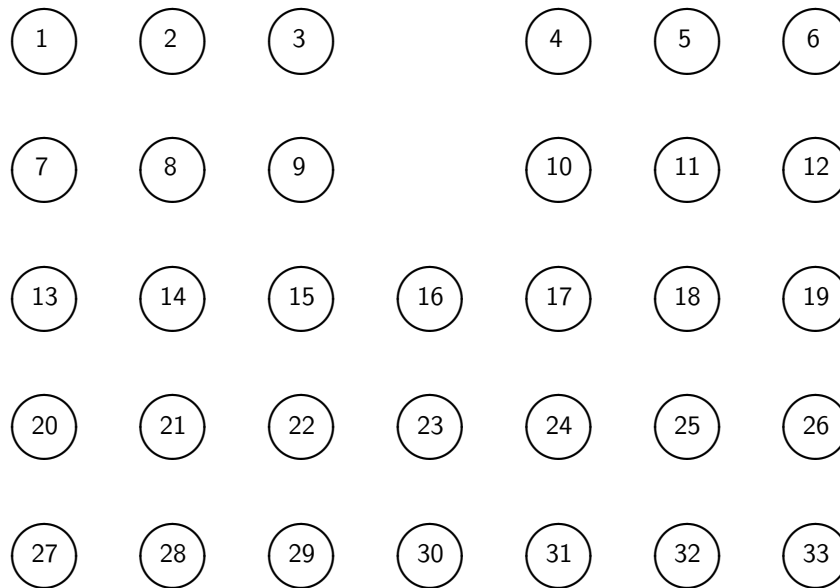


Figure 6.1: Castle Topology for Congestion Problems

The simulations encompass a variety of topology scenarios that are challenging for routing protocols. The *castle* topology was created to model congestion situations where the shortest path is not always the best route. In the real world, congestion situation might come about because nodes may be placed in a landscape whose topography causes constrictions in node dispersal and/or obstacles to wireless communication. One could easily imagine many nodes on one side of a mountain range trying to communicate with nodes on the other side of the mountain range through nodes in a mountain pass, or nodes in an urban environment trying to

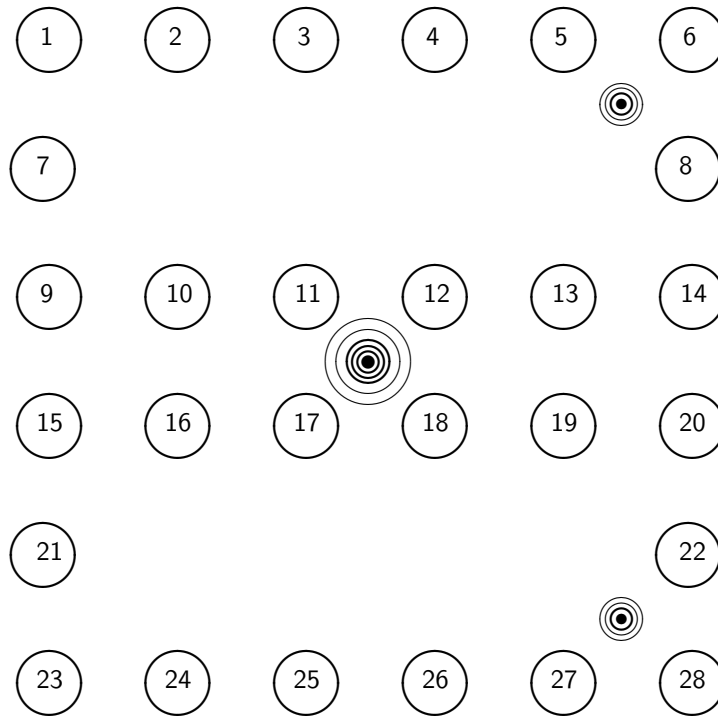


Figure 6.2: Square Topology With Active Noise Sources

communicate despite the presence of buildings. In the castle topology, Node 1 wants to send data packets to Node 6, Node 2 wants to send data packets to Node 5, and Node 3 wants to send data packets to Node 4. The shortest path for all three routes is through the intermediate nodes 15, 16 and 17. The castle topology models the conflict between shortest path and best path when the offered load of the routes are sufficiently high to demand a significant portion of the routing capacity of the intermediate nodes.

Although the castle topology has only 33 nodes, it is enough to illustrate a complex set of routing problems, listed as follows:

1. Many routes overloading a router.
2. Some routes overloading a router while a set of older routes does not affect the router.
3. Some routes overloading a router while a set of newer routes does not affect the router.
4. Old and new routes overloading a router while routes of intermediate age do not affect

the router.

Another topology used in the simulations is the *square* topology that models noise problems, again where the shortest path may not always be the best route. Noise problems might come about in the real world in military scenarios where an opponent places noise transmitters intended to disrupt communication on a battlefield, or in more benign urban environments where non-hostile environmental noise transmissions interfere with the wireless communication of an ad hoc network. In the square topology, nodes on the left side of the topology want to send data packets to nodes on the right side. Node 1 wants to send data packets to Node 6, Node 7 wants to communicate with Node 8, Node 9 wants to communicate with node 14, Node 15 wants to communicate with node 20, Node 21 wants to communicate with Node 22, and Node 23 wants to communicate with Node 28. The square topology models the conflict between shortest path and best path when noise sources (represented by the radiating dots in Figure 6.2), effectively disrupt wireless communication enough to make longer alternate paths more productive.

The routers in the simulations transmit packets using an emulation of the 802.11 MAC protocol [24]. Large data packets (500 bytes) were used because the large packets help to congest the network and are more susceptible to noise than smaller packets.

Even though the nodes in the castle and square topologies are the same distance apart and the routing and communication radii are the same for all nodes, the purpose of this work is to evaluate the Warp-5 routing protocol with respect to noise and router congestion. There are no assumptions in the design of the Warp-5 protocol that preclude different data transmitter powers, router queue lengths, receiver sensitivities or routing speeds, thus the experiments and results in this work can be expected to apply generally to ad hoc networks consisting of nodes with different and more heterogeneous characteristics operating in more varied and challenging environments.

6.2 Scientific Properties For Investigation

Application data throughput in wireless ad hoc networks is affected by noise, router congestion and packet collisions. Collision loss is managed by the random exponential backoff algorithm

in the 802.11 MAC layer [24]. Router congestion is determined by the packet arrival rate and the forwarding capacity of the router. As the packet arrival rate at a router increases, the mean length of the router input queue increases and the time the router requires to forward packets increases. When the packet arrival rate equals or exceeds the forwarding capacity of the router, the router input queue fills up and the router drops incoming packets it is unable to put in its input queue. Noise causes corruption of packets, which is detected by MAC layer cyclic redundancy checks in the receiving node. The corrupted packets are dropped at the MAC layer and not delivered to the higher layers of the protocol stack. The loss of data packets from router congestion or noise reduces overall application data throughput.

The properties investigated in this work are noise and router congestion. Noise can be a pre-existing condition in the wireless communication environment before the ad hoc network begins to function or it can be introduced after the network has established routes and begun to transmit application data packets. Router congestion can occur when routes initially form in an ad hoc network or when new routes are added to an ad hoc network that did not formerly suffer from router congestion. The problems of noise and congestion lead to the four properties investigated in this work:

1. What actions and learning can prevent data packet loss due to router congestion in a wireless ad hoc network?
2. What actions and learning are effective in responding to router congestion that occurs in a wireless ad hoc network?
3. What actions and learning can prevent packet loss due to noise in a wireless ad hoc network?
4. What actions and learning are effective in responding to noise that occurs in a wireless ad hoc network?

The key feature of all of these properties is that they are *dynamic*. The location of a noise source and the strength of the noise transmissions tend to be beyond the control of the distributed applications running on the wireless ad hoc network and the noise sources may in fact be hostile to those applications. The location of nodes in the network and the timing of when

one node chooses to send data packets to a possibly distant node affects the router congestion of the intermediate nodes in ways that could not always be predicted beforehand. The dynamic and unpredictable nature of noise and congestion means that the nodes in an ad hoc wireless network could *learn* as part of effective responses to noise and router congestion conditions as they arise.

6.2.1 Preventing Data Packet Loss Due To Router Congestion

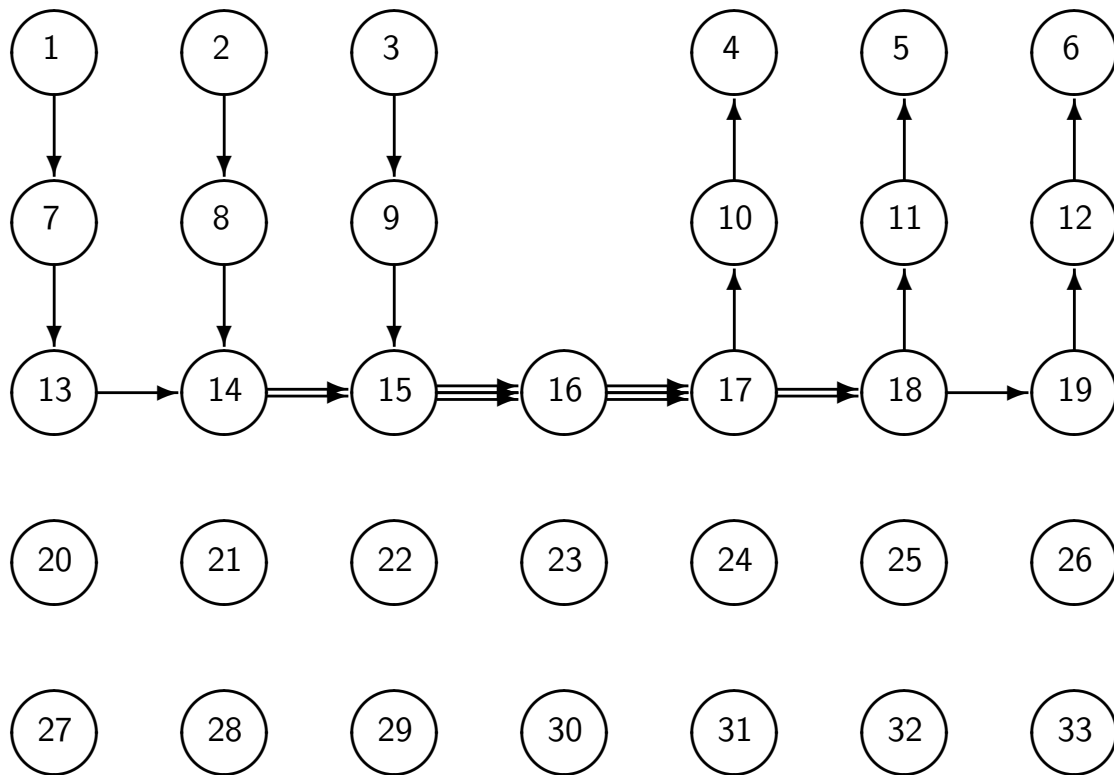


Figure 6.3: Preventable Router Congestion.

Router congestion can occur when too many routes are sending too many packets through routers whose forwarding capacity is exceeded by the combined packet arrival rate. Consider the wireless topology of Figure 6.3. The routes were created using a shortest path metric first for a route from Node 3 to Node 4, followed by a route from Node 2 to Node 5 and then a route from Node 1 to Node 6. When the first route was discovered, the routing protocol was free to choose the shortest path without harm. The second route then overlapped the first at nodes

15, 16 and 17, requiring those nodes to forward packets for both routes. The third route then overlapped the second at nodes 14 and 18, requiring them to forward packets for both routes and adding to the workload of nodes 15, 16 and 17 by requiring them to now forward packets for three routes. Data packets start getting lost if the combined arrival rates at any node exceeds its forwarding capacity. The loss of data packets could have been prevented because there are other underutilized nodes available that could carry packets for all the routes without packet loss.

The loss of data packets could be prevented during route discovery if the nodes sending and forwarding data packets in the ad hoc network learned the combined data packet arrival (and sending) rates. This rate is the λ_q portion of the formula for the component of the routing metric described in Section 3.1 that represents the mean time a packet spends in the router before it is forwarded. Adding this component to the time it takes to forward a packet at the MAC layer gives the time cost of moving data through the node. Later route discoveries using Warp-5 would use the time cost in deciding the time-to-destination cost of each neighbor.

The time cost calculation Warp-5 uses in calculating time-to-destination comes from information learned from experience with earlier routes in the ad hoc network.

6.2.2 Responding to Router Congestion To Prevent Data Packet Loss

Routers can still become congested, even when experience-based routing metrics are used in the process of route discovery. Each route discovery attempts to find the best route from source to destination without considering possible future routes. The potential for router congestion arises when new routes are added to an otherwise congestion-free network. Consider the situation in the wireless ad hoc network depicted in Figure 6.4.

Here, the route from Node 3 to Node 4 was discovered first, followed by the router from Node 1 to Node 6. The routes do not overlap and the traffic level does not exceed the forwarding capacity of the routers. The problem of router congestion arises when Node 2 wants to send data to Node 5. There is no route from Node 2 to Node 5 that does not use routers from a previous route. If the combined traffic level on any node sending or forwarding data packets for multiple routes exceeds its forwarding capacity, data packets will be dropped. The loss of data packets is unnecessary and the router congestion can be repaired because there are other

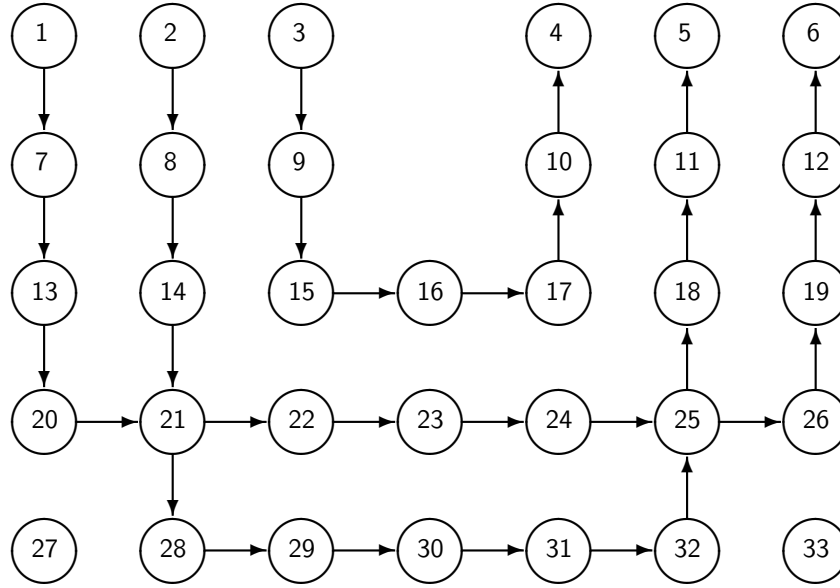


Figure 6.4: Correctable Router Congestion.

underutilized nodes available that could carry packets for all the routes without packet loss.

A wireless ad hoc network using Warp-5 could resolve this problem using learned information. The nodes would learn the order that routes were created, the data packet arrival rates for specific routes, the link-level unicast times and the estimated time between the first appearance of a detangling RREQ and the time the node stops receiving packets for a specific route. A node whose data packet arrival rate exceeds its forwarding capacity will broadcast a special detangling RREQ packet for one of the routes overloading it. Other nodes receiving this packet will make routing decisions based only on the packet arrival rates for routes that were created after the route specified in the detangling RREQ. It takes time for the detangling RREQ to propagate through the wireless network, for the route to change (if it changes at all) and for the nodes in the network to recognize that the route has actually changed and not just experienced a brief lull in offered load. The overloaded node that initially broadcast the detangling RREQ packet will only detect a change in the route if the data arrival rate for that route reduces to zero. Other

nodes may experience overloading while the previous route is changing. In either event, further detangling actions may be needed to alleviate router congestion, but each detangling effort requires stable routes to ensure correct router load information. Nodes experiencing congestion therefore have to estimate the time from the initial appearance of a detangling RREQ packet until routes stabilize before attempting to detangle another route.

Nodes in a wireless ad hoc network using Warp-5 would also learn the data packet arrival times for specific routes and recognize the time between the first appearance of a RREQ packet for a specific route and the time the arrival rate for that route reduces to zero. An overloaded node would use its learned time for the changed routes to stabilize before taking the next route detangling step by broadcasting another RREQ packet. The subsequent route re-discovery would make use of link-level unicast times and data packet arrival rates, both learned from recent experience of the nodes in the wireless network.

6.2.3 Preventing Data Packet Loss Due To Noise

Pre-existing noise sources in the wireless communication environment can cause the loss of data packets. A weak noise source may not have a measurable effect on data packet transmissions. A very strong noise source may completely disrupt some links and prevent routers from using these links. The problem is most interesting when the noise sources are strong enough to interfere with data packet transmissions, but not strong enough to completely prevent the formation of routes in the wireless ad hoc network. Consider the situation in the square topology of Figure 6.5.

The noise source in the center of the topology is strong enough to disrupt data traffic transmitted at high transmission rates and only partially disrupt data traffic transmitted at lower transmission rates due to the greater resilience of modulations at lower transmission rates. The routes were created using a shortest path metric, ignoring proximity to the disruptive noise source. Many of the data packets transmitted along these routes are subsequently lost. The loss of data packets is unnecessary and preventable because there are other underutilized nodes available that could carry packets to their destination with smaller likelihood of packet loss.

A wireless ad hoc network using Warp-5 could minimize data packet loss using information learned from experience with link-level unicasts. In a noisy environment, the probability of a

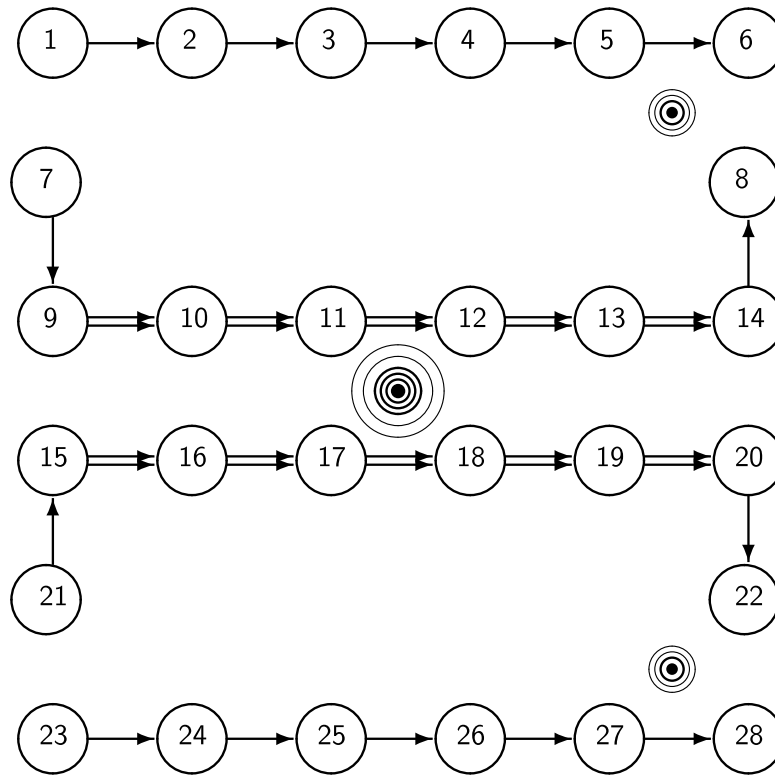


Figure 6.5: Square Topology With Poorly Chosen Routes

link-level unicast transmission failing increases in relation to the signal-to-noise ratio. The 802.11 MAC wireless hardware automatically retries unicast transmission some fixed number of times until the transmission is acknowledged. The probability of unicast failure and the time taken to complete a unicast (whether resulting in success or failure) can be learned from recent experience with link-level unicast transmissions. These factors are part of the time-based routing metric Warp-5 uses to select the next hop when forwarding data packets. In the square topology, Nodes 9 and 15 have more than one neighbor available to select as the next hop. Increasing packet loss from unicasts to Nodes 10 and 16 will increase the time cost of using those nodes. Eventually, the time cost will be greater than the time cost of forwarding to Nodes 7 and 21, and the data packets will be directed away from the noise source.

6.2.4 Responding To Noise To Minimize Data Packet Loss

Noise sources that dynamically appear in the wireless environment used by a wireless ad hoc network can also cause the loss of data packets. When the noise sources are strong enough to interfere with data packet transmissions, but not strong enough to completely prevent the formation of routes in the wireless ad hoc network, the loss of data packets need not be inevitable. Consider the situation in the square topology of Figure 6.6, which shows routes established under noise-free conditions and three potential noise sources.

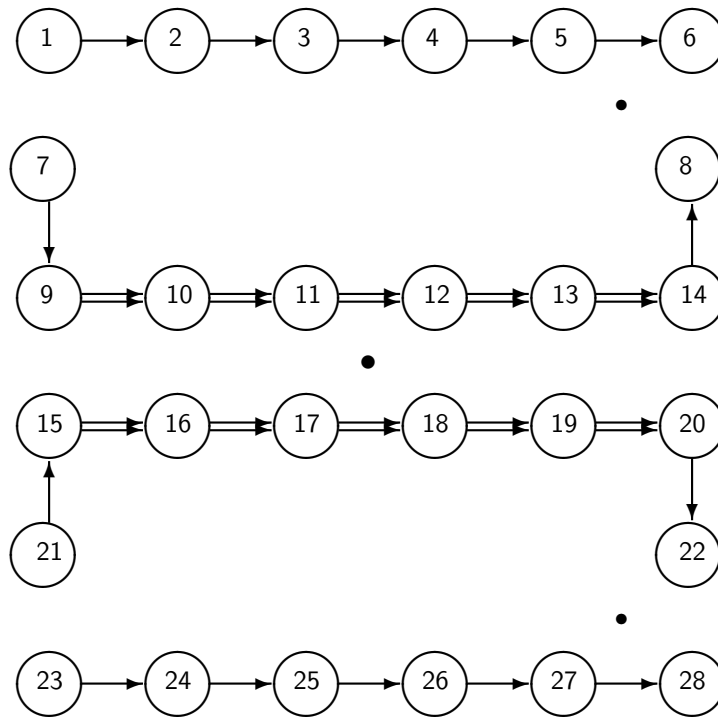


Figure 6.6: Square Topology Before Noise Source Activation

Suppose that once activated, the noise source in the center of the topology is strong enough to disrupt data traffic transmitted at high transmission rates, yet only partially disrupt data traffic transmitted at lower transmission rates. Also, assume the routes were created using a shortest path metric, before the noise sources were activated. When the noise sources become active, many of the data packets transmitted along these routes would be lost. The loss of data packets is unnecessary and correctable because there are other underutilized nodes available that could

carry packets to their destination with smaller likelihood of packet loss.

A wireless ad hoc network using Warp-5 could minimize data packet loss using information learned from experience with link-level unicasts when the noise levels change. The probability of unicast failure and the time taken to complete a unicast (whether resulting in success or failure) can be learned from recent experience with link-level unicast transmissions in the changed environment. These factors are part of the time-based routing metric Warp-5 uses to select the next hop when forwarding data packets. In the square topology, Nodes 9 and 15 have more than one neighbor available to select as the next hop. Increasing packet loss from unicasts to Nodes 10 and 16 will increase the time cost of using those nodes. Shortly thereafter, the time cost will be greater than the time cost of forwarding to Nodes 7 and 21, and the data packets will be directed away from the noise source. This example demonstrates how an ad hoc network using Warp-5 would adjust to changing environmental noise conditions.

6.3 Experimental Scenarios

This section describes the experimental scenarios used to investigate the noise and congestion properties described in the previous section.

6.3.1 Preventing Data Packet Loss Due To Router Congestion

The first property to investigate is the prevention of data packet loss due to router congestion in wireless ad hoc networks. The exploration scenario for this problem requires that multiple routes are established in a wireless topology simulation where the shortest path metric results in router congestion and data packet loss. Warp-5 and AODV congestion-avoidance simulations run on the static “castle” topology shown in Figure 6.1. The effective communication radius for all nodes is 10 meters. The nodes are placed so that the nearest neighbors are 9 meters away. The effect is that the transmission from a node will reach the neighbors above, below, left and right of the transmitting node.

The nodes in the congestion-avoidance simulations are homogeneous with regard to packet forwarding capacity and routing queue size. There are three routes to discover and use during the simulation: Node 3 to Node 4, Node 2 to Node 5, and Node 1 to Node 6, all discovered

in that order for all simulations. Four router/radio configurations are run in the simulations: AODV on single-radio nodes, AODV on dual-radio nodes, Warp-5 on single-radio nodes and Warp-5 on dual-radio nodes. For each router/radio configuration, three simulations are run, each with the routes taking a different proportion of the router forwarding capacity. The offered load of each route in the “low” simulations is equivalent to 20 percent of the router forwarding capacity, the offered load of each route in the “medium” simulations is equivalent to 40 percent of router forwarding capacity and the offered load of each route in the “high” simulations is equivalent to 66.67 percent of router forwarding capacity, making a dozen simulations in all. The low, medium and high offered loads represent distinctly different congestion behaviors relative to the router forwarding capacity rather than specific percentages. The route discovery from Node 3 to Node 4 begins at the start of the simulation, the route discovery from Node 2 to Node 5 begins 4.0 seconds into the simulation and the route discovery from Node 1 to Node 6 begins 8.0 seconds into the simulation. Each source node generates data packets at a constant rate.

The offered load of the low simulations means that three routes could multiplex packets through one or more nodes without packet loss because the combined packet arrival rate is still less than the router forwarding capacity. Only two routes could multiplex the offered load of the medium simulations without loss of packets. The offered load of each route in the high simulations is large enough to mean that packet loss is minimized when no more than one node is used in any single route. Each node has a non-zero time to forward and transmit a node to the next hop on a route, so the first Warp-5 route discovery is free to select a node with the fewest hops between source and destination. The second Warp-5 route discovery will have to consider the effects of the first route when selecting a route that minimizes source-to-destination time. The third Warp-5 route discovery will have to consider the effects of the first two routes when selecting the route with the smallest source-to-destination time. Depending on the offered load offered by each route, the second and third routes may not always have the fewest hops in the simulated topology.

Routers using AODV will always select the shortest visible route, which leads to intersecting routes regardless of the load offered by the routes involved. Nodes 15, 16 and 17 in the castle topology are bottlenecks, suffering loss of data packets when the offered load exceeded

the router forwarding capacity.

Each simulation in this scenario runs for 120 (simulated) seconds.

6.3.2 Responding To Router Congestion To Minimize Data Packet Loss

The second property to investigate is the protocol's response to router congestion and the minimization of packet loss in wireless ad hoc networks. The exploration scenario for this problem requires that multiple routes are established in a wireless topology simulation where the shortest path metric results in router congestion and data packet loss. Warp-5 and AODV congestion-response simulations run on the castle topology with the same effective communication radius of 10 meters for all nodes. The nodes for the simulations are placed so that the nearest neighbors are 9 meters away. The effect is that the transmission from a node reaches the neighbors above, below, left and right of the transmitting node.

The nodes in the congestion-response simulations are homogeneous with regard to packet forwarding capacity and routing queue size. There are three routes to establish and use during the simulation: Node 3 to Node 4, Node 2 to Node 5, and Node 1 to Node 6. Simulations run with four router/radio configurations: AODV on single-radio nodes, AODV on dual-radio nodes, Warp-5 on single-radio nodes and Warp-5 on dual-radio nodes. Six different simulations run for each router/radio configuration with the three different routes discovered in different orders for a total of 24 simulations in all. The first route discovery begins at the start of the simulation, the second discovery begins 4.0 seconds into the simulation and the third route discovery begins 8.0 seconds into the simulation. Each source node generates data packets at a constant rate equal to two-thirds of the router forwarding capacity. Thus, any two routes using the same node send traffic at a combined rate that exceeds the forwarding capacity of that node's router by 33.33 percent, resulting in a 25 percent loss of data packets. Three routes sharing the same node send traffic at a combined rate twice that of the forwarding capacity of the router, resulting in a 50 percent loss of data packets.

Setting the offered load for each route at two-thirds of router forwarding capacity means that expected time to move a packet from source to destination for each route in the simulated topology is minimized when all three routes do not overlap (i.e. no node is used in more than one route). Each node has a non-zero time to forward and transmit a node to the next hop

on a route, so the first Warp-5 route discovery is free to select a node with the fewest hops between source and destination. The second Warp-5 route discovery will have to consider the effects of the first route when selecting a route that minimizes source-to-destination time. The third Warp-5 route discovery will have to consider the effects of the first two routes when selecting the route with the smallest source-to-destination time. Depending on the order in which the routes were created, the three routes may intersect and result in congested routers in the simulation topology.

Routers using AODV will always select the shortest visible route, which leads to intersecting routes and congested routers in the simulation topology, regardless of the order in which the routes were created. The nodes 15, 16 and 17 will be bottleneck nodes when the shortest route is selected for more than one of the desired routes.

Each simulation for this scenario runs for 300 (simulated) seconds.

6.3.3 Preventing Data Packet Loss Due To Noise

The third property to investigate is the prevention of data packet loss due to noise in the wireless network environment. The exploration scenario for this problem requires that multiple routes are established in a wireless topology simulation where the shortest path metric results in data packet loss due to proximity to a noise source. Warp-5 and AODV noise-avoidance simulations run on the square topology with an effective communication radius for all nodes of 10 meters. The nodes are placed so that the nearest neighbors are 9 meters away. The effect is that the transmission from a node reaches the neighbors above, below, left and right of the transmitting node.

The nodes in the noise-avoidance simulations are homogeneous with regard to packet forwarding capacity and routing queue size. There are six routes to establish and use during the simulations. The route discoveries for Node 1 to Node 6, Node 9 to Node 14 and Node 21 to Node 22 begin at the start for the simulation and the route discoveries for Node 7 to Node 8, Node 15 to Node 20 and Node 23 to Node 28 begin 1.0 seconds into the simulation. Each node generates data packets at a constant rate. A noise source is placed at the geometric center of the topology, between Nodes 11, 12, 17 and 18. The noise source is calibrated to cause a 50 percent loss of 500 byte packets transmitted at 6 Mbits/sec on links between Nodes 11,

12, 17 and 18. Two other less powerful noise sources are placed in two corners of the square topology. These sources are calibrated to cause a 10 percent loss of 500 byte data packets transmitted at 54 Mb/s on the links between the nearest nodes. Simulations run with four router/radio configurations: AODV on single-radio nodes, AODV on dual-radio nodes, Warp-5 on single-radio nodes and Warp-5 on dual-radio nodes. For each router/radio configuration, one simulation runs with the default transmission rate of 54 Mb/s, and another simulation runs with the default transmission rate of 6 Mb/s. The 54 Mb/s rate is the fastest 802.11g transmission rate, and it is the rate that is the least resilient to noise. The 6 Mb/s rate is the slowest 802.11g transmission rate, but it is the rate that is the most resilient to noise.

The performance issue explored in these simulations is how many application data packets actually arrive at their intended destination. Warp-5 is free to select alternate routes for any source-to-destination pair as needed using routing information from the RREQ/RREP packets not lost due to noise. AODV will always choose the shortest route constructible from the RREQ/RREP control packets not lost due to noise.

Each simulation for this scenario runs for 20 (simulated) seconds.

6.3.4 Responding To Noise To Minimize Data Packet Loss

The fourth property to investigate is the response to new noise sources and the minimization of data packet loss in the wireless ad hoc network. The exploration scenario for this problem requires multiple route discoveries in an initially noise-free wireless topology simulation environment. Once the routes were established and data traffic was moving through the network, multiple noise sources are then activated. Warp-5 and AODV noise-injection simulations run on the square topology with an effective communication radius for all nodes of 10 meters. The nodes are placed so that the nearest neighbors are 9 meters away. The effect is that the transmission from a node reaches the neighbors above, below, left and right of the transmitting node.

The nodes are homogeneous with regard to packet forwarding capacity and routing queue size. There are six routes to establish and use during the simulations. The route discoveries for Node 1 to Node 6, Node 9 to Node 14 and Node 21 to Node 22 begin at the start for the simulation and the route discoveries for Node 7 to Node 8, Node 15 to Node 20 and Node 23 to

Node 28 begin 1.0 seconds into the simulation. Each node generates data packets at a constant rate. A noise source is placed at the geometric center of the topology, between Nodes 11, 12, 17 and 18. The noise source is be calibrated to cause a 50 percent loss of 500 byte packets transmitted at 6 Mb/s on links between Nodes 11, 12, 17 and 18. Two other less powerful noise sources are placed in two corners of the square topology. These sources are calibrated to cause a 10 percent loss of 500 byte data packets transmitted at 54 Mb/s on the links between the nearest nodes. The three noise sources activate 4.0 seconds into the simulation. Simulations run with four router/radio configurations: AODV on single-radio nodes, AODV on dual-radio nodes, Warp-5 on single-radio nodes and Warp-5 on dual-radio nodes. For each router/radio configuration, one simulation runs with the default transmission rate of 54 Mb/s, and another simulation runs with the default transmission rate of 6 Mb/s. The 54 Mb/s rate is the fastest 802.11g transmission rate, but the least resilient to noise while the 6 Mb/s rate is the slowest 802.11g transmission rate, and the most resilient to noise.

The performance issue explored in these simulations is how many application data packets actually arrive at their intended destination. Warp-5 is free to select alternate routes for any source-to-destination pair as needed using routing information learned during the initial route discoveries. AODV will always choose the shortest routes between source and destination.

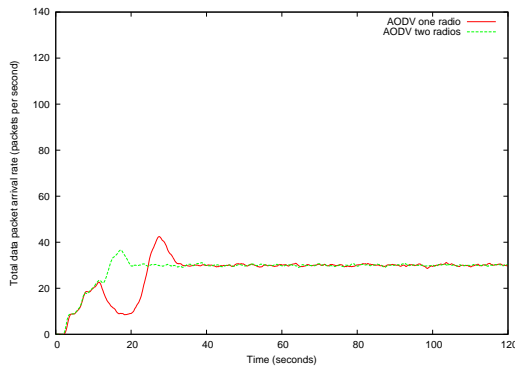
Each simulation for this scenario runs for 20 (simulated) seconds.

6.4 Simulation Results and Discussion

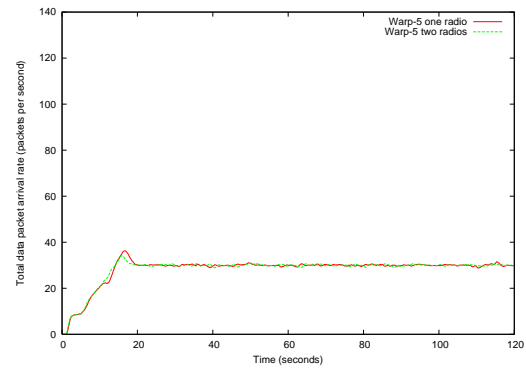
This section contains descriptions of the simulation results related to managing noise and congestion in wireless ad hoc networks. There are several problems explored in the simulations. The first problem concerns the prevention of data packet loss due to improper route construction. The second concerns the response to router congestion when it occurs. The third concerns the construction of routes in a noisy environment to minimize data packet loss, and the fourth concerns the response to noise that arises in the wireless environment after routes have been established.

6.4.1 Preventing Data Packet Loss Due To Router Congestion

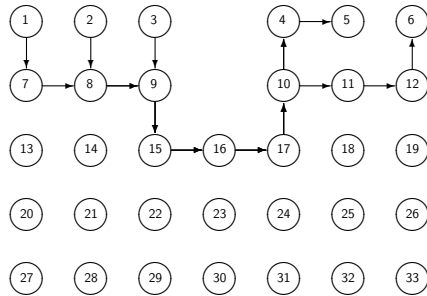
The objective of the congestion-avoidance simulations was to show that Warp-5 could effectively prevent router congestion and packet loss in wireless ad hoc networks. Figures 6.7, 6.8 and 6.9 plot application data packet arrival rate over time throughout the 120-second simulation runs. The packet arrival rate was sampled every 1/10 of a (simulated) second. Both Warp-5 and AODV used expanding ring searches with identical interval and time-to-live parameters to find initial routes. Each router forwarded packets as an exponential server with a mean service capacity of 50 packets per second (i.e. an average of 0.02 seconds between packets). For the low offered load simulations, each source node generated 500-byte data packets at a constant rate of 10 per second. For the medium offered load simulations, each source node generated 500-byte data packets at a constant rate of 20 per second. For the high offered load simulations, each source node generated 500-byte data packets at a constant rate of 33.33 per second.



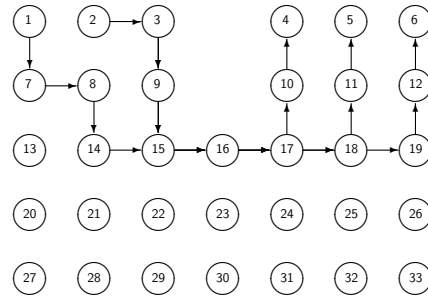
(a) AODV on single-radio and dual-radio nodes



(b) Warp-5 on single-radio and dual-radio nodes



(c) Typical AODV routes



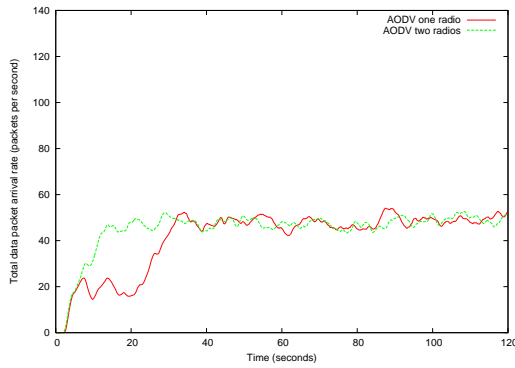
(d) Typical Warp-5 routes

Figure 6.7: AODV and Warp-5 Data Packet Arrival Rates For Low Offered Load Simulations

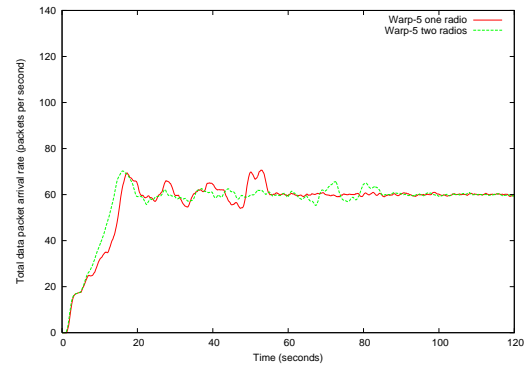
The plots of data packet arrival rates for three routes as a function of time are shown for AODV in Figure 6.7(a) and for Warp-5 in Figure 6.7(b) for the low offered load simulations using single-radio and dual-radio nodes. With the total offered load for the three routes being less than the router forwarding capacity, all three routes can share the shortest path from source to destination in Warp-5. For AODV, the shortest path was sufficient for all three routes without router congestion. All four router/radio configurations maintained a total data packet arrival rate of 30 packets per second in the 120-second simulation run. The route discovery for the third route under AODV on single-radio nodes conflicted with the surge of packets initially buffered from the second route, delaying the completion of the third route discovery briefly as visible in the figure. If the offered load is low enough, as they were in this simulation, Warp-5 selected the shortest route. Castle topologies for AODV in Figure 6.7(c) and for Warp-5 in Figure 6.7(d) show typical routes from the low offered load simulations. The routes selected by AODV and Warp-5 in the low offered load simulations deliver data packets at the same rate and are not significantly different.

The plots of data packet arrival rates for three routes as a function of time are shown for AODV in Figure 6.8(a) and for Warp-5 in Figure 6.8(b) for the medium offered load simulations using single-radio and dual-radio nodes. The total offered load for all three routes was 60 data packets per second. AODV chose the shortest path for all three routes, with some routers receiving data packets at a rate that exceeded their forwarding capacity of only 50 packets per second. With the medium offered load, AODV fell short of the offered load by 10 packets per second. For the Warp-5 simulations, the router forwarding capacity was high enough for Nodes 15, 16 and 17 to support the first two routes with minimal time cost. The third route did not intersect the previous two routes at all, resulting in a sustained data packet arrival rate that matched the offered load of 60 packets per second. Castle topologies for AODV in Figure 6.8(c) and for Warp-5 in Figure 6.8(d) show typical routes from the medium offered load simulations.

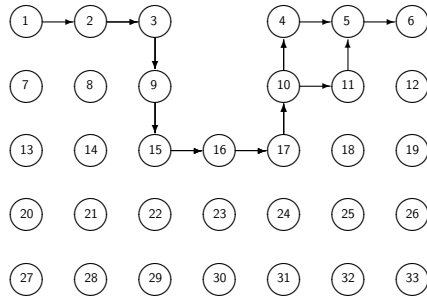
The plots of data packet arrival rates for three routes as a function of time are shown for AODV in Figure 6.9(a) and for Warp-5 in Figure 6.9(b) for the high offered load simulations using single-radio and dual-radio nodes. With each of the three routes requiring more than half of the router forwarding capacity, none of the three routes could share a router without



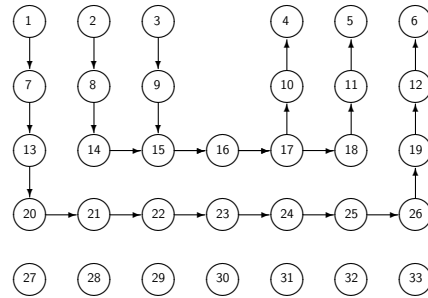
(a) AODV on single-radio and dual-radio nodes



(b) Warp-5 on single-radio and dual-radio nodes



(c) Typical AODV routes

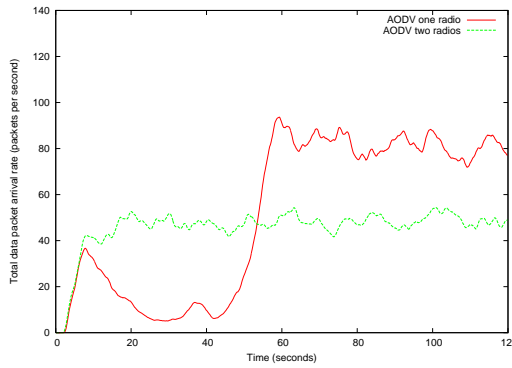


(d) Typical Warp-5 routes

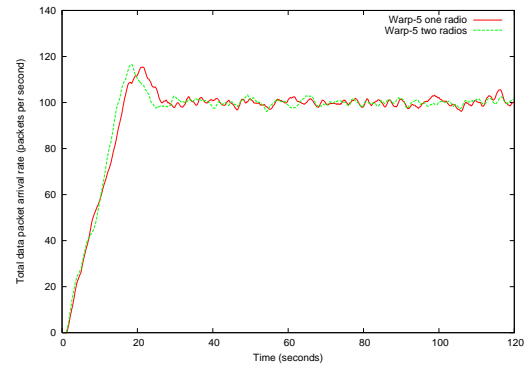
Figure 6.8: AODV and Warp-5 Data Packet Arrival Rates For Medium Offered Load Simulations

losing data packets. AODV on dual-radio nodes chose the shortest path for all three routes, with some routers receiving data packets at a rate that exceeded their forwarding capacity of only 50 packets per second. With the high offered load, AODV on dual-radio nodes lost data packets at a rate of 50 packets per second.

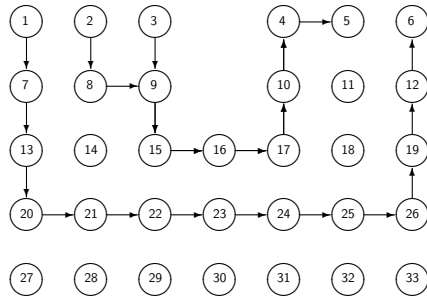
AODV on single-radio nodes actually outperformed AODV on dual-radio nodes. The offered load of the first two routes repeatedly thwarted route discovery attempts for the third route, reducing the total data packet arrival rate for almost 50 seconds into the simulation. The eventual completion of the third route discovery resulted in a route that did not share any nodes with those used by the first two routes. This example clearly illustrates how AODV implicitly handles congestion. AODV interpreted the highly congested routers as “down” during the third route discovery and appropriately found a route that avoided the congested routers.



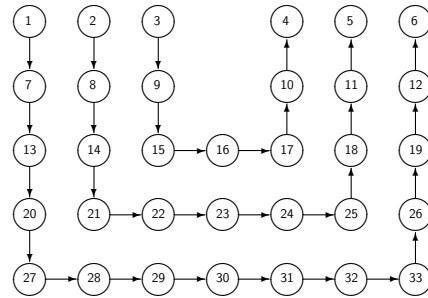
(a) AODV on single-radio and dual-radio nodes



(b) Warp-5 on single-radio and dual-radio nodes



(c) AODV routes (single radio)



(d) Warp-5 routes (single- and dual-radio)

Figure 6.9: AODV and Warp-5 Data Packet Arrival Rates For High Offered Load Simulations

However, because the handling of router congestion is implicit, the use of a second radio actually makes route discovery worse—AODV wouldn't notice that some routers are congested and would continue to assign new routes to congested routers. By explicitly measuring and considering congestion delays, Warp-5 much more adeptly handled the router congestion.

The total data packet arrival rate for these three routes was 83.33 data packets per second, falling short of the offered load by 16.66 data packets per second, but single-radio AODV still outperformed AODV on dual-radio nodes. Warp-5 managed the high offered loads by finding separate routes that did not share any nodes. The dual-radio configuration of Warp-5 found the three routes slightly faster than Warp-5 on single-radio nodes, but both Warp-5 configurations found routes whose total data packet arrival rate matched the total offered load of 100 data packets per second without data loss. Castle topologies for AODV in Figure 6.9(c) and for Warp-5 in Figure 6.9(d) show typical routes from the high offered load simulations.

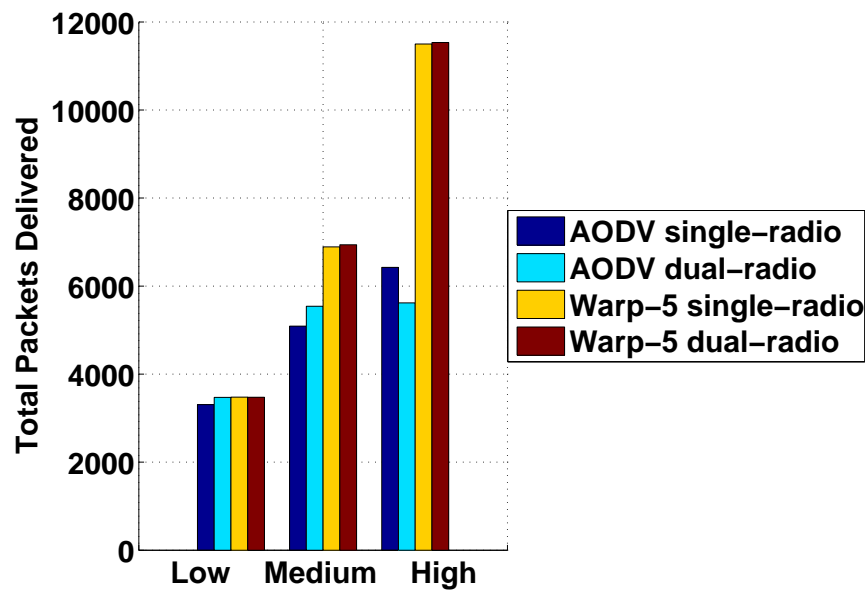


Figure 6.10: Preventing Router Congestion.

The results of the individual congestion-avoidance simulations for both protocols using single-radio and dual-radio nodes are shown in Figure 6.10. The vertical axis is the number of application data packets delivered during the simulation. AODV and Warp-5 on single-radio nodes and dual-radio nodes delivered about the same number of data packets in the low load simulations. With the offered load of each route requiring only 10 packets per second, the use of single- or dual-radio nodes was not significant for either protocol. In the medium offered load simulations, AODV added a third route that intersected the previous routes, resulting in router congestion and data packet loss. Warp-5 outperformed AODV by adding a third route that did not compete with the previous routes for router resources. AODV on single-radio nodes outperformed AODV on dual-radio nodes in the high load simulations, but both were outperformed by Warp-5 on single-radio nodes or dual-radio nodes. By learning the router forwarding time cost of previously established routes, Warp-5 was able to use this information to select sensible routes that could deliver data packets at the same rate they were offered in all three situations.

The results of the congestion-avoidance experiments shows the feasibility and usefulness of learning router forwarding time cost from recent experience with current network conditions in

avoiding router congestion in wireless ad hoc networks and improving distributed application throughput consistent with the thesis of this dissertation.

6.4.2 Responding To Router Congestion To Minimize Data Packet Loss

The objective of the congestion-response simulations was to show that Warp-5 could effectively respond to router congestion bottlenecks as they arise in wireless ad hoc networks. Figures 6.11 and 6.12 plot application data packet arrival rate over time throughout the 300-second simulation runs. The packet arrival rate was sampled every 1/10 of a (simulated) second. Both Warp-5 and AODV used expanding ring searches with identical interval and time-to-live parameters to find initial routes. Each source node generated data packets at a constant rate of 33.33 packets per second (0.03 seconds between packets). Each router forwarded packets as an exponential server with a mean service capacity of 50 packets per second (0.02 seconds between packets).

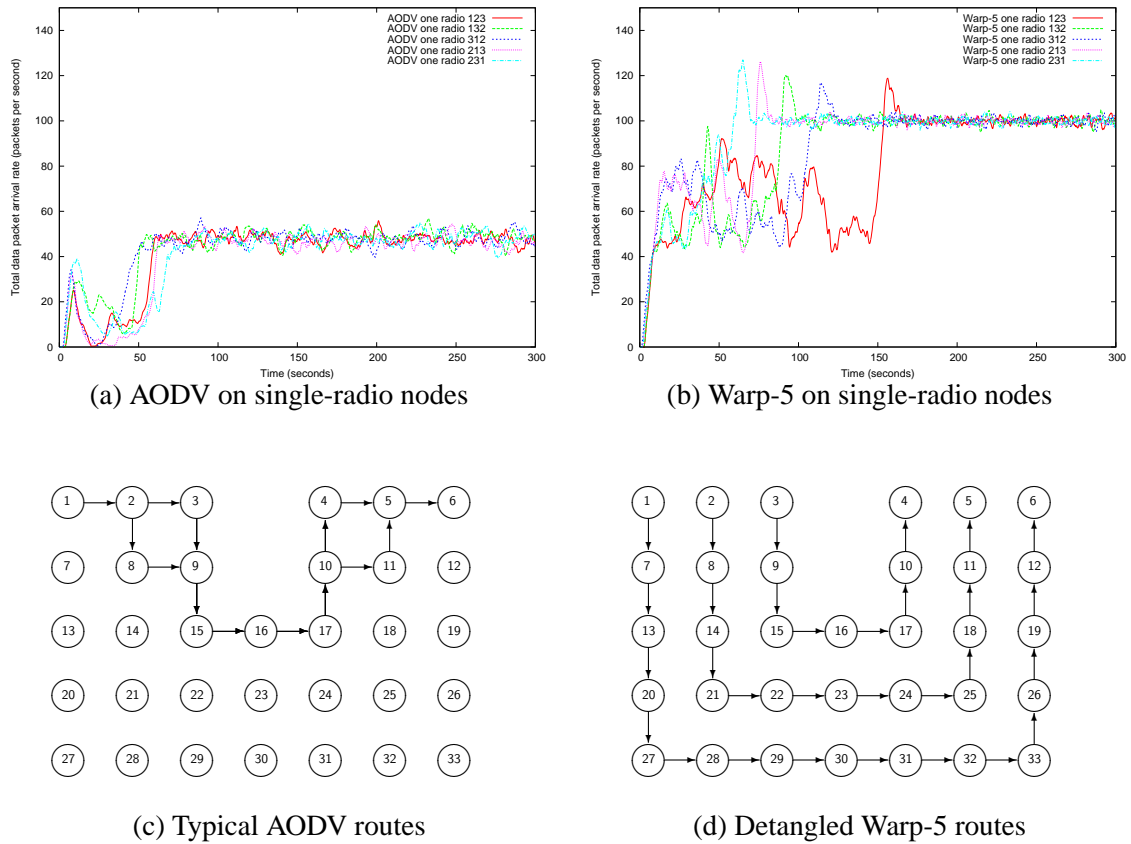


Figure 6.11: AODV and Warp-5 Data Packet Arrival Rates For Router Congestion Problems (single-radio nodes).

The total data packet arrival rates as a function of time are plotted for five router congestion tests for AODV on single-radio nodes in Figure 6.11(a). In the AODV simulations, one test found a route within a couple of seconds and started sending buffered packets through the network at the maximum forwarding rate of 50 packets per second. The application packet arrival rate for this test and the other five tests was quickly reduced by the loss of application data packets due to route discovery packets contending for the same router input queues. The tests took between 40 and 60 seconds to find routes for all three source-destination pairs. The delay in some of the tests finding the right route was the result of repeated thwarted attempts due to the inability to get RREQ and RREP packets past the congested routers. The result is a data packet arrival rate plot that is far below the expected rate of 50 packets per second for much of the simulation. The castle topology of Figure 6.11(c) shows the routes for the single-radio AODV simulations.

Figure 6.11(b) shows the simulation results for Warp-5 on single-radio nodes. With congested routers, detangling RREQ and RREP packets either took longer to move through the network or got dropped by some nodes, which slowed the detangling process. The route detangling caused the high variability in data packet arrival rates in the early part of the simulation. One of the five tests, actually had the routes detangled correctly a few seconds into the simulation, but because it lacked sufficient experience to estimate how long it took packet arrival rates to stabilize after a route change, prematurely continued to change routes and continued detangling until it returned to the correct route detangling about 150 seconds into the simulation. Once routes were detangled, the average data packet arrival rate became consistent with the data packet generation rate of 100 data packets per second. The remaining variability after the route detangling was due to the exponential service process of the routers. The castle topology of Figure 6.11(d) shows the detangled routes for the single-radio Warp-5 simulations.

The total data packet arrival rates as a function of time are plotted in Figure 6.12(a) for five router congestion tests for AODV using dual radios. In the AODV simulations, route discovery is much faster with all three routes in all five tests completed in the first 10 seconds because the RREQ and RREP packets could move through the network without contention from data packets for router input queues. The variability in application data packet arrival rates once routes were established is due to the exponential service function in the router forwarding

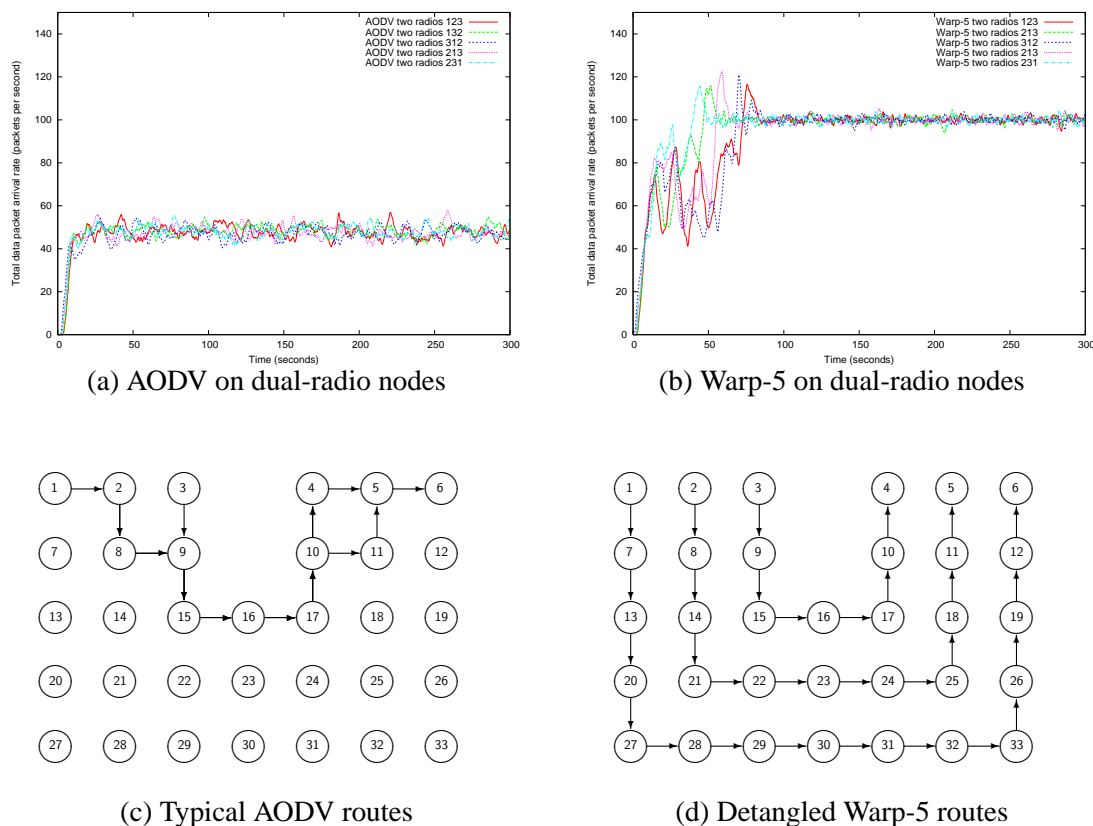


Figure 6.12: AODV and Warp-5 Data Packet Arrival Rates For Router Congestion Problems (dual-radio nodes).

times. AODV on dual-radio nodes found the same routes as AODV on single-radio nodes, but the dual-radio configuration performed better because the RREQ and RREP packets could move through the network faster on dual-radio nodes. The castle topology of Figure 6.12(c) shows the routes for the dual-radio AODV simulations.

Figure 6.12(b) shows the results for Warp-5 using dual radios. With the ability to move RREQ and RREP packets through the network unaffected by congested data input queues, all five tests found stable routes faster than Warp-5 on single-radio nodes. Stable routes with a total packet delivery rate of 100 data packets per second took between 11 and about 70 seconds to find, including time for initial route discovery. The higher variability in data packet arrival rates between 10 and about 70 seconds is due to changing routes during detangling as the network tried different routes. Any variation after that point in time is due to exponential service rates in the individual routers. The castle topology of Figure 6.12(d) shows the detangled routes for the dual-radio Warp-5 simulations.

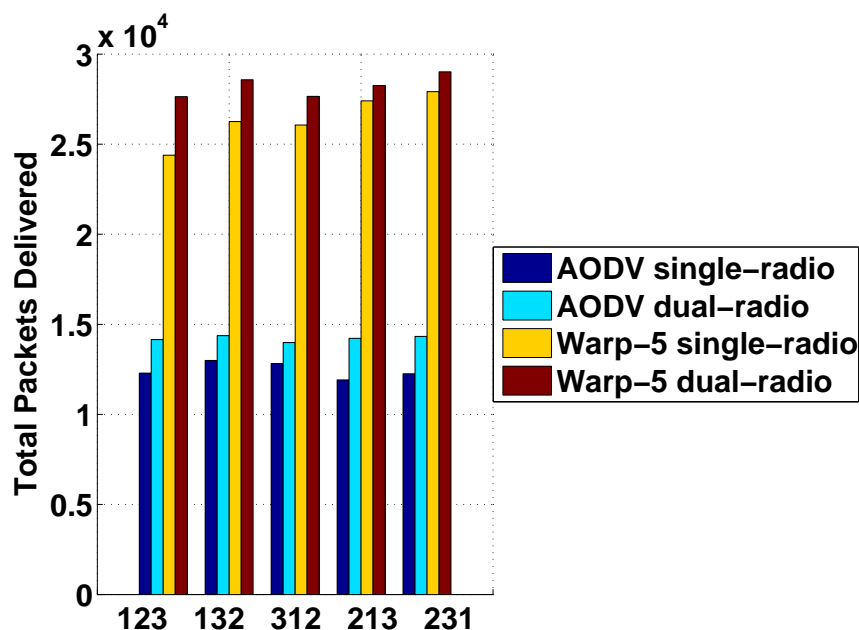


Figure 6.13: Adjusting to Router Congestion.

The results of the individual congestion-response simulations for both protocols using single and dual radios are shown in Figure 6.13. The vertical axis is the number of application data packets delivered during each simulation. The horizontal axis identifies the order of route discovery in each test. AODV with dual radios slightly outperforms AODV on single-radio nodes because the route discoveries were not affected by previous traffic in the dual-radio configuration. AODV with either radio configuration found the shortest route between source and destination regardless of existing data traffic. Warp-5 on single-radio nodes outperformed AODV in all five test cases, demonstrating that the detangling algorithm works even when the propagation of RREQ and RREP packets is hampered by congested routers. Warp-5 on dual-radio nodes consistently outperformed Warp-5 on single-radio nodes and AODV with single- or dual-radios.

The superior performance of Warp-5 is attributable to its ability to learn and respond. Routers learn the order in which routes were created and share different (pretended) route creation orders during detangling to coordinate detangling efforts within the ad hoc network. Individual routers learn their own data packet arrival rates from recently received unicasts, and when congested, can alter routes as needed. Routers also learn an estimate of how long it takes

for a route alteration to stabilize with the ad hoc network as part of the coordinated route detangling effort. Warp-5 learned from recent learned experience with route creation and congestion levels to deal with router congestion in a heavily-used network environment.

The results of the congestion-response experiments shows the feasibility and usefulness of learning router forwarding time cost from recent experience with current network conditions to adjust existing routes in wireless ad hoc networks to correct for router congestion and improve distributed application throughput consistent with the thesis of this dissertation.

6.4.3 Preventing Data Packet Loss Due To Noise

The purpose of the noise-avoidance simulations was to show that Warp-5 could minimize data packet loss by building routes for an ad hoc network operating in a noisy environment. Figures 6.14 and 6.15 plot application data packet arrival rate throughout the 20-second simulation runs. The packet arrival rate was sampled every 1/10 of a (simulated) second. Both Warp-5 and AODV used expanding ring searches with identical interval and time-to-live parameters to find initial routes. Each source node generated data packets at a constant rate of 33.33 packets per second (i.e. 0.03 seconds between packets). Each router forwarded packets as an exponential server with a mean service capacity of 10,000 packets per second (i.e. 0.0001 seconds between packets), which allowed the routers to potentially share all the routes in the square topology without becoming congested. The simulations remain valid because the combined offered load of all routes did not approach the maximum packet flow rate for any unicast transmission rate, much less the high forwarding rate of the routers.

Figure 6.14(a) shows the simulation results for AODV where the default transmission rate was 54 Mbits/sec. AODV on single- or dual-radio nodes performed poorly because the 54 Mbits/sec transmission rate was very susceptible to noise. The single-radio configuration was able to establish and use only two of the six routes. The powerful noise source at the center of the topology prevented the completion of most of the route discoveries due to loss of RREQ and RREP packets. The dual-radio configuration was able to establish all six routes, but the routes were built using the shortest path metric, which resulted in routes passing near the powerful central noise source and significant loss of data packets due to that proximity. The data packet delivery rate for AODV in either configuration was only 7 to 10 packets per second out of a

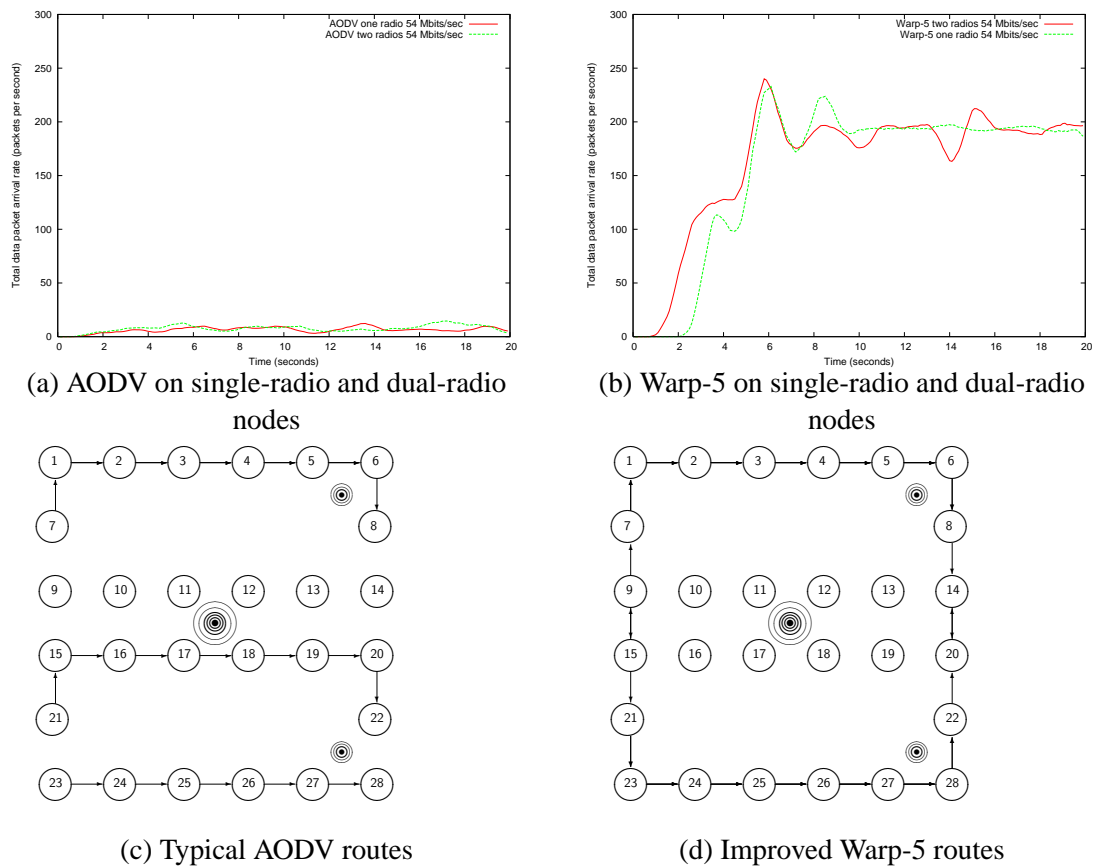


Figure 6.14: AODV and Warp-5 Data Packet Arrival Rates For 54 Mbits/sec in a noisy environment.

total offered load of 200 packets per second. The square topology of Figure 6.14(c) shows the routes for the single-radio and dual-radio AODV simulations for the 54 Mbits/sec transmission rate.

The simulation results for Warp-5 using a default transmission rate of 54 Mbits/sec appear in Figure 6.14(b). Warp-5 was able to establish all six routes despite the noise, although the dual-radio configuration did so slightly faster than the single-radio configuration. In both cases, Warp-5 raised the data packet arrival rate to match the offered load of 200 packets per second. It did so by finding better unicast transmission rates and selecting better next hops from experience gained during forwarding. The improved data packet arrival rate continued to vary throughout the remainder of the simulation. The square topology of Figure 6.14(d) shows the improved routes for the single-radio and dual-radio Warp-5 simulations for the 54 Mbits/sec transmission rate.

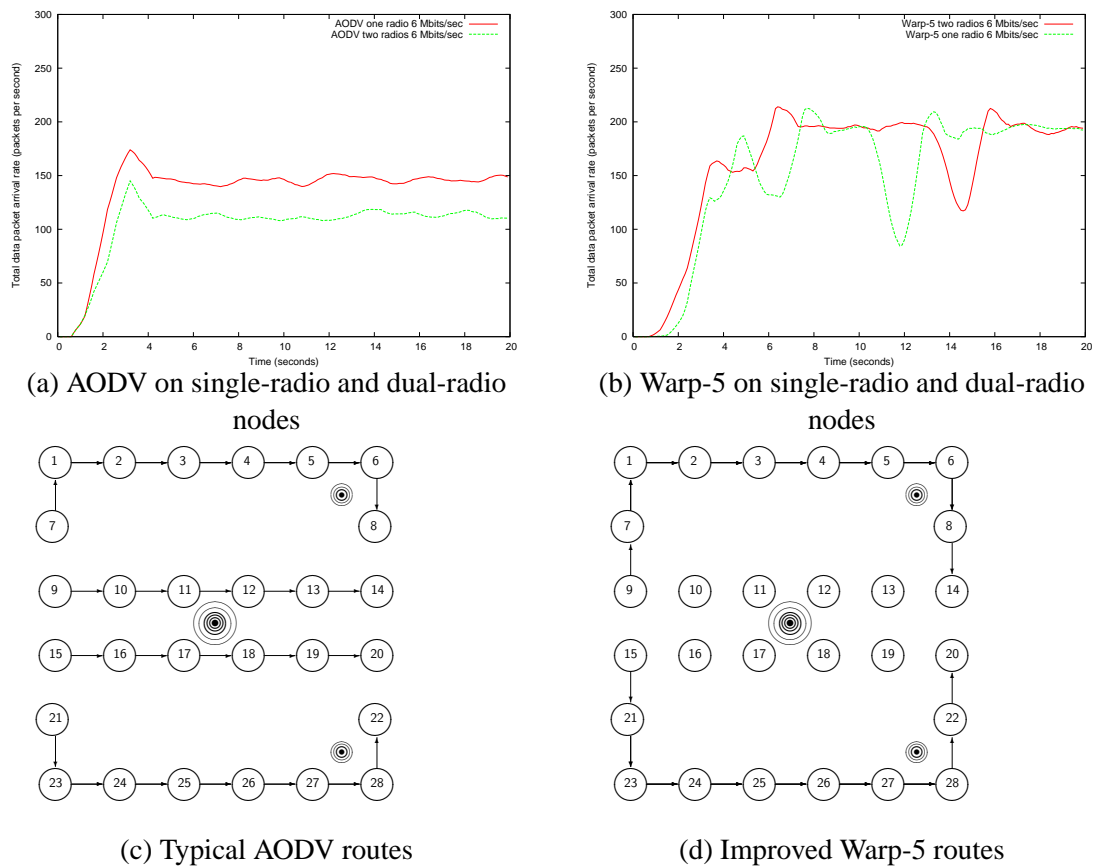


Figure 6.15: AODV and Warp-5 Data Packet Arrival Rates For 6 Mbits/sec in a noisy environment.

Figure 6.15(a) shows the simulation results for AODV where the default transmission rate was 6 Mbits/sec. AODV on single-radio nodes was able to establish all six routes, but two of the routes were in close proximity to the powerful noise source at the center of the topology, which resulted in the loss of half the packets on those two routes. The total data packet arrival rate for AODV on single-radio nodes was about 150 packets per second. AODV on dual-radio nodes also established all six routes, but three of the routes were near the central noise source and half the data packets on three routes were lost, which reduced the data packet arrival rate to less than the rate experienced with the AODV single-radio simulation. The reduced data packet arrival rate experienced in the dual-radio AODV simulation was due to the poor arbitrary choice of three routes with nodes in close proximity to the central noise source and is not related to the use of single- or dual-radio nodes. The square topology of Figure 6.15(c) shows the routes for the single-radio and dual-radio AODV simulations for the 6 Mbits/sec transmission rate.

The Warp-5 plots of Figure 6.15(b) shows the higher data packet arrival rate for Warp-5 with single- or dual-radio nodes. Warp-5 on single-radio nodes was able to establish all six routes, and raised the data packet arrival rate to 200 data packets per second by finding better unicast transmission rates and selecting better next hops from experience gained during packet forwarding. The improved data packet arrival rate continued to vary throughout the remainder of the simulation. Warp-5 on dual-radio nodes was able to establish routes somewhat faster using the second radio and succeeded in establishing all six routes and raising the data packet arrival rate to about 200 packets per second to match the total offered load. The data packet arrival rate also continued to vary throughout the remainder of the simulation. Figure 6.15(c) shows the routes for the single-radio and dual-radio Warp-5 simulations for the 6 Mbits/sec transmission rate in the square topology.

Both the AODV plots show a stable data packet arrival rate, while the Warp-5 plots are more variable. The intermittent drops and rises in the Warp-5 data packet arrival rates are caused by random and transient asymmetries between the data packet arrival rate and the data packet forwarding rate at the MAC layer for nodes in the wireless network. Such an asymmetry may arise when there are many packets arriving at an intermediate wireless node with a high forwarding rate. In forwarding a packet to the next hop, the MAC 802.11 random exponential backoff used to control access to the communications medium sometimes chooses a large backoff counter, which means a longer wait to transmit the packet to the next hop. The simultaneous arrival of many packets to the same node during the backoff would delay the decrementing of the backoff counter, further preventing the forwarding transmission while incoming packets continue to arrive and get added to the outgoing packet queue in the MAC card. The MAC outgoing packet queue would quickly fill to capacity and further outgoing packets would get dropped at the MAC layer. The delay in transmitting the packet at the front of the queue appears as a drop in the data packet arrival rate in the Warp-5 plots. Eventually, the MAC layer does transmit the packet and succeeds in transmitting the other packets in the queue quickly because of small random backoff counters used for the later packets. This effect appears in the plots as the immediately following increases in data packet arrival rates. Unfortunately, because data packets were dropped from the outgoing MAC queue, the subsequent increases in data packet transmissions from the node never compensate for the lost packets, which reduces the total

number of data packets delivered to their destination node. These MAC-level asymmetries occur randomly and are transient. They do not become less likely over time.

The AODV and Warp-5 routers used the same MAC layer implementation, but the AODV simulations did not suffer from this random asymmetry because none of the AODV simulations ever sent a high enough offered load through any intermediate nodes to experience the effect. The AODV simulations never sent the traffic for more than two routes through any intermediate node. The Warp-5 simulations sent as many as four routes of traffic through some intermediate nodes to avoid noise. The internal forwarding speed of the routers was more than fast enough to handle the offered load from all six routes, but the offered load from as few as three routes was sufficient to cause the asymmetry to occur in the simulations.

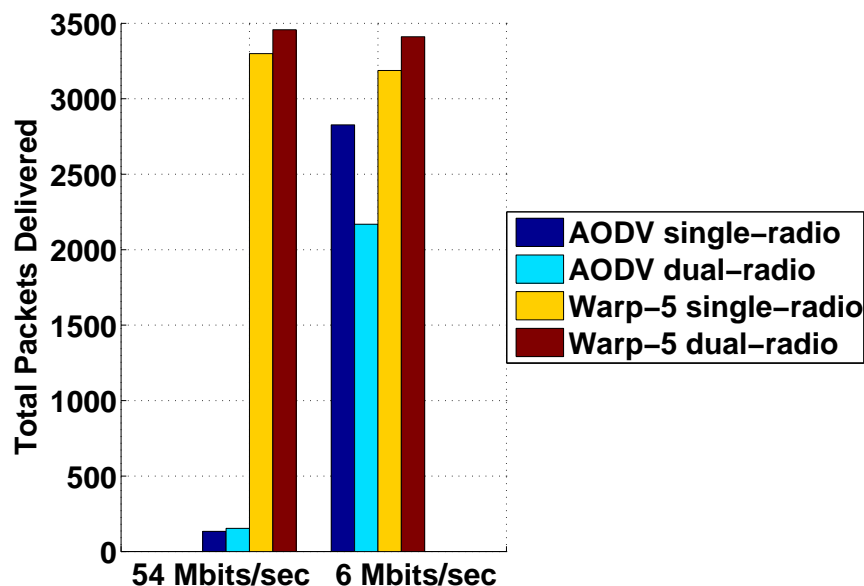


Figure 6.16: Preventing Data Packet Loss In Noisy Environment

The results of the individual noise-avoidance simulations for both protocols using 6 Mbits/sec and 54 Mbits/sec as the default transmission rate are shown in Figure 6.16. The vertical axis is the number of application data packets delivered over the course of the simulation. The horizontal axis identifies the initial (or for AODV, fixed) link-level transmission rate. AODV on single-radio nodes outperforms AODV on dual-radio nodes for the slowest and most noise-resilient transmission rate, because of the effects of noise on route discovery. AODV with the

fastest transmission rate performed the worst, on single-radio nodes or dual-radio nodes. Warp-5 used the ability to make routing decisions based on recent learned experience with link-level unicasts to outperform AODV overall in dealing with multiple heterogeneous noise sources in the communication environment, despite the occasional transient asymmetry between packet arrival rate and packet forwarding rate.

The results of the noise-avoidance experiments shows the feasibility and usefulness of learning link-level time cost from recent experience with recent link-level unicasts in avoiding noisy links in wireless ad hoc networks to improve distributed application throughput consistent with the thesis of this dissertation.

6.4.4 Responding To Noise To Minimize Data Packet Loss

The purpose of the noise-injection simulations was to show that Warp-5 could minimize data packet loss by making better routing decisions for a wireless ad hoc network when noise is introduced into the wireless environment. Figures 6.17 and 6.18 plot application data packet arrival rate throughout the 20-second simulation runs. The packet arrival rate was sampled every 1/10 of a (simulated) second. Both Warp-5 and AODV used expanding ring searches with identical interval and time-to-live parameters to find initial routes. Each source node generated data packets at a constant rate of 33.33 packets per second (i.e. 0.03 seconds between packets). Each router forwarded packets as an exponential server with a mean service capacity of 10,000 packets per second (i.e. 0.0001 seconds between packets), which allowed the routers to potentially handle the total offered load of all the routes in the square topology without becoming congested.

Figure 6.17(a) shows the simulation results for AODV where the default transmission rate was 54 Mbits/sec. In both the single- and dual-radio configurations, the data packet arrival rates for both protocols were identical, briefly leveling off at 200 data packets per second before the noise sources were activated 4.0 seconds into the simulation. The data packet arrival rates for AODV dropped off sharply when the noise sources became active, delivering only 7 to 10 data packets per second out of a total offered load of 200 data packets per second. The dramatic drop off in data packet arrival rates in the AODV simulations is due to the consistent use of 54 Mbits/sec as the only unicast transmission rate, which was the most susceptible to noise.

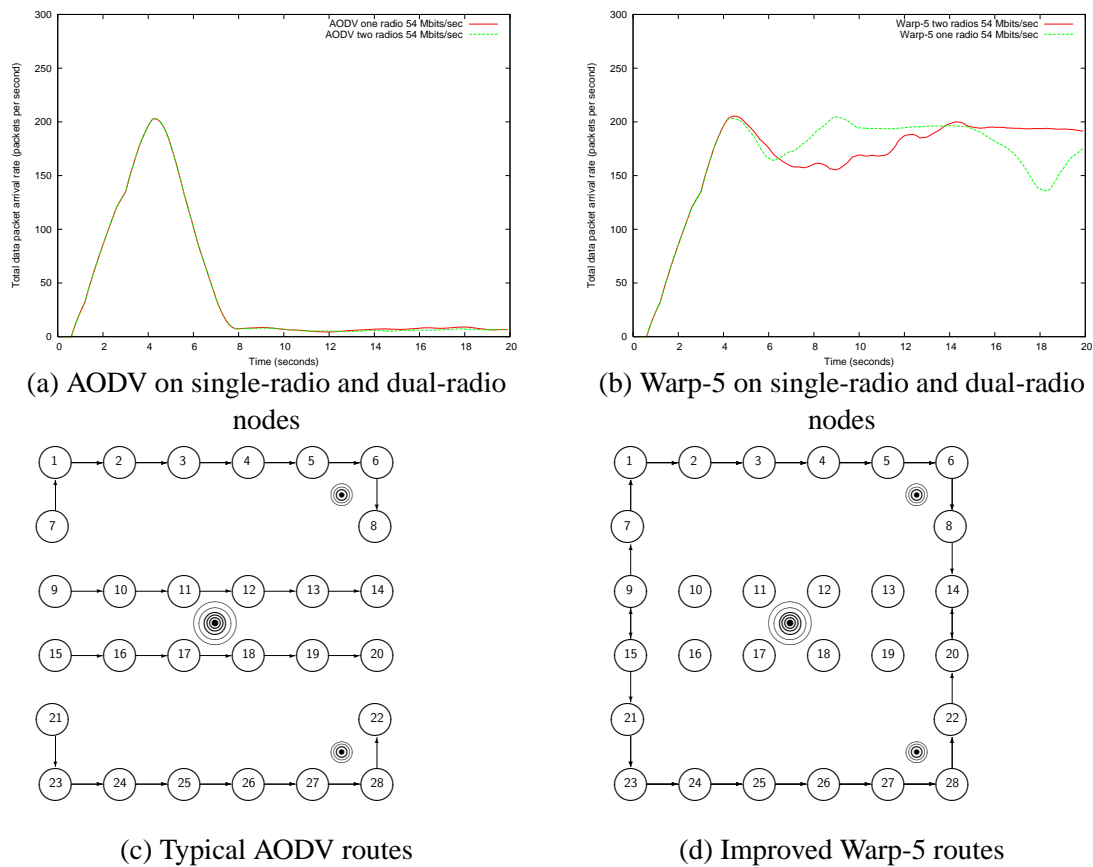


Figure 6.17: AODV and Warp-5 Data Packet Arrival Rates For 54 Mbits/sec Response to Noise.

The powerful noise source at the center of the topology caused most of the data packet losses. The simulation results for Warp-5 shown in Figure 6.17(b) also reflect a change in data packet arrival rates when the noise sources became active. Warp-5 adapted to the new noise sources by changing unicast transmission rates and making different routing decisions through links less affected by noise. The Warp-5 plots show the data packet arrival rate returning to a level near 200 data packets per second, close to the total offered load. The variability in the Warp-5 plots is explained by occasional transient asymmetry between packet arrival rate and packet forwarding rate of intermediate nodes. The square topology of Figure 6.17(c) shows the routes for the single-radio and dual-radio AODV simulations for the 54 Mbits/sec transmission rate.

Figure 6.18(a) shows the simulation results for AODV where the default transmission rate was 6 Mbits/sec. In both the single- and dual-radio configurations, the data packet arrival rates for both protocols were identical, briefly leveling off at 200 data packets per second before the noise sources were activated 4.0 seconds into the simulation. The data packet arrival rates for

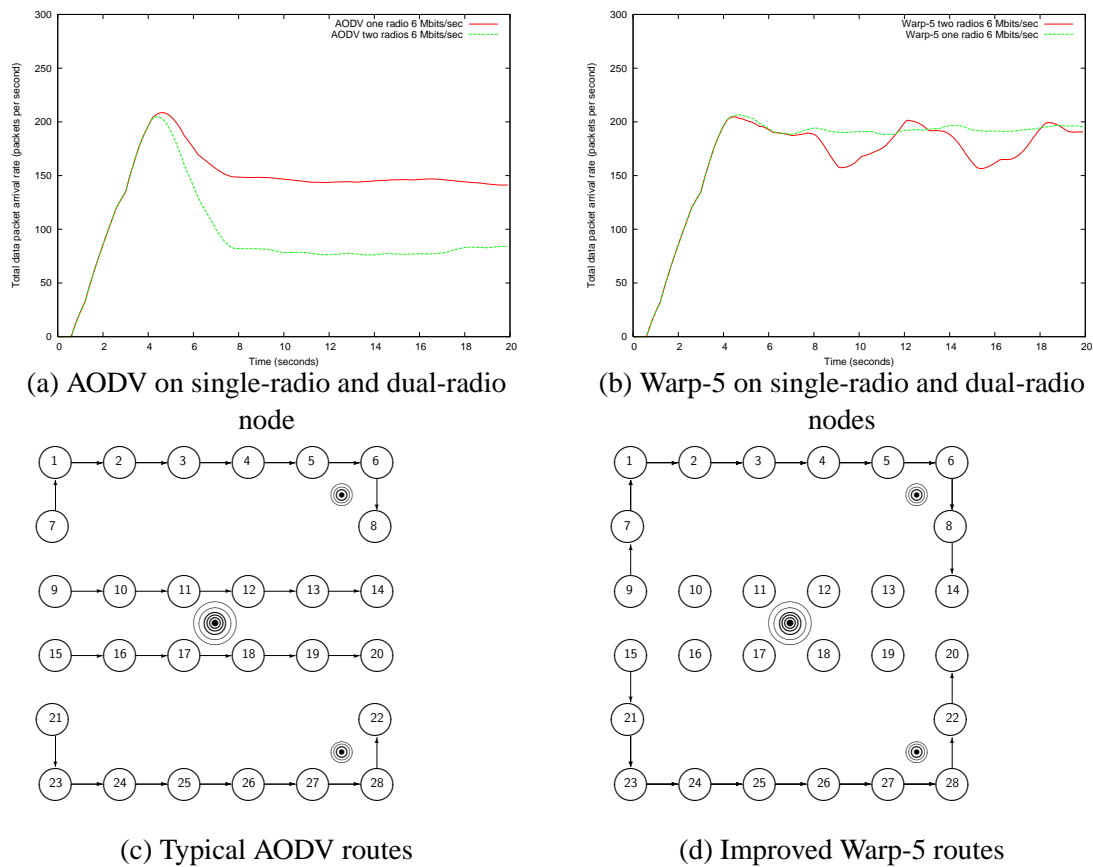


Figure 6.18: AODV and Warp-5 Data Packet Arrival Rates For 6 Mbits/sec Response to Noise.

AODV dropped off less sharply when the noise sources became active, delivering only half of the packets passing through routes near the powerful noise source in the center of the square topology. The total data packet arrival rate after the noise sources were activated in the AODV simulations was around 150 data packets per second out of a total offered load of 200 data packets per second. The reduction in the data packet arrival rate corresponds to the calibrated strength of the central noise source and the use of 6 Mbits/sec as the unicast transmission rate for AODV. The powerful noise source at the center of the topology caused most of the data packet losses in the 6 Mbits/sec simulations. The simulation results for Warp-5 shown in 6.18(b) also reflect a change in data packet arrival rates when the noise sources became active. Warp-5 adapted to the new noise sources by changing unicast transmission rates and making different routing decisions through links less affected by noise. The Warp-5 plots show the data packet arrival rate returning to a level near 200 data packets per second, close to the total offered load. The variability in the dual-radio Warp-5 plot is due to two occurrences of the transient

asymmetry between packet arrival rate and packet forwarding rate of intermediate nodes. The square topology of Figure 6.17(d) shows the routes for the single-radio and dual-radio Warp-5 simulations for the 54 Mbits/sec transmission rate.

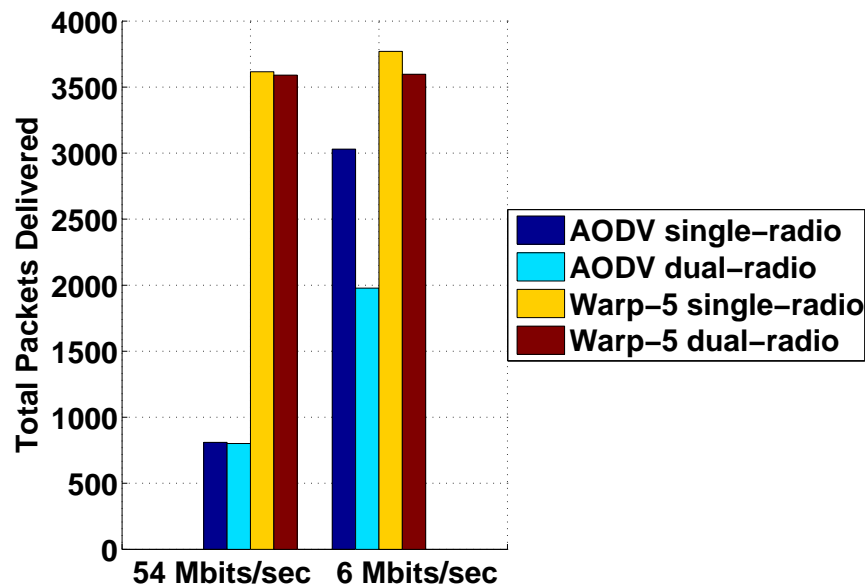


Figure 6.19: Adjusting to Noise.

The results of the individual noise-injection simulations for both protocols using 6 Mbits/sec and 54 Mbits/sec as the default transmission rate are shown in Figure 6.19. The vertical axis is the total number of data packets delivered during the simulations. The horizontal axis identifies the initial (or for AODV, fixed) link-level transmission rate. AODV using the least noise-resilient rate of 54 Mbits/sec suffered the worst performance, using either single- or dual-radio nodes. AODV was more successful using the most noise-resilient transmission rate of 6 Mbits/sec using either single- or dual-radio nodes, but was still unable to adapt to the new noise conditions. Warp-5 offered better performance than any AODV configuration, because of the ability to change transmission rates and routes in response to noise. The experiments show that Warp-5 on single-radio nodes offered slightly better performance than Warp-5 on dual-radio nodes in responding to new noise sources, but the outcomes cannot be considered conclusive because of transient MAC-level arrival and forwarding asymmetries that occurred during the simulations. What is clearer from these experiments is that Warp-5 on single- or dual-radio

nodes used the ability to make transmission rate and routing decisions based on recent learned experience with link-level unicasts to outperform AODV overall in dealing with the introduction of multiple heterogeneous noise sources into the wireless environment.

The results of the noise-response experiments shows the feasibility and usefulness of learning link-level time cost from recent experience with recent link-level unicasts to adjust routes as noise sources are introduced into wireless ad hoc networks to improve distributed application throughput consistent with the thesis of this dissertation.

6.5 Summary and Key Findings

The simulations presented in this chapter were designed to show that the learning capabilities of Warp-5 are useful and feasible in managing noise and router congestion in wireless ad hoc networks. The congestion-avoidance simulations showed that Warp-5 could prevent the loss of application data packets by constructing routes that avoided congested routers and minimized the time taken to get packets through the wireless network in an environment where the routers were congested. The congestion-response simulations showed that the novel Warp-5 detangling algorithm could correct router congestion by making new routing decisions that selectively considered or ignored the effects of other routes in the network and by observing the effects of individual route changes on the network. The noise-avoidance simulations showed that Warp-5 could build routes in a wireless ad hoc network that avoided existing noise sources and in so doing, prevent the loss of application data packets moving on those routes. The noise-injection simulations showed that Warp-5 could respond to the introduction of new noise sources in a wireless environment by making different forwarding decisions based on information gained from experience from the effects of noise sources on link-level unicasts.

The properties investigated in this work that affect data throughput in wireless ad hoc networks are noise and router congestion. The approach to minimizing the effects of noise and router congestion has been to apply machine learning techniques to how routes are formed and how forwarding decisions are made. The key findings of this work are as follows:

The time-based routing metric introduced in Section 3.6 has been demonstrated to be useful in making routing decisions in wireless ad hoc networks that are superior to the classic shortest

path routing metric. Combining the probability of packet loss and unicast transmission time as effects of noise with router overhead into a single metric allowed routers to avoid data packet loss from router congestion and noise as well as to respond effectively to router congestion and new noise sources that occur in wireless networks.

A “detangling” algorithm that alleviates router congestion by iteratively changing one route at a time in a wireless ad hoc network works in simulated topologies that may reflect real-world situations where nodes need to communicate through intermediate nodes in challenging environments. The selective use of recent router overhead information for some routes while deliberately ignoring the same information for other routes allows an ad hoc wireless network to solve its own congestion problems and minimize the loss of data packets.

The ad hoc network using Warp-5 acts as a distributed agent in responding to router congestion. Individual nodes may experience congestion, but the detangling actions acting on the network as a whole are coordinated through the route ordering information contained in the detangling RREQ packets.

The detangling algorithm will work in less-than-ideal environments, as shown in the congestion experiments using only single-radio nodes. Not all the nodes in the vicinity of the congested router(s) have to get the detangling RREQ and RREP packets to make the detangling work to alleviate router congestion. Perfect communication of detangling control packets is not a requirement for the successful alleviation of router congestion.

The action taken by a node to alleviate router congestion may or may not have an effect that becomes apparent to the node. RREQ and RREP packets have to propagate through the network, routers in the nodes have to change their forwarding choices and other nodes have to notice the changes in offered load for specific routes. All of these things take time, and knowledge of how long these things take is critical. Waiting too long allows data packets to get dropped by congested routers when further corrective action could be taken. Acting too soon will result in either changing routes that don’t need to be changed or changing routes based on transient conditions that do not reflect the stable state of the ad hoc network. The router congestion experiments have demonstrated that routers can learn an estimate of the time between the initiation of a detangling action and the time the route actually changes to a new stable state to make distributed multi-step detangling actions work effectively.

The individual node is the agent in managing noise. Experience with recent link-level unicasts, whether successful or otherwise, is used as part of the dynamically calculated routing metric used to make forwarding decisions. These decisions are made within the node and are not distributed. Forwarding decisions based on noise experience are therefore faster than the distributed actions taken to alleviate router congestion.

Nodes that use one radio to transmit data packets and another radio to transmit routing control packets can propagate the routing control information faster and more effectively than routers using only one radio for both. The result is shorter latency between the initial route discovery broadcast and the availability of a viable route. This property has been shown to be true for both AODV and Warp-5. However, a routing protocol that uses the shortest path routing metric will work better on single-radio nodes in a noisy or congested environment, because the routing control packets tend to get lost near noise sources or dropped by congested routers, which results in routes that do not go near the affected nodes.

Random and transient asymmetries between data packet arrival rates and packet forwarding rates at the MAC layer may cause a loss of data packets in an intermediate node when the data packet arrival rate is high enough. Increasing the internal forwarding speed of the routers does not alleviate the problem, instead it increases the likelihood of occurrence. These asymmetries are an artifact of the 802.11 Distributed Coordination Function (DCF).

Chapter 7

Current Status and Future Work

Wireless ad hoc networks can be formed from any number of available nodes and can be tailored to a wide variety of specific applications in home, industrial or military environments. Wireless ad hoc networks can be rapidly deployed and reconfigured without the installation and maintenance costs of a network infrastructure. Due to their distributed nature, wireless ad hoc networks can withstand node loss or communication failure in hostile environments, whether due to battlefield scenarios, disaster relief situations, potentially hazardous industrial environments, or even benign causes of failure.

The strengths of wireless ad hoc networks that make them so versatile must be contrasted with the weaknesses inherent in wireless communication. Wireless links are susceptible to noise or interference, which undermines the reliability of communication between nodes. The physical layer defines how bits in messages are able to be represented and transmitted. Medium access control protocols determine when nodes in the network can transmit messages to other nodes. Wireless links do not have the capacity to match their wired counterparts, thus while processor speed has continued to increase, it is the constraints of the physical and MAC layers that determine the data packet forwarding capabilities of a wireless ad hoc network. Distributed applications that exchange large amounts of video, audio or sensor data between nodes in a wireless ad hoc network need to make the best use of the available router capabilities. The need to exchange of large amounts of data through wireless links emphasizes the importance of well-constructed routes in a wireless ad hoc network.

The Warp-5 routing protocol was designed to manage noise and router congestion in wireless ad hoc networks with the goal of minimizing the time data packets spend between source and destination nodes. Warp-5 accomplishes its goal by decomposing the task into a set of

learning problems and corresponding optimization algorithms. The time to complete a link-level unicast and the probability of link-level unicast failure are necessary inputs to the Warp-5 routing metric. Nodes in the ad hoc network estimate the time required to complete a link-level unicast from recent experience gained from observations of the number of retransmissions done by the MAC layer at different transmission rates. Nodes also learn the probability of link-level unicast failure from recent experience sending unicast packets to specific neighbors. To manage congestion, each node tracks the data packet arrival rate (again from recent experience) for different routes to be able to recognize its own congestion and changes in offered load level for specific routes. Routers learn time-to-destination estimates for different neighbors as part of the route discovery process. The time-to-destination estimates are based on the Warp-5 routing metric, which is based on current offered loads, the time required to complete link-level unicasts and the probability of link-level unicast failure. Routers also have to estimate the time between cause events and later effect events as routes are modified as part of the route detangling algorithm to alleviate router congestion. The use of information learned from the wireless ad hoc network allows Warp-5 to manage noise and router congestion conditions that could not have been predicted beforehand.

Warp-5 currently has been validated using a simulator written by the author. Further improvements to the protocol would extend it to cover varied Quality of Service requirements and demonstrate the scalability of the protocol.

7.1 Detecting Link Failure

In noisy environments, the likelihood of packet loss from a transmitting node to its neighbors increases as the level of noise increases. Thus, the failure of a single unicast is not sufficient evidence of link failure. Even when multiple links are available, all alternatives may be prone to unicast failure to various degrees. The challenge, then, is to decide when a link has failed. Learning mechanisms that calculate things like probability of packet error, estimated time to destination or average packet arrival rates use numerical information that is *evaluative*, but not *instructive*. Evaluative information about one option, like a time-to-destination estimate, has

no value by itself. Evaluative information about one option can only be compared to evaluative information about another option in order to make a decision. Conversely, instructive information about one option has value by itself. Unfortunately, no magical mechanism exists that can inform its upstream neighbor that the link between the two is now broken without requiring feedback in the form of further transmissions. To save on additional communication, the upstream node has to make that determination on its own. Standard, non-learning routing protocols and transmission rate selection algorithms use arbitrary decisions like how many successive unicasts have to fail before the upstream node infers link failure. Learning algorithms cannot determine that a link has failed from evaluative information alone. Link failure can only be inferred using criteria applied to evaluative information. The criteria used to determine link failure may be application specific.

A future research effort for detecting broken links would involve finding what externally set criteria best correspond to actual link failures. Experimentation with deliberately broken links in simulated topologies with nodes using arbitrary link-failure criteria would reveal how well different criteria compare in detecting failed links in terms of speed and accuracy of detection. Different criteria would also have to be considered for different application-specific performance requirements. The results would remove the arbitrariness of current link-failure criteria for wireless networks.

A second issue for investigation is how to best repair a broken link. An intermediate node may be able to detect a broken link, but a repair would require some sort of route re-discovery. The options for route repair by an intermediate node would include a local repair or a global repair. The local repair would continue to route data packets through the intermediate node that discovered the broken link, even if the repaired route is not the most efficient under the changed network conditions. A global repair could result in an altogether different route that does not use the node that first detected the broken link. An upstream neighbor is closest to the broken link, but it would only be able to report the problem through route requests and not actually fix the problem with new routing information that is available from route reply packets. The propagation of route requests takes time to move through the network and, during that time, the data packets moving to the broken link are not arriving at their destination. Downstream intermediate nodes or the destination nodes themselves might also be better candidates for repair.

Nodes that monitor the arrival rate for individual routes could notice the lack of packets for specific routes and send out route reply packets to repair broken links upstream. The advantage of downstream repair is that there is no need for route requests once the problem is detected, the downstream node can immediately send out route reply packets to fix the broken link without losing time spent in moving route request packets through the network.

7.2 Mobile Ad Hoc Networks

There are multiple issues related to mobility in ad hoc networks that warrant further investigation. The first is determining how mobile the nodes can be and still support multi-hop communication between non-adjacent nodes. Routing protocols for mobile ad hoc networks, whether proactive or reactive, take time to discover or maintain current route information. As nodes move, the network topology changes and formerly-working routes cease to move data from source to destination when adjacent nodes move out of communication range. Conceivably, nodes in a mobile ad hoc network could move fast enough to break routes faster than routes can be discovered or repaired, preventing multihop communication entirely. A research effort to determine the balance of factors such as mobile node speed, time required to discover or repair routes and density of mobile nodes (i.e. how many mobile nodes per unit area) and communication radius would be a useful basis for analyzing routing protocols to isolate factors that constrain performance. With such information, it would be possible to improve how routing protocols are designed, evaluated and improved.

The performance results for routing protocols in mobile ad hoc networks are typically studied using the *random waypoint* simulation model, where some predetermined number of nodes move in randomly chosen directions within a fixed simulated area to randomly chosen destinations. The speed of the individual nodes is randomly selected with predetermined bounds. Upon arrival at its destination, each node ceases to move for a certain randomly selected length of time before choosing another destination and speed. Source nodes choose destination nodes at random. The random waypoint model is good for evaluating overall performance, but it does not serve to isolate specific problematic circumstances for routing protocols. Another potential research effort would be to start with the random waypoint model and then isolate specific

situations for mobile ad hoc networks, much the same way the castle topology isolated congestion bottlenecks in static topologies. A catalog of problematic ad hoc routing situations would allow researchers to investigate the problems in isolation before using an overall performance simulation.

Another area for further investigation specific to routing protocols like Warp-5, which monitor data packet arrival rates, would involve finding better ways of measuring data packet arrival rates. Variability in data packet arrival rates is inevitable in wireless ad hoc networks, whether due to exponential service processes within mobile routers or the variability introduced by the 802.11 MAC exponential backoff algorithm. The research effort here would be to find mechanisms that manage the inevitable variability in packet interarrival times with fast detection of changes in overall arrival rates. The mechanisms would be evaluated in simulated routing problems. The results could be applied to reducing the time required for Warp-5 routers to detect router congestion and the time required for adjusted routes to stabilize, which would improve the Warp-5 detangling algorithm.

7.3 Quality Of Service

The routing metric presented in this dissertation assumes only the minimum of Quality of Service (QoS) guarantees, namely that as many application data packets get to the destination nodes as possible. There are many other QoS criteria including path length, power consumption, variance in packet delay and overall security level [16]. Different QoS criteria may require the use of different routing metrics, all within the same wireless network. Most current routing protocols use a single metric, represented as a number with an implicit meaning. Different QoS criteria in the same wireless network would require explicit description of the required criteria in the routing protocol. Nodes processing such a protocol would have to decode the QoS representation and make routing decisions accordingly. The research effort here would require investigation into the QoS criteria to learn applicable characteristics like minimum requirements, maximum levels, etc. For example, a QoS criteria that requires a minimum threshold may require nodes to disqualify themselves from route discovery and route detangling if current conditions prevent them from fulfilling the QoS criteria. The results would be applied to

designing an extensible QoS criteria representation that explicitly describes the metric applied in route request and route reply packets.

A closely related area for further investigation is the area of combining multiple QoS criteria in a single route request. A reasonable example of combined QoS criteria would be a route request that sets security requirements, maximum variance in packet delay and minimal packet delivery time. The associated effort would be to design an expression calculus for multiple combined QoS metrics, possibly as a weighted linear combination of factors and/or explicit lists of factors. The weights would possibly be set by the designers of the distributed application. The result is an explicit expression of QoS needs that the individual nodes would mathematically evaluate whose result would be the basis of routing decisions.

7.4 Extensions To The Detangling Algorithm

Practical situations may have dozens or hundreds of routes going through a set of nodes before they become overloaded. Application of the current Warp-5 detangling algorithm to dozens or hundreds of routes would be time consuming and largely ineffectual when many of the routes consume only a small fraction of the forwarding capacity of the routers involved. Attempting to adjust routes that consume the larger portion of the router's forwarding capacity would be more beneficial than adjusting all the routes that overload a router. The focus of further research into route detangling under conditions where many routes cause router congestion would be to find suitable criteria for selecting subsets of routes for detangling, possibly limiting the detangling to the routes that consume the largest fractions of the routers' resources.

Another potential area of inquiry would be detangling congested routes in hierarchical wireless networks. Hierarchical networks have multiple tiers. Nodes in close physical proximity create peer-to-peer networks in the lower tier with at least one node acting as "gateway" to the higher tier. The gateway nodes in the higher tier form a larger peer-to-peer network using more powerful transmitters to communicate over greater distances than the nodes in the lower tier. A future direction for research might involve determining if the Warp-5 detangling algorithm works for hierarchical wireless networks and what modifications, if any, would be required to make congestion management work in hierarchical wireless networks.

7.5 Conclusion

Application throughput in wireless ad hoc networks can be adversely affected by environmental noise and router congestion. Distance vector routing protocols have proven superior to link-state protocols in supporting on-demand route construction. Using minimal hop count as a routing metric fails to consider the effects of previous routes on router congestion when new routes are constructed, thus failing to take advantage of the routing resources that are available in the ad hoc network. This dissertation has presented a routing metric that factors both environmental noise and router congestion into a single time-based routing metric. Also presented was a new routing protocol, Warp-5, that uses this new routing metric to make better routing decisions in wireless ad hoc networks.

The Warp-5 protocol also adjusts existing routes to minimize packet loss when routers become overloaded, using a new detangling algorithm. Simulation results have shown that Warp-5 can adapt to routing problems when they arise and alter routes to adapt to new routing situations. Simulations of Warp-5 and AODV have demonstrated that the new routing metric results in better routing decisions than minimal hop count metrics that ignore link quality and router congestion. The ability to recognize noise and congestion problems based on recent experience in wireless ad hoc networks demonstrates the feasibility of using machine learning to manage noise and router congestion in wireless ad hoc networks. The improved distributed application throughput seen in the simulation results demonstrates the usefulness of machine learning in managing noise and router congestion in wireless ad hoc networks consistent with the thesis of this dissertation.

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