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On indoor multi-hopping capacity of wireless ad-hoc mesh networks

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Abstract
The capacity and multi-hopping performance of ad hoc mesh networks in dynamic environment still remains an open research issue. Previous theoretical studies suggest that they do not scale in densely distributed networks. However, a study has shown that scalability and hence the multihopping capacity of mesh network is not only bound by the number of nodes in the network but also the number of hops [3]. In this paper we investigate the performance of multihop ad hoc mesh networks, using both simulation studies and an experimental test-bed, and monitor the performance of the network as the number of hops in the network increases. Our results show that the drop in performance in multi-hopping is much more significant when the traffic levels are high. Furthermore our test-bed study shows that ad hoc mesh networks can maintain high levels of packet delivery and throughput when traffic levels are low, however, the delay experienced continues to increase after each hop.

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On Indoor Multi-hopping capacity of Wireless Ad-Hoc Mesh Networks

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Abstract

The capacity and multi-hopping performance of ad hoc mesh networks in dynamic environment still remains an open research issue. Previous theoretical studies suggest that they do not scale in densely distributed networks. However, a study has shown that scalability and hence the multi-hopping capacity of mesh network is not only bound by the number of nodes in the network but also the number of hops [3]. In this paper we investigate the performance of multi-hop ad hoc mesh networks, using both simulation studies and an experimental test-bed, and monitor the performance of the network as the number of hops in the network increases. Our results show that the drop in performance in multi-hopping is much more significant when the traffic levels are high. Furthermore our test-bed study shows that ad hoc mesh networks can maintain high levels of packet delivery and throughput when traffic levels are low, however, the delay experienced continues to increase after each hop.

1 Introduction

Wireless ad hoc mesh networks consist of a set of mobile or static end-user nodes with the capability of receiving, transmitting and performing routing to form a mesh topology, which can provide end-to-end routes to every other node in the network through multiple hops. This flexibility of ad hoc mesh networks introduces a number of interesting challenges, such as maintaining low overhead multi-hop routes in a dynamic environment. To address this problem, a number of protocols and algorithms have been proposed specifically for use in ad hoc mesh networks [1].

While the performance of ad hoc mesh networks have been extensively researched through theoretical and simulation-based studies, actual performance in the field is often considerably worse than these studies would suggest. Researchers are now looking towards practical test-beds to better understand real-world performance and overcome some of the limitations of the analytic and simulation-based approaches [4]. Implementation of any proposed MANET protocols and algorithms on real-world test-beds is an essential part of demonstrating their worth.

In this study, we examine the performance of ad hoc mesh networks using both a custom-built test bed and simulation studies. The aim of this study is to investigate the performance of ad hoc mesh networks as the number of hops increase in the network. Furthermore, we compare our simulated results with those from our test bed and describe how accurately can current simulation tools can model such networks.

Our test bed consists of a number of self-contained and self-configured nodes, called Portable Wireless Ad hoc Nodes (PWANs). These nodes are based around a battery-powered Linux-based embedded system with multiple radios. They are pre-configured with a variety of ad hoc routing protocols and provide a range of convenient tools for network diagnostics, performance evaluation, data logging and network-wide configuration, as well as a set of test applications to qualitatively evaluate link quality. This study presents the result of our experiments based on the Optimized Link State Routing (OLSR) [2] protocol.

The rest of this paper is structured as follows: Section 2 presents a simulation study, which examines the performance of ad hoc mesh networks as the number of hops increases. Section 3 provides a detailed description of the PWAN nodes; Section 4 describes the test-bed setup and details the scenarios used to investigate the performance of the PWANs; Section 5 presents test-bed results and a discusses its performance over each scenario; finally, Section 6 presents the conclusions of the paper.

2 Scalability of Ad Hoc Network

Due to the multi-hop nature of ad hoc network, the nodes cooperatively forward each others' packets in the network. Therefore every packet has to be replicated multiple times

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through multiple nodes before reaching its destination. In affect, the available throughput for each node is not only limited by the raw channel capacity, but also by the forwarding loads imposed by other nodes. Further, since wireless medium is a shared resource, the network exhibits serious contention problems as only one node can grant the access to the wireless medium at a time. This means the data must be repeated in a store-and-forward manner in order to be relayed from one node to another.

However, a study by Li et al[3] indicated that two sufficiently distant radios can transmit concurrently; the total amount of data that can be simultaneously transmitted over one hop increases linearly with the total area of network. This implies that for a network with n nodes uniformly distributed across the physical area of network, A. The *total one-hop capacity of the network*, C, which is the aggregate capacity of concurrent one-hop transmission at any given time, should be proportional to the area of the network - that is, $C = kA$ for some constant k. If it is assumed that each node generates packets at the rate of λ, and the traffic pattern in the network has the length of L between source and destination, then the minimum number of hops, h, will be $\frac{L}{r}$ where r is the fixed radio range. Based on these assumptions, the minimum amount of total one-hop capacity required must obey $C > n \cdot \lambda \cdot \frac{L}{r}$. This also implies that the capacity available for each node, λ, is bounded by

$$\lambda < \frac{C/n}{L/r} = \frac{C}{n \cdot h} \qquad (1)$$

The above equation illustrates that, given a fixed one-hop capacity, the bandwidth available for each node is not only bound by the number of nodes, but also by the number of hops. Thus, as the number of hops increases, the bandwidth available for each node *decreases*.

To verify the impact of hop counts on the overall ad hoc network capacity, a set of simple simulations have been performed. In this scenario, all nodes are arranged in a straight line, and separated by 200 meters from its neighbors. This immediately forms a chain topology, where the packets travel along a chain of intermediate nodes towards the destination. Each node equips with a single 802.11b radio interface running at data-rate of 11 Mbps, and interference range is set to 283.55 meters. The OLSR is chosen as the routing protocol for the simulation. The simulation consists of the first node on the chain sending CBR traffic to a destination node along the chain for 300 seconds. Each CBR packet contains 512 bytes of payload at transmission interval of 0.2s, 0.02s, and 0.002s respectively. The results are collected and compared against different hop counts and transmission intervals. For accurate performance estimation, each pair of hop counts and tranmission intervals parameters is going through a monte carlo simulation process, where each set of results is collected from at least 50 independent runs with different random seeds.

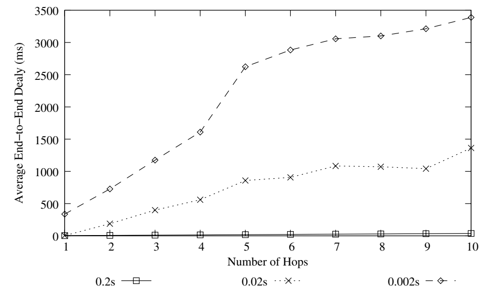

Figure 1. Delay vs Hops

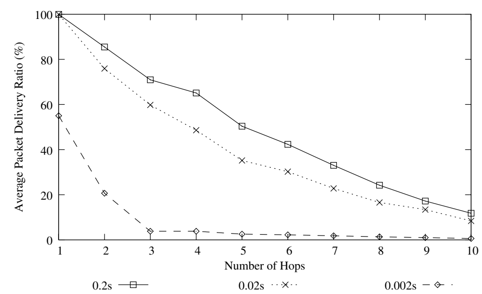

Figure 2. Packet Delivery Ratio vs Hops

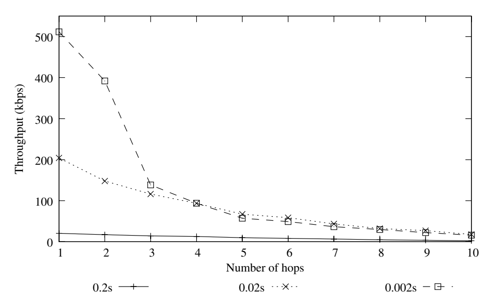

Figure 3. Throughput vs Hops

Figure 1 illustrates the end-to-end delay versus number of hops. For low rates of packet transmission (packet intervals of 0.2 seconds), the end-to-end delay is not severely affected by the number of hops; however as the traffic levels are increased (with the packet interval decreasing to 0.002 seconds), we can see that the end-to-end delay increases dramatically due to network congestion at the routers. This increased delay has a significant implication on the reliability of delivery of control messages throughout the network.

Figure 2 depicts the packet delivery ratio versus number of hops. From the figure, it can be seen that for the highest packet transmission rate (a packet interval of 0.002 seconds), the network saturates at the first hop and the achievable packet delivery ratio is less than 60%. By contrast,

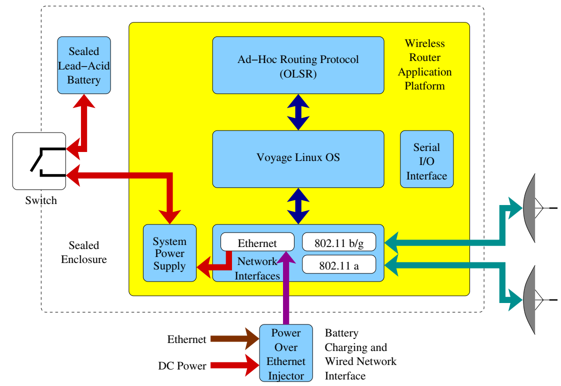

Figure 4. Portable Wireless Ad hoc Node (PWAN) Architecture

Figure 5. Portable Wireless Ad hoc Node (PWAN) prototype

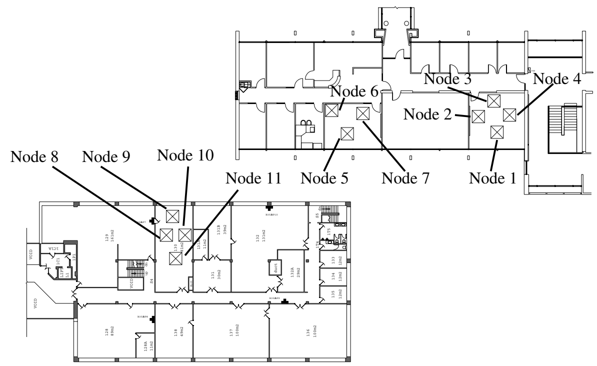

Figure 6. Multi-hop Distributed Topology setup

networks subject to lower transmission rates (0.2 and 0.02 second packet intervals) are able to maintain a packet delivery ratio of 100%. Further, at the highest transmission rate, the packet delivery ratio deteriorates very rapidly as the number of hops increases, and from 3 hops onward, the PDR approaches 0%. Similarly, the packet delivery ratio at moderate and light traffic loads also exhibits a decline toward 0% when number of hops increases, although the rate of decline is markedly less. Clearly, when traffic load levels are high, the ability of a network to deliver packets deteriorates rapidly as the number of hops increases.

Although the offered load increases throughput up to a point, the results depicted in Figure 3 show that the total achievable throughput is fundamentally bounded by number of hops, which directly reflects the relationship described in Equation 1 (in which the number of hops effectively determines the available capacity for each node).

3 Testbed Design

The aim of our experimental studies was to investigate the performance of multi-hop ad hoc networks in indoor scenarios. To achieve this we developed a number of Portable Multi-hop Ad hoc Nodes (PWANs), which could be easily moved from one location to another. Our PWAN architecture is based on the Wireless Router Application Platform (WRAP) boards from PCEngines (see Figure 4). To operate the PWANs, the Voyage Linux OS was installed on a compact flash card for each WRAP board. The Optimized Link State Routing (OLSR) routing protocol was used to enable multi-hop ad hoc routing between the PWANs [2].

Atheros-based 400mW 802.11b/g wireless radio were used as wireless network interface on each node. Each wireless interface was configured to operate in ad hoc mode and the MadWifi Linux driver used to interface to the radios. The RTS/CTS threshold was set to 40 bytes, fragmentation was turned off and the transmission power was set on maximum power. The PWAN components were placed in a sealed enclosure and powered by a lead-acid battery, with power-over-Ethernet (PoE) re-charging capability. We also modified each enclosure to provide external interfaces for two antennas, an Ethernet port (also used for recharging via PoE), and also a switch to turn the PWANs on and off. Figure 5 illustrates the PWAN prototype device.

4 Test-bed model and scenarios

We investigated the performance of the PWANs using two different testbed configurations. We refer to these configurations as "Multi-hop Distributed Topology" (MDT) and "Multi-hop Uniform Chain" (MUC). The MDT setup was used to measure the performance of the mesh network for various different levels of traffic, while the MUC setup was used to investigate the limits of the network in terms of number of hops. In the MDT setup, 11 PWANs were distributed between three rooms in two separate buildings as

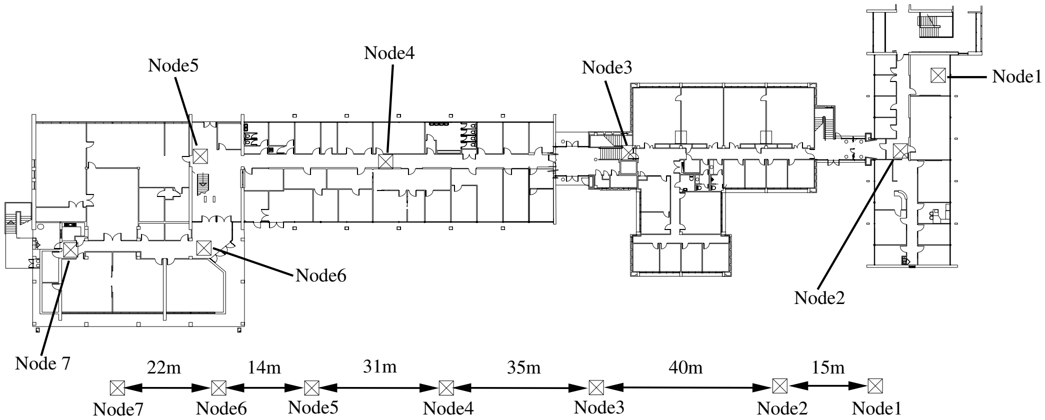

Figure 7. Multi-hop Uniform Chain setup

shown in Figure 6. The distance between the two buildings is approximatley 30 meters and the distance between the two room in the top building in Figure 6 is approximately 20 meters. In the MUC setup, we placed 7 nodes along the corridor within one building to form a radio chain, with the first and the last node being 6 hops away from each other (See Figure 7). Each node where sufficiently spaced so that they only form a link with their intermediate neghbouring nodes in order to form a multi-hop chain. Note all nodes where fitted with two 5dBi external antennas and diversity was enabled.

To introduce traffic into the network, we simultaneously introduced ping (ICMP) traffic between pairs of nodes in the network. Each ping session was set to transmit packets of 70B and 520B (which included an 8 byte header), where used for the MDT and MUC setups respectively[1], which effectively simulates a bi-directional CBR traffic flow between the specified end-points. In the MUC setup, we used two flows, since we are specifically examining the performance of a radio chain, while for the MDT,the number of ping flows in the network was progressively increased for each test run to evaluate the performance of the network under increasing load. Furthermore, in the MDT setup the number of bi-directional flows was increased in steps of two, up to a total of twelve flows (24 individual flows). For each set of flows, three different tests were performed with different packet transmission rates. Pings were transmitted at intervals of 0.2s, 0.02s,0.004s (i.e. 5, 50 and 250 packets per second respectively) for the MDT setup and 0.2s, 0.02 and 0.002s (i.e. 5, 50 and 500 packets per second respectively) for the MUC setup. Each test was run for a period of 5 minutes.

To evaluate the performance of the network, average throughput, packet deliver ratio (PDR) and average round trip delay (ARTD) were measured for each set of network conditions. The throughput measures the average data transmission rate achieved per flow. The PDR metric is the ratio of the data packets sent by the source to the number of packets received at the destination (or the rate of successful packet delivery) as the network conditions change over time. The ARTD metric measures the length of time it takes for a packet to complete a round trip between the source and destination.

[1] Note since the MUC setup did not include the 1-hop background traffic, which existed in the MDT setup, we used larger packet sizes (i.e. 520B) to introduce higher levels of traffic into this setup.

5 Results

5.1 Multi-hop Distributed Topology

To investigate the performance of multi-hopping in this scenario, we measured the performance of the flows, which traveled over two hops or more only. To do this we set up four flows, with two traveling over two hops and the other two over three hops to reach their destination. We then increased the amount of 1 hop traffic flows for each test-run and measured the performance of the multi-hop routes.

Figure 8, presents the throughput of multi-hop routes as the number of flows was increased. This figure shows that for 0.2s dissemination rates, the throughput stayed fairly steady as the number of flows was increased. However, when the dissemination rate was increased to 0.02s, the throughput began to drop significantly when the number of flows was increased. To investigate this further, we monitored the routing table at one of the source nodes. We observed that as the number of flows where increased the routing table became unstable. We noticed that the routing table kept changing although the physical topology remained the same. This was more evident in the 0.004s scenario, where the routing table was unable to maintain accurate information about the multi-hop routes. Hence, we were unable to establish multi-hop flows when the number of flows were

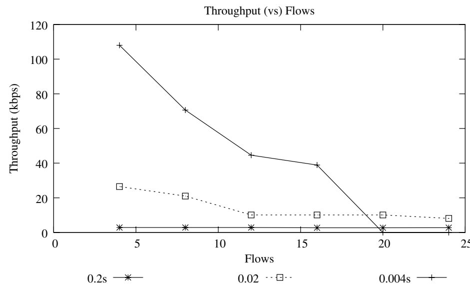

Figure 8. MDT: Throughput vs Flows

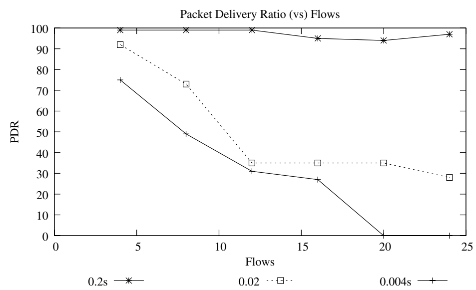

Figure 9. MDT: PDR vs Flows

increased beyond 20.

Figure 9, presents the packet delivery ratio results versus the number of flows. From this figure, it can be seen that in the 0.2s scenario a PDR of over 94% were achieved for all different flow levels. However, when the dissemination rate was increased to 0.02s, the PDR levels begins to fall significantly after 4 flows. This drop was mainly due to packet loss resulting from inaccurate routing information and contention. In the 0.004s scenario inaccurate routes had an even greater effect on PDR, which saw PDR drop to less than 50% when the number of flows were increased to 8.

Figure 10, illustrates the average delay versus the number of flows. By observing the curves, it can be seen that the 0.2s scenario has the best performance, where an average delay of less than 3.5ms was maintained as the number of flows were increased. In the 0.02s, the average delay slowly increased toward 20ms as the number of flows was increased to 24. In the 0.004s scenario, the delay levels where increased dramatically when the number of flows were increased to 8, and it continued to increase until multi-hop connections were unable to be established. Two observations can be made from this. Firstly, the introduction of 1-hop traffic has a significant affect on the multi-hop flows. This is because contention increases at each hop, which creates further delays. Secondly, the loss of topology control packets reduces the accuracy of the routing table at each forwarding node, which adds further delay to the delivery of each packet as it travels towards the destination.

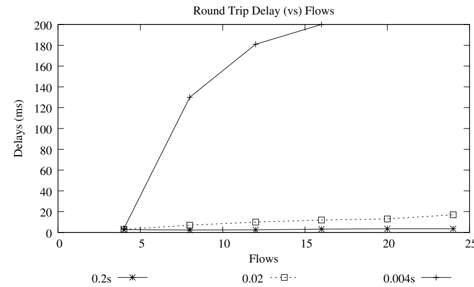

Figure 10. MDT: Delays vs Flows

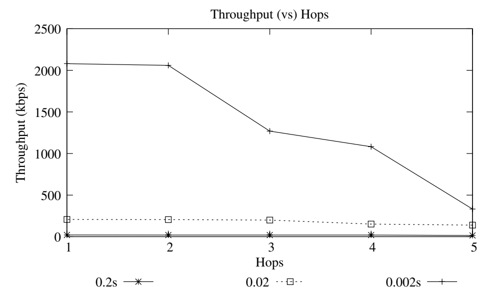

Figure 11. MUC: Throughput vs Hops

5.2 Multi-hop Uniform Chain Topology

To examine the performance of our MUC setup, we measured the performance of two CBR flows initially from one hop and then we increased the number of hops for each test until there were 5 hops between the source and the destination nodes. Note that we also experimented with running 6 hops in this setup, however, the network conditions where not stable enough, particularly for larger levels of traffic, to record consistent results. Therefore, our results illustrate the performance of the MUC setup from 1 to 5 hops respectively.

Figure 11, presents the throughput of multi-hop routes as the number of hops was increased. Looking at the low traffic scenarios (i.e. 0.2s and 0.02s), it can be seen that the network maintains similar level of throughput as the number of hops is increased, with a small drop in performance after 3 hops. For the 0.002s traffic scenario a significant drop in performance resulted after two hops. This result supports the simulation output in Figure 3, where a drop in performance is very clearly illustrated after 2 hops. It further supports the theory in equation 1, which suggests that available bandwidth is bounded by both the number of nodes and hops.

Figure 12, presents the packet delivery ratio results versus the number of hops. From this figure it can be seen that an increase in the level of traffic significantly effects the level of PDR achieved. For example, at 3 hops the 0.2s and 0.02s curves achieve close to 99% PDR, whereas the

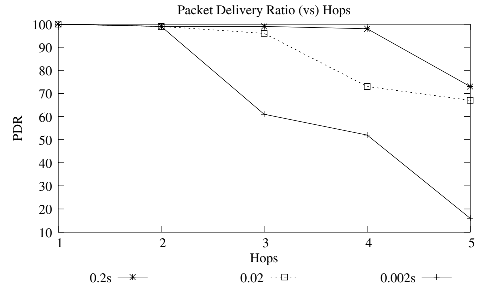

Figure 12. MUC: PDR vs Hops

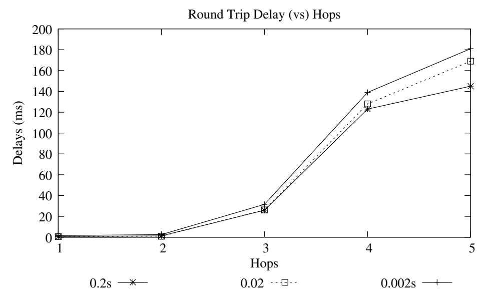

Figure 13. MUC: Delays vs Hops

0.002s shows only 60% at the same number of hops. At 4 hops the 0.2s curve continues to achieve close to 99% PDR, where as the 0.02s and 0.002s curves achieve approximately 75% and 55% PDR respectively. This further supports that the available bandwidth is directly effected by the number of nodes and hops. Similar to the MDT setup, here two main factors contribute to a drop in performance. Firstly, since each packet must be buffered and re-transmitted at each hop, there is a higher chance of packets being lost (or dropped) due to buffer overflows and collisions. Secondly, since the structure of network is maintained dynamically, critical control packets, may be dropped or lost due to collisions. This then results in routing loops and instability in the routing table. We monitored the routing table at the transmitting (src) nodes and observed that when the data rate was set to 0.002s, a high levels of instability was present when the number of hops was more that 2 (i.e the structure of the table kept changing despite the fact that there where no node movement).

Figure 13, illustrates the average delay versus the number of hops. Here all curves show similar levels of performance as the number of hops was increased. Furthermore, the delay levels stayed fairly low until the number of hops was increased beyond 2. At 4 hops, it can be seen that the delay is more that 100ms, which is high enough to effect the performance of real-time Internet-based applications such as Video and Voice over IP. Hence, for such applications, it may not be feasible to establish routes over more than 3 hops.

6 Conclusions

This paper investigated the performance of multi-hop ad hoc mesh networks in indoor environments using simulation studies and a real test-bed. Our test-bed was made up of a number of custom developed Portable Wireless Ad hoc Nodes (PWAN), which used the OLSR routing protocol to establish multi-hop routes. We set up two different scenarios to investigate the performance of these nodes. The first scenario studied the behavior of multi-hop routes in a purely distributed environment with presence of background traffic. The second scenario investigated the performance of multi-hop ad hoc mesh networks as the number of hops is increased. Our studies showed that for high levels of traffic the topology of the multi-hop network maintained at each node becomes highly unstable, which can reduce the data throughput and increased the delays experienced by each data packet. Furthermore, we observed sever performance degradation as the number of hops was increased. Both our simulation and experimental results show that for more that 3 hops the network experiences large amounts of delay. Hence, we it can be concluded that the provision of real-time applications over such networks should be limited to a maximum of 3 hops. While our results show the performance of single ad hoc mesh networks suffer significantly as the number of hops is increased, we believe that it may be possible to improve their performance by developing new strategies which handle the channel and data transmission more efficiently at the MAC and the physical layer. Furthermore, we believe that it may be possible to significantly improve the performance of multi-hopping through multi-radio mesh devices. For our future work, we plan to develop and investigate the performance of multi-radio ad hoc mesh networks.

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