Measuring the Performance Gains from Directional Antennas in an Unplanned 802.11b Mesh Network

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Abstract

Wireless mesh networks are becoming increasingly popular. Most proposed mesh algorithms are evaluated using simulation. Simulations frequently oversimplify real world scenarios and can lead to results that are significantly different. Thus, although it is more difficult to run controlled experiments in already deployed real-world networks, it is important to understand how proposed improvements perform under these realistic scenarios. Several authors have suggested the use of directional antennas, but their merits have only comprehensively evaluated in simulators. Roofnet is an unplanned 802.11b wireless mesh network deployed by MIT and is constructed primarily of omni-directional antennas. We use measurements to evaluate performance gains from using a directional antenna on this network. Other factors such as user location and number of hops to the gateway are considered. Using throughput, latency, and streaming video tests, this paper examines the end-to-end performance of the network. Five working locations were chosen in total and three permitted directed performance comparisons between directional and omni-directional antennas. The directional antennas improved throughput by 21% reduced roundtrip times by 15% quicker round trip times. The directional antenna also provided more consistent video quality, and stabilized faster.

1. Introduction

Wireless networks based on the 802.11 standard have recently become increasingly popular. A more recent trend involves creating publicly accessible 802.11 wireless networks for much larger metropolitan areas [17]. Such wireless networks are convenient to use, facilitate ubiquitous computing, and provide affordable Internet access to underprivileged communities.

Roofnet[19] is a free wireless mesh network developed by the City of Cambridge, Massachusetts in partnership with the Massachusetts Institute of Technology (MIT). The Roofnet network is comprised of nodes that combine to form an unplanned 802.11b mesh network with access to the Internet through four Internet gateways. Volunteers can expand Roofnet by adding their own node to the network using a Netgear router and the open software provided by MIT. Roofnet is still in the experimental stages and is being used for research, but is also available for public use.

Roofnet emphasizes an unplanned network topology with omni-directional antennas and multi-hop routing. Omni-directional antennas are chosen because they do not require network planning or aiming the antenna, are easier for volunteers to setup and encourage network growth by being accessible to more nodes. However, it has been recognized that the network may benefit from the use of directional antennas. Directional antennas have been used in other Roofnet studies to cover selected distances that omni-directional antennas cannot. In this scenario, a directional antenna is used to bridge a gap.

This paper investigates the benefits of using a directional antenna in Roofnet, a fully deployed operational mesh network, ***from a user perspective***. Most performance studies of wireless mesh networks have been done in simulators. Although simulations offer significant control of performance parameters, they frequently oversimplify real world scenarios and can lead to results that are significantly different citeKNG+04. Thus, measurement results from real networks are necessary to compliment the results from simulation. In this paper, we measure the performance of a deployed wireless mesh network. Since high bandwidth applications such as live streaming video are envisaged on mesh networks [17], we also investigate the benefits of directional antennas to streaming applications. Throughput, latency, and streaming video performance are examined over the mesh network. Tests were attempted at five different locations around the city of Cambridge, but only three provide Internet connectivity and are usable for our tests. We find that when pointed in the right direction, directional antennas significantly increased throughput and reduced latency. However, when pointed in sub-optimal directions, directional antennas performed worse than omni-directional antennas. Achievable gains were largely location-dependent. The rest of the paper is as follows. Section 2 provides some background on directional antennas, section 3 presents our experimental setup, section 4 presents our results, section 5 discusses related work, and section 6 concludes.

2 Background: Antennas

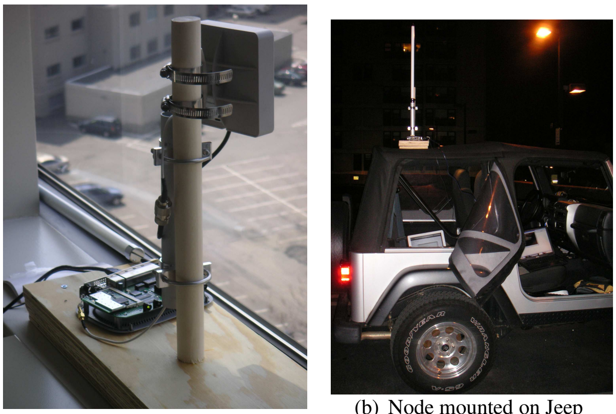
The IEEE 802.11 protocol used in all of these wireless systems is transmitted by antennas. The most commonly used antenna is considered omni-directional, which uniformly transmits and receives in all directions. A directional antenna is an antenna which transmits or receives maximum power in a particular direction, resulting in the ability to transmit a longer distance in a particular direction. The Beamwidth of a directional antenna is the angle in which the antenna will transmit, and is traditionally set in the range of 5°-90° (we use 30° in our testing). Roofnet uses directional antennas for its biggest nodes to increase their range, and to shape the wireless network in conjunct with the shape of Cambridge.

3 Experimental Setup

Our experiments used a Netgear WGT634U router with upgraded firmware upgraded and Roofnet software downloaded from [19]. The router had a small built-in omni-directional antenna that was replaced with a TNC connector to allow us to attach various antennas to the router. Our tests used a Hawking Outdoor Hi-Gain 9 dBi Omni-Directional antenna and a Hawking Hi-Gain 9 dBi Outdoor Directional antenna. The directional antenna is reported to have a horizontal coverage of 70°. Our experiments showed that the antenna also has decent coverage from behind the antenna but poor coverage from the side lobes.

The antennas were mounted on a small portable stand shown in figure 1(a). For convenience, the antennas and router were then placed in a Jeep Wrangler as shown in figure 1(b), so that the equipment could be driven to new locations to conduct tests. The router was powered with an AC power car adapter and backup power to the laptops was provided by an Uninterrupted Power Supply (UPS) unit.

For convenience purposes we used three separate laptops for our experiments. A Dell C640 laptop with a Microsoft Windows operating system was used to run the streaming video tests. A Dell C600 Linux laptop was used for the wget download tests and also had tcpdump setup to monitor traffic. Lastly, an Apple iBook running Mac OSX 10.3.2 was used to monitor router status and conduct ping tests. The Linux laptop was connected directly to the router via an Ethernet cable. The other two laptops were connected wirelessly to the laptop.



(a) Antenna mast

(b) Node mounted on Jeep

Figure 1. Experimental setup

3.1 Test Descriptions

Our evaluation of each tested location consisted of a wget throughput test, a ping latency test and a MediaTracker streaming video test. The throughput tests used wget to download two files from the host debian.lcs.mit.edu. An MIT host that minimized delays between the Roofnet Internet gateway and the download host, was chosen. The two downloaded files were 3 MB and 13 MB in size. The latency tests pinged the Roofnet Internet gateway and then pinged the download host used in the throughput tests. We averaged the round trip times of ten pings to each target.

MediaTracker [18] is a modified version of Windows Media Player developed from the Windows Media SDK. It was created to provide the normal playback capabilities of Windows Media Player while gathering statistics the streamed video in the background. Three video trailers for the movies Soldier, Matrix and A.I, were streamed using MediaTracker, while performance statistics were gathered.

3.2 Test sites

Our tests were run from five selected locations in the city of Cambridge, which correspond to the red dots in figure 2. These locations were 1) the tenth floor of an office building on Main Street near Kendall Square 2) The roof of a parking garage in Central Square 3) Roadside near 800 Main Street 4) Roof of a parking garage in Kendall Square 5) Roadside on Massachusetts avenue near People's republic.

At locations 1 and 3, we were able to connect and test both the omni-directional and directional antennas. At location 2, no usable links weer available even placing the

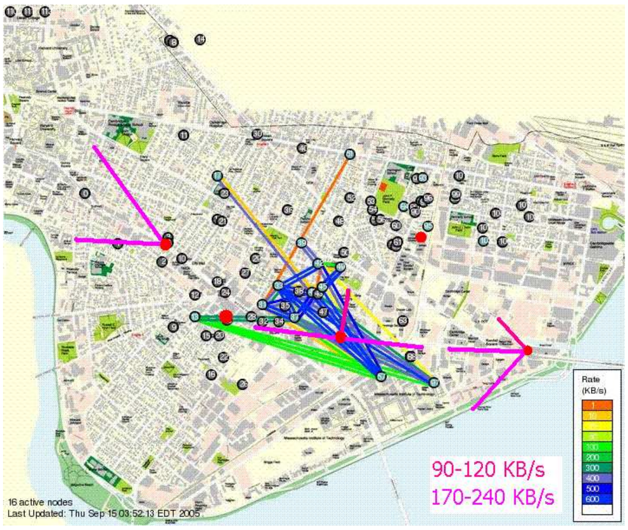


Figure 2. Roofnet map

antenna on the roof of the Jeep. At location 4, we were able to connect to two Roofnet nodes using the omni-directional antenna. However, since these nodes were only connected to each other but not to the Internet, we could not conduct our tests. Attempts to use a directional antenna to connect to other further nodes with Internet access were not successful. Location 5 was unique in that we connected directly to an Internet gateway (instead of the gateway being another hop away) and was only accessible using the directional antenna. Only throughput and latency tests were conducted at this site, as it was very difficult to maintain

4 Results and Analysis

4.1 Throughput tests

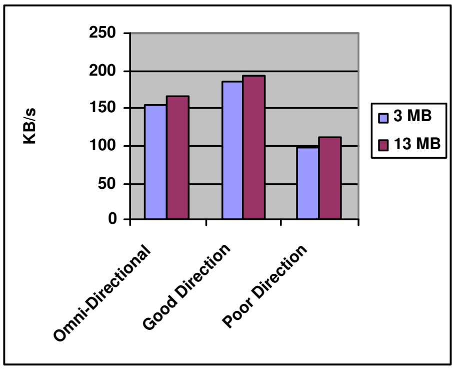


Figure 3. Average throughput (dir. Vs. omni.)

This section analyzes the results of the wget throughput tests and compares the performance of an omni-directional antenna with that of a directional antenna.

	ETT	3MB	13MB
Omni-Directional	7161	145.83	157.75
Southwest	4566	183.30	171.85
West	6938	190.27	184.85
Northwest	14976	93.18	121.12

Table 1. Throughput at office site

Figure 3 shows that the average throughput attained with a directional antenna that is pointed in a good direction outperforms an omni-directional antenna by more than 17% for the 13 MB file and almost 21% for the 3 MB file. The highest observed throughput using a directional antenna pointed directly at the Internet Gateway was 306.34 KB/s. All omni-directional tests had two hops to the gateway.

Figure 3 shows that using a directional antenna, there is a large discrepancy between the results for the good direction and the poor direction. In fact, measured performance was almost distinctly bi-modal: performance was either good or bad with few data points in between. The standard deviations of the 13 MB download with the antenna in poor and good directions were only 21.1 and 35.8, respectively. These results show that ***a directional antenna can increase performance when used properly but conversely could hurt performance if not optimally placed***.

Table 1 shows the average download speeds for tests performed at the Office building test site (location 1). The table also shows the Estimated Transmission Time (ETT) metric that the router uses to determine its routes. Pointing the antenna in the northwest direction often resulted in poor and constantly changing ETT values. Consequently, the routing table fluctuated back and forth between choosing two different neighbors as the first hop. Unfortunately, the route established through one of these neighbors happened to be unusable. Overall, this northwest direction had the worst download times. We concluded that ***antenna directions with unstable ETT values negatively affected download times***.

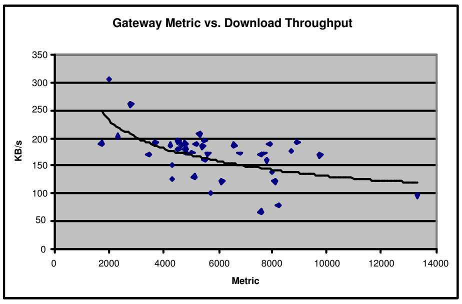


Figure 4. ETT Vs. download times

Figure 5 shows the ETT values measured at the office

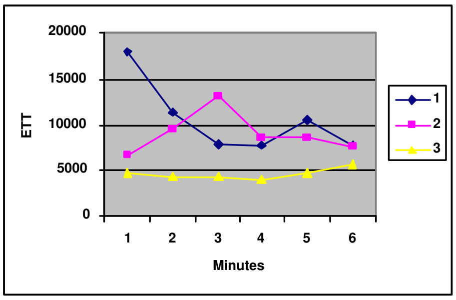


Figure 5. ETT at locations 1, varied directions

	3MB	13MB
West	188.35	209.48
Northwest	182.13	241.14

Table 2. Throughput at People's republic

test site for three slightly varied directions all in the northwest direction. It can be seen that one direction (yellow) is clearly better than the other two. Figure reffig:throughput2 shows direct evidence that antenna direction was important and in general ***lower ETT values resulted in greater throughputs***. The better ETT values for the third direction resulted in approximately 50% better download performance.

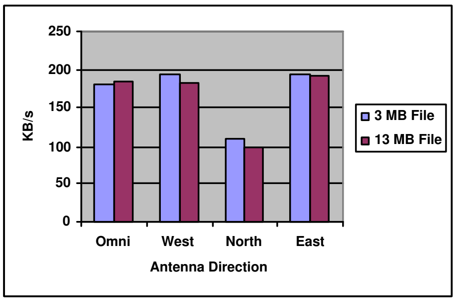


Figure 6. Throughput results for main street

Figure 6 shows the throughput for the tests conducted at the Main Street test site (location 3). Similar to the tests at the office site, the directional antenna had one direction that was significantly worse than the other two and resulted in throughputs that were more than 40% worse. However, the positive effect for a directional antenna was not as significant at this site. Compared to a peak throughput improvement (over the omni-directional antenna) of 30% for the Office building test site, the directional antenna increased throughput by at most 7% at location 2. This leads us to conclude that ***the benefits of directional antennas were location-dependent***.

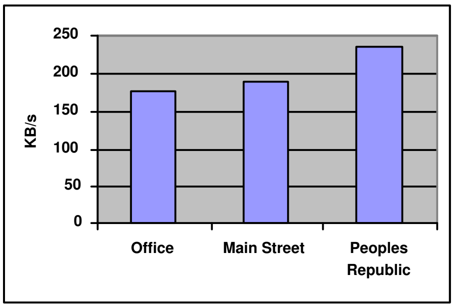


Figure 7. Throughput for three sites

As previously stated, the network at the People Republic test site (location 5) was only accessible with a directional antenna. It was one hop away from the gateway and had a very high packet error rate. Table 2 shows that despite the high packet error rate, the one hop to the gateway resulted in the only tests that averaged over 200 KB/s. Figure 7 shows the People's republic site had at least a 25% better throughput than the other two sites'. We conclude that ***although directional antennas generally experience higher error rates as they cover greater distances, the can reduce the number of route hops and increase throughput***.

The People's republic site also gave the highest single-test throughput results for both the large and small file download with 306.34 KB/s and 262.91 KB/s, respectively. Unfortunately, this site was also unreliable, and was completely unusable when the antenna was directed to the west.

4.2 Ping latency tests

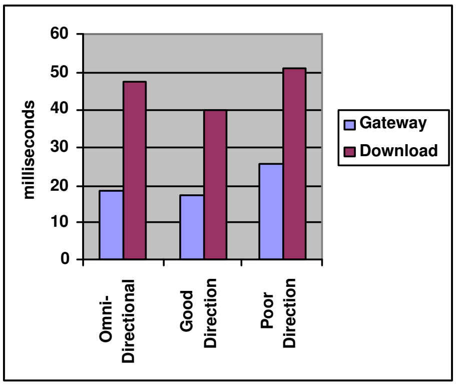


Figure 8. Rountrip time

This section analyzes the results of the ping latency tests and compares the performance of an omni-directional antenna and directional antenna.

Figure 8 shows the round trip times to the gateway node and to the download site used for the wget tests. In comparison to the omni-directional antenna, directional antennas

	Gateway (ms)	Diff. from Omni	Download (ms)	Diff. from Omni
Omni-Dir.	19		53	
Southwest	16	-16%	45	-15%
West	16	-16%	51	-4%
Northwest	27	42%	66	25%

Table 3. Latency test results (Office)

resulted in 15% shorter round trip times to the download site when pointing in a good direction and only 7% longer when poorly directed.

The Office building test site showed the greatest differences in the round trip times. Table 3 shows that the two directions that showed high throughput also had better round trip times and the third direction was significantly worse. This implies that at this site, ***there was a strong correlation between throughput and good roundtrip times*** for all tested directions.

Similar to the Office site, the Main Street test site showed round trip times to the gateway with the antenna pointed in the direction with the worst throughputs (north) to be 29% worse than the omni-directional antenna. However, tests with the antenna pointed to the best (west) direction also showed 18% worse round trip times to the gateway node.

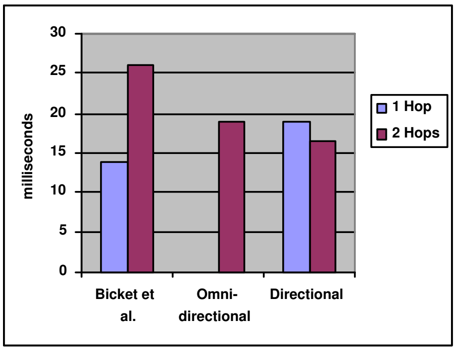


Figure 9. Latency values (People's republic)

The best round trip times to the gateway were found at the Peoples Republic test site. With the antenna pointed to the best direction (west), round trip times averaged just under 15 milliseconds. This is comparable to the 14 milliseconds reported by Bicket et al. for latencies with one hop to the gateway. Bicket et al only used omni-directional antennas. We see in Figure 9 that for all tests for one hop to the gateway, the round trip time is still only 19 milliseconds. However, pointing the directional antenna in a good direction with two hops was faster (16 milliseconds on average). All of our tests for two hops to the gateway demonstrated quicker round trip times than those found by Bicket et al.

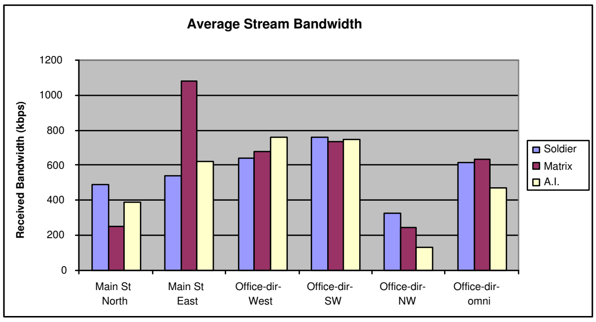


Figure 11. Summary of streaming results

4.3 Video Streaming tests

In this section we report results of our streaming tests with frame rate (fps) and received bandwidth statistics obtained from MediaTracker. Movie trailers (clips) of three movies (Matrix Reloaded, AI and Soldier) where used. Figure 10 is a set of graphs which show the averages of the some of the results obtained of the streaming of video while in the office and on the street. We noticed two unexplained behaviors from MediaTracer. First, the bandwidth recorded for the Matrix Reloaded and the A.I. trailers both start off with one high reading before dropping to zero and then proceeding to record fine (graphs 8, 9, and 12). Since this behavior does not happen for the Soldier trailer that runs first (graph 7 and 10), we suspect that it reads and records the last frame of the previous video, and then continues fine; The other strange occurrence we noticed was that when the connection became really poor the reading for the bandwidth would be exactly the same for a long period of time (notice middle-to-end of the A.I. stream in graph 9). We believe that when the connection gets poor, a small window size is maintained for communications between the host server and the local computer. Since MediaTracker did not record any lost packets for us, we simply used ping to get a general sense of the degree of packet loss, but did not run controlled tests to collect data.

Figure 11 is a summary of the average bandwidth recorded for each of the video streaming runs using the directional antenna and the omni-directional antenna. The fastest stream of all the tests was with the directional antenna pointed east on Main Street; the Matrix Reloaded video streamed at an average of just over 1Mbps (Figure 10, graph 8). The slowest stream was also on Main St., with the directional antenna pointing north while streaming the Matrix video; at a rate of 248 kbps (Figure 10, graph 11). 250 kbps seems to be about the threshold for bandwidth required to finish these types of streams (resolution: 320 * 240 pixels). Whenever the bandwidth exceeded that amount the streams played well; below that bandwidth (Figure 10, graph 9), the video was never able to buffer enough

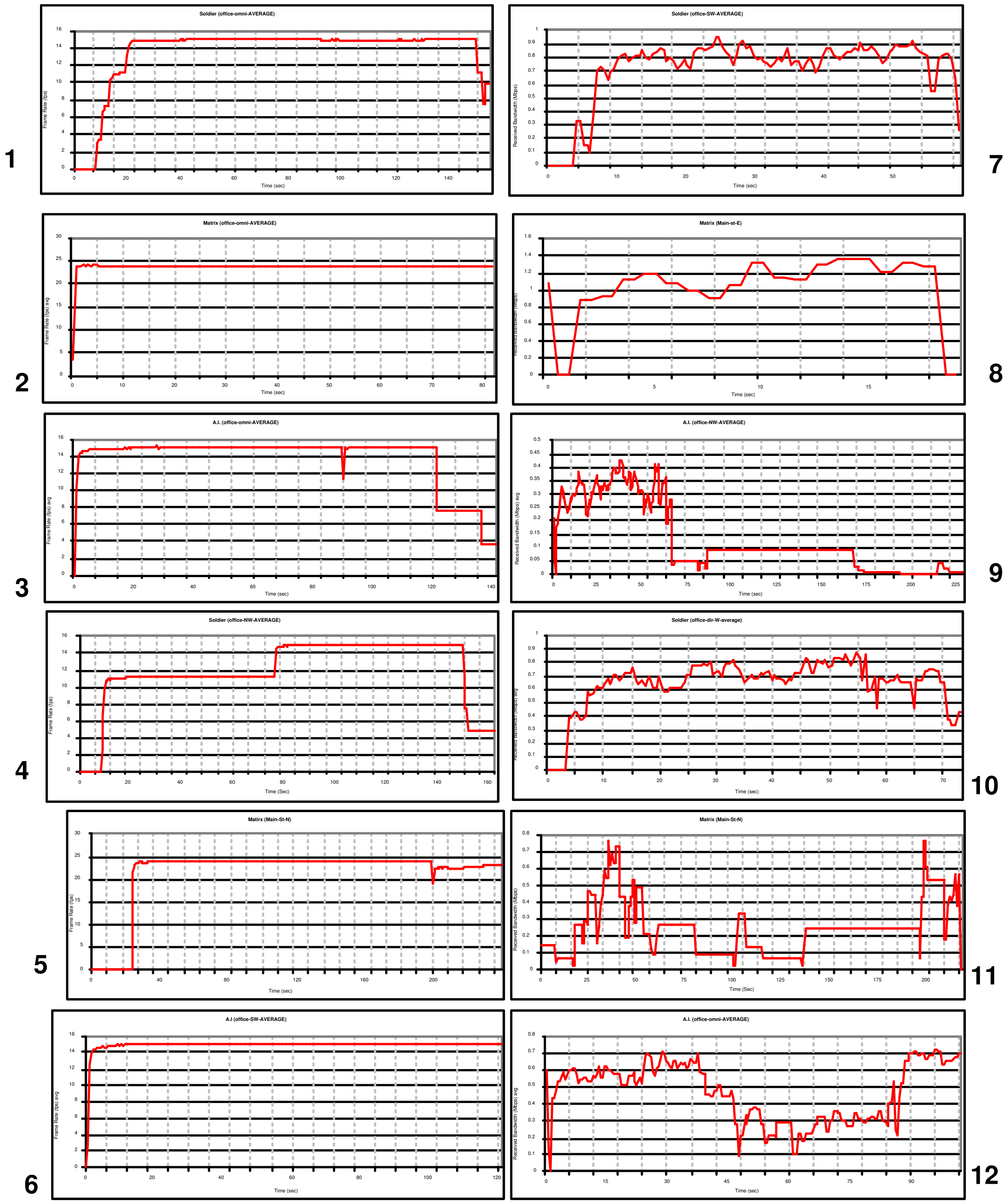


Figure 10. Streaming test results

to start streaming. In general, when bandwith was available the Matrix movie, which had the highest encoded frame rate would download the quickest (compare graph 2 to graphs 1 and 3). However, when bandwidth was low, the same high frame rate movie yielded the slowest stream (compare graph 5 to 4 and 6 in Figure 10). As expected, the longest video (Soldier had 1407 packets, 2 minutes 22 seconds long) took the most time to start streaming (Figure 10, Frame Rate graphs). Figure 11 also shows that when the directional antenna was used to point remotely toward the closest node (west and north-west in our position) the bandwidth on our streams were on average 26% higher than the omni-directional.

5 Related Work

[1, 2, 3] have previously evaluated the performance of Roofnet and its routing algorithms using metrics such as throughput, latency and packet loss. In addition to measuring attainable transmission speeds across nodes [1], and the transmission speed while Roofnet traffic is turned off [2], our measurements are performed from the point-of-view of a Roofnet user trying to access the Internet. We also relocate our measurement equipment using the available map of 38 known nodes [1] to determine how usable Roofnet from 'hot-spots' on the streets of Cambridge, as well as areas at the 'edge' of the network.

[5, 11] carefully placed directional antennas in mobile and ad hoc networks in locations where omni-directional antennas did not perform well. Unlike [5], our results were measured not simulated and we compare the performance gains of directional to omni-directional [11] antennas over a comprehensive set of angles.

Streaming of media over wireless networks has been investigated in [8, 12, 13]. We used Media Tracker [18] and techniques described in [8, 10]. Specifically, we gathered statistics at the application and network layers.

Our work is related to the research in [10] regarding the characteristics of a wireless network in a home. However, our testing dealt with a much larger and less manageable environment. We used their conclusions that antenna direction impacts channel quality more than distance, in our experiments. We also compared our findings to those from previous Roofnet studies [3]. We believe that our results are helpful to researchers studying unplanned mesh networks, as well as to any volunteers and potential users who may wish to connect or help expand Roofnet.

6 Conclusions

Roofnet is a working wireless mesh network free to the public throughout the city of Cambridge. We measured the performance benefits of roofnet using directional antennas. Roofnet's strongest signals are found around the MIT campus and surrounding streets. Nodes can make good bandwidth connections to Roofnet through a small number of gateways. Since Roofnet is still in its infancy, and we had difficulty finding locations that could connect to the network.

At Roofnet hotspots, we were able to obtain a very usable bandwidth connection to the Internet. At the 'edges' of the mesh network, the omni-directional antenna could not effectively pickup the nearest signals. In one edge location, we were unable to connect to the Internet through Roofnet using an omni-directional antenna. For these edge locations, a directional antenna improved performance.

Our results also show that even when an omni-directional was usable, it never outperformed a directional antenna pointed in a good direction. The streaming of the videos in the office averaged a 31% increase in bandwidth when we pointed the antenna at the best angle, and was 21% higher than omni-directional when pointed at the second best an angle. The omni-directional did perform about 125% better than the directional antenna when pointed in a poor direction. Average directional antenna round trip times improved by about 15%.

Additional works is needed to further investigate the affect of directional antennas on an unplanned 802.11b wireless mesh network. In this paper only a patch antenna was used, and future work should consider other directional antennas such as Yagi and parabolic. More work is needed to determine the scenarios where an unplanned network would benefit from a strategically located directional antenna. For future work, a real-time coverage map with locations of the nodes would be useful. The location or GPS coordinates of Roofnet nodes would also be useful. The authors would like to thank Sanjit Biswas of MIT for his assistance.

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