The Impact of Directional Antenna Orientation, Spacing, and Channel Separation on Long-distance Multi-hop 802.11g Networks: A Measurement Study

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***Abstract*— With the increasing popularity of 802.11 wireless technology, such equipment has recently been used to set up long distance links for wireless mesh networks. To be able to increase the range of 802.11 equipment directional antennas are required. In this paper, we investigate the effects of interference between collocated directional antennas, which would be the case for a typical multi-hop node. Results of measurements taken in an experiment show that antenna orientation and placement and channel separation at such a multi-hop node have a significant impact on the achievable throughput.**

I. Introduction

Mesh networks based on 802.11 long-distance links have become increasingly popular in recent years. They are an attractive alternative to provide Internet connectivity to remote locations and communities since high costs and meager revenue make commercial wire-line deployments infeasible. Two typical examples for this trend are the use of such a mesh network to provide Internet access for remote communities [1] or, as links between remote locations in a sensor network for habitat monitoring [2]. This 802.11-based technology is an attractive alternative to wired Internet access because the components needed are low-priced and are commercial-off-the-shelf. As we will show later in this paper, all the equipment that is needed to set up a long-distance wireless link are: two laptops, a pair of 802.11 adapters, a pair of directional antennas, and antenna cables. Such links can easily establish connections over a distance of several 10s of kilometers[1]. Although the setup of such links is fairly easy and economical (e.g., compared to the setup of a DS-3 wireless link) initial investigations have shown that the usage of these links in a multi-hop environment (which is often used to built a mesh network infrastructure) can lead to performance degradations. Especially, in the case of high-frequency wireless equipment interference and antenna characteristics can have a significant impact on performance.

Our interest in the performance and configuration of multi-hop long-distance 802.11g mesh networks is driven by the need for a solution that allows us to connect low-powered radars which are spaced approximately 10 km apart on the island of Puerto Rico [3]. There is little knowledge of how weather, terrain, and interference between radio equipment influences the quality of multi-hop, long-distance wireless links. In the case of interference, antenna placement and channel allocation can have an impact on throughput. To investigate this impact in more detail we created an experimental test setup in which we varied the orientation of the antennas and the distance between antennas at the multi-hop node. We performed throughput measurements for each of the configurations. The results of these measurements show that the placement and orientation[2] of antennas at multi-hop nodes has an significant impact on the throughput. For example, in the case of an end-to-end data transmission without channel separation between the two links at a multi-hop relay, the throughput can vary from 3 to 14 Mbps, depending on the antenna orientation and placement. In the case of completely separated channels, almost full channel capacity can be achieved on both links during simultaneous transmission on the links.

The remainder of this paper is structured as follows. Section II presents related work on interference measurements for 802.11 based networks. We present the setup and the different scenarios we choose for our measurements in Section III and discuss the results in Section IV. Further analysis of the measurements based on packet traces is presented in Section V. Finally, Section VI concludes the paper and takes a look at future work.

II. Related Work

The effect of interference between different 802.11 radios has been investigated for different scenarios. A series of investigations has been performed in an indoor environment with omni-directional antennas [4], [5], [6], [1]. In addition, there is work that reports on measurements for long-distance links with directional or omni-directional antennas [1], [7], [8], [2]. Despite the fact that this work on long-distance 802.11 measurements reveals some very interesting insights, these

[1]The actual distance is dependent on the gain of the directional antenna and the characteristics of the environment in which the link is set up.

[2]Throughout the paper, orientation defines the direction in which the directional antennas are pointing their main lobe.

investigations have not been approached in a systematic way. The authors usually chose one or more problems that were specific to their network topology or to an application that is used on top of the multi-hop wireless network. As an example, in [7] the authors measure the interference between two directional antennas, which have a 90° difference in orientation, but no information about the spatial separation of these antennas is given. This latter consideration has been shown to be a particularly important factor in determining the performance of a multi-antenna relay node [2]. Our approach is somewhat different from the methods applied in the indoor and outdoor measurements mentioned above. Since we are primarily interested in the influence of interference caused by the placement of directional antennas at a multi-hop node, indoor measurements are not an option. On the other hand, extreme long-distance links with distances of several kilometers would not have allowed us to determine placement and direction of the antennas with the appropriate degree of freedom. Therefore, we chose a setup that gave us a high degree of freedom as can be seen in Section III.

III. MEASUREMENTS

The main goal of our measurements was to better understand the basic effects of interference and antenna characteristics in a multi-hop long-distance setup. A schematic overview of the three different setups used for the measurements is shown in Figure 1. The relay point in the center of the setup can be seen as virtually one node. To avoid inter-radio interference effects *within* a single node that have already been investigated in detail in earlier work [6], [7] and to simplify the measurement setup we used two laptops (Lenovo T60) each equipped with a Proxim 802.11 b/g WLAN adapter. The laptops at the multi-hop node were placed 4 ft apart from each other to assure that interference between the wireless radios is negligible. Each WLAN adapter was connected to a directional antenna while, for the cases in which routing between those laptops was enabled, the laptop pair itself is directly connected via their wired Gigabit Ethernet interfaces. Nodes 1 and 4 in Figure 1 are identical to Nodes 2 and 3. All four laptops have Linux 2.6 and the MadWifi 0.9.2 Linux kernel device driver for the Atheros WLAN chip set installed. The directional antennas connected to each WLAN adapter are Hyperlink Technology 14.5 dBi Yagis (HG2415Y). For all measurements the WLAN interfaces were configured in ad-hoc mode and each of the two links was configured with a different ESSID. Figure 2 shows the setup of the antennas at the multi-hop node.

We performed the measurement reported here in an open field (part of the university soccer fields) with no obstacles (trees, buildings). The decision to use this location was made because i) we are mainly interested in effects on the data throughput caused by the antenna characteristics and their positioning on a multi-hop node, and not by the effects of different outdoor environments (urban/rural areas, trees, hills), ii) an open field gave us the most flexibility in node locations, e.g., this location allowed us to freely move Node 4 to vary the angle of link 2 in the way as shown in Figure 1. We

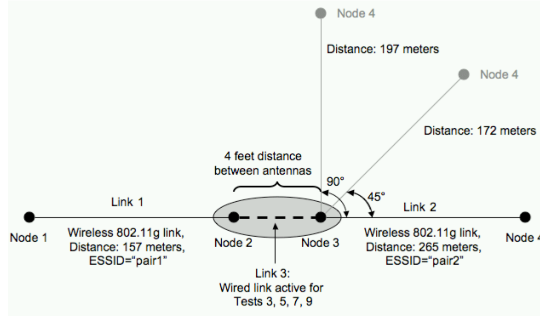

Fig. 1. Measurement setup

Fig. 2. Multi-hop node setup

used Iperf[3], a tool to measure maximum TCP bandwidth, to investigate how the different setups would change the overall performance of the multi-hop link. Additional tcpdump[4] traces were taken in order to obtain more detailed information on a per-packet level. Each measurement ran for 30 seconds and was repeated 10 times. We decided to repeat each measurement 10 times to average out the effects of any short-term artifacts on the wireless channel.

A. Node Location and Spatial Separation

As shown in Figure 1, Node 4 was set up in 3 different locations while Node 1 and the multi-hop node (composed of Nodes 2 and 3) stayed in fixed locations. In the multi-hop node the only change that was made for the different setups was the orientation of Node 3's antenna to line it up with Node 4's antenna. For all measurements except one the two antennas at the multi-hop node were placed 4 feet from each other in the horizontal plane, with no separation in the vertical plane. In the setup for the final measurement we also separated the two antennas at the middle node by 4 feet in the vertical plane. We assumed that a distance of 4 feet would be a separation distance typical of installations on communication towers.

Five different setups, which are explained in more detail in the following, were used for the throughput measurements. In

[3]http://dast.nlanr.net/Projects/Iperf/
[4]http://www.tcpdump.org/

setup 1, all nodes are located along a virtual line. The two antennas at the multi-hop node are mounted in a way that they point directly away (180°) from each other. In setup 2, link 2 is shifted by 45°, resulting in a 135° angle between the main lobes of the two antennas at the multi-hop node. Link 2 is shifted by 90° in setup 3, which also results in a 90° separation of the antennas. Setup 4 is identical to setup 3 with the difference that the polarization of the antennas of link 2 is changed from horizontal to vertical. This is achieved by rotating the mounting of the Yagi antennas by 90° in the horizontal plane. Setup 5 is identical to setup 1 with the difference that the antennas were not only separated by 4 feet in the horizontal but also by 4 feet in the vertical plane.

B. Transport Scenario

We performed measurements where data was transmitted in two different ways.

- N4 → N3 | N2 → N1: Here, N4 and N2 are sending data simultaneously to N3 and N1, respectively.
- N4 → N3 → N2 → N1: N4 is sending data all the way to N1 in this scenario. Thus, routing between N2 and N3 is enabled.

We chose this specific routing configuration for several reasons. In the first scenario we want to investigate the interference that is caused at a multi-hop node with directional antennas when one radio is receiving while the other one is sending. In the second scenario, we were interested in studying the effects of concurrent forwarding on the N1-N2 and N3-N4 links, as well as the effects of routing on the wired link 3 in the multi-hop node. The second case is interesting since in many cases data will be routed through the multi-hop node between the two end nodes. For example, in the case where such a multi-hop node is used to allow data transmission from a remote sensor network. Here, the multi-hop node is neither a source nor a sink. The first case reflects a scenario in which the multi-hop node also acts as a source or a sink. One example for such a scenario is the radar network described in [3] where data is not only forwarded at the multi-hop node but new data is also generated by the sensor (radar) located at that node. Another example is the case where overlay mechanisms like overlay routing or TCP relay are applied which "split" the end-to-end TCP connection.

C. Baseline Measurements

We performed two preliminary measurements in a single link setup to measure the maximum throughput on that link without any interference from the other link. The first measurement was executed in the same open field where all multi-link measurements were performed. We ran an Iperf measurement on one link only, while the other one was idle, which resulted in 27 Mbps of average throughput. This throughput value is the upper limit for the multi-hop measurements. In the second setup we were interested how the throughput would change on a much longer link. Therefore, we set up a link of approximately 1 Mile in hilly terrain. Here, the Iperf measurement resulted in an average throughput of 25.54 Mbps.

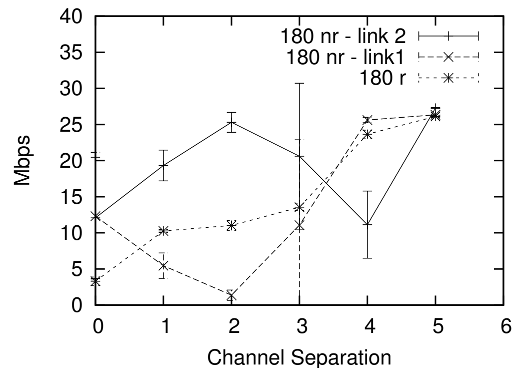

Fig. 3. Throughput results for routing vs. non-routing (180°)

IV. Results

In the following we present the results of the measurements described in Section III. The x-axis shows the channel separation between links 1 and 2. Channel separation was varied by fixing link 1 at channel 1 and varying the channel for link 2 from 1 to 6. The y-axis shows the throughput in Mbps measured by Iperf. An 'nr' in the legend refers to the non routed configuration; 'r' refers to the routed configuration. We plot the mean value for these measurements; the interval width shows one standard deviation.

A. Routing vs. Non-routing

If we compare the cases with routing at the middle node enabled, and disabled, it becomes obvious that routing has a coordinating effect on the data transmission. As shown in Figure 3, the throughput on link 1 and 2 is quite asymmetric for the non-routing case (1.35 Mbps for link 1 and 25.29 Mbps for link 2 at a channel separation of 2).

In the routing case, the effective end-to-end bandwidth is higher except when links 1 and 2 are operating on the same channel. This improvement in throughput in the routing case is caused by the fact that the transmission of packets is more correlated than in the non-routing case. In the routing case, it is less likely that both interfaces will send packets simultaneously.

We looked deeper into this problem to analyze the root cause of the worse performance in the non-routing case. Results from analysis of the tcpdump traces that were taken during the measurements are presented in Section V.

B. Antenna Orientation at the Multi-hop Node

The influence of the orientation of the two directional antennas at the multi-hop node becomes most obvious in the routing case (see Figure 4). When both links are operated on the same channel (both on channel 1), the throughput is increased by more than 10 Mbps when the orientation of the antennas is changed from 180° (3.29 Mbps) to 135° (13.52 Mbps). The increase becomes smaller with increasing channel separation and throughput is equal in the case of complete channel separation for link 1 and 2. Figure 4 also shows that, in

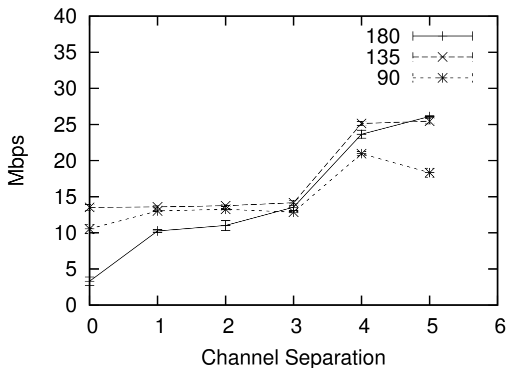

Fig. 4. Throughput results for the routing case with varying antenna separation (180°, 135°, 90°)

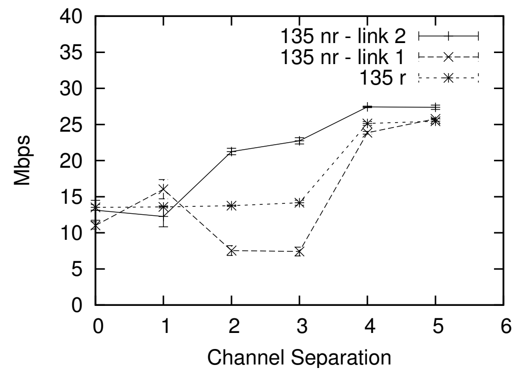

Fig. 5. Throughput results for routing and non-routing in the 135° case

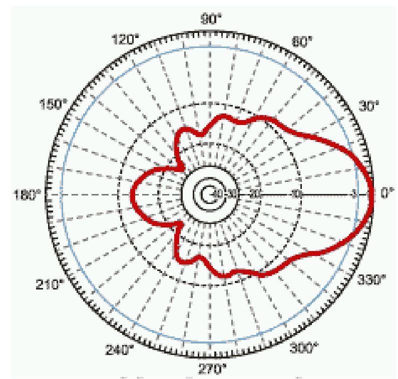

Fig. 6. Horizontal pattern for 14.5 dBi directional antenna

the case of completely separated channels, almost full channel capacity (Section III-C) can be achieved on both links despite concurrent transmissions on both links. We should mention that the result for 5 channel separation in the 90° case was influenced by unidentifiable interference on channel 6. We repeated this measurement with a channel setting of 3 and 8 for links 1 and 3, respectively. In this case, the throughput results were similar to the 180° and 135° cases.

For the 135° non-routing case (shown in Figure 5) the difference in throughput on link 1 and 2 still exists but is smaller than in the 180° case (7.53 Mbps for link 1 and 21.25 Mbps for link 2 for a channel separation of 2). Compared with the routing case, the end-to-end bandwidth is still lower but also here the difference has decreased.

A closer look at the antenna gain patterns (see Figure 6) explains the difference in throughput. The directional antennas used in the measurements have a strong back lobe. In the 180° measurement the interference between the antennas is high due to these back lobes which are directly pointing at each other. This is different for the 135° measurement, since the side lobe in the horizontal plane has its minimum at this angle. We should mention that there was some interference at Node 1 from Node 4's signal in the 180° case which make the results for that case slightly worse as in the case of no interference (Nodes 1 and 4 would be placed further apart or, alternatively the transmit power at Node 1 could be reduced). Due to the directional characteristics of the antennas the interference between Nodes 1 and 4 is negligible in the 135° and 90° cases. Nevertheless, the influence of the antenna pattern, and hence, orientation at the multi-hop node is reflected in the resulting throughput. Compared to the 135° case the throughput in the 90° case is lower if both links are operated on the same channel due to the increased side lobe of the antennas at 90°.

These measurement results clearly show how important the role of antenna orientation at the multi-hop node is in relation to interference.

C. Mixed Antenna Polarization

In this setup, we changed the antenna polarization of link 2 from horizontal to vertical by rotating the antennas by 90°. As can bee seen in Figure 7, changing the antenna polarization has a more significant effect in the non-routing case. Here, the throughput on link 2 (the one with the mixed/opposite polarization) improves between 10.79 Mbps (no channel separation) and 3.72 Mbps (completely separated channels). There is also an improvement in throughput in the routing case but it is less significant. This might be caused by the fact that link 1 is the limiting factor in the end-to-end transmission between Nodes 1 and 4. We plan on conducting an additional measurement where link 1 is a regular wired Ethernet connection to investigate if our assumption about link 1 being the limiting factor in the routing case is correct.

D. Antenna Separation

As it has been shown in Section IV-B, the orientation of the directional antennas at the multi-hop node has an impact on interference and thus throughput. In many cases the antenna locations cannot be chosen as freely as in our experimental setup. The physical locations of the end nodes and the multi-hop node will determine the orientation of the antennas. Thus, we conducted a 4th experiment in which we added a 4 ft vertical separation (in addition to the 4 ft horizontal separation) between the antennas at the middle node for the 180° case. The measurement results (see Figure 8) reveal that additional vertical separation of the antennas at the multi-hop node can

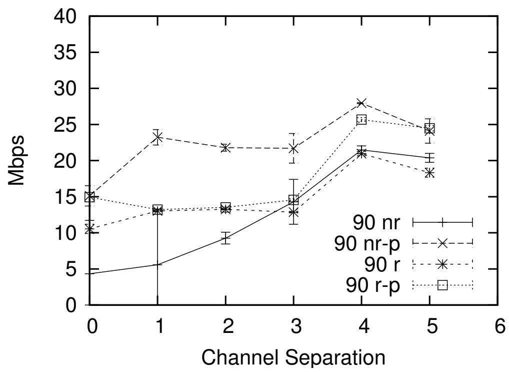

Fig. 7. Throughput results for mixed and uniform polarization on link 2

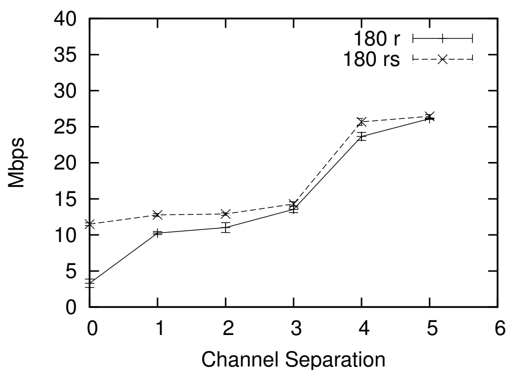

Fig. 8. Throughput results for additional separation in the vertical (180° setup, 'r' routing without vertical separation, 'rs' routing and 4 ft vertical separation)

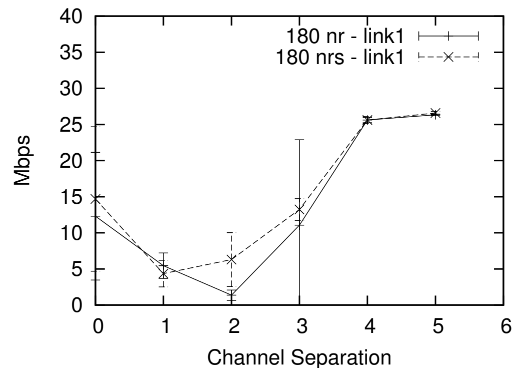

Fig. 9. Throughput results for link 1 with (nrs) and without (nr) additional separation in the vertical (180° setup)

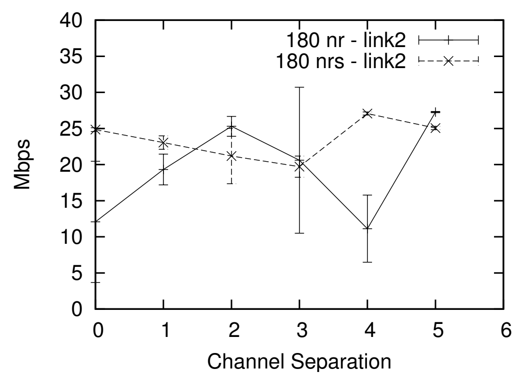

Fig. 10. Throughput results for link 2 with (nrs) and without (nr) additional separation in the vertical (180° setup)

increase throughput for overlapping channels. For example, in the case that both links are operated on the same channel and a vertical separation of 4 ft is introduced, the throughput increases by 8.2 Mbps. The advantage of the setup used for this experiment is the fact that an increase in throughput can be achieved independently from the azimuthal orientation of the antennas at the multi-hop node and thus is applicable for many mesh network topologies.

In the non-routing case the results for link 1 are almost similar to the corresponding 180° experiment without vertical antenna separation (see Figure 9). The results for link 2 are different, they clearly show a trend towards higher throughput in the case of additional vertical separation of the antennas. In the case of no channel separation the throughput for the experiment with vertical antenna separation is 12.78 Mbps higher as shown in Figure 10. In this case, future measurements that also analyze the behavior of the MAC layer protocol are required to find the cause for these results.

V. TRACE ANALYSIS

As already mentioned in Section III, we took additional tcpdump traces for each measurement. We further analyzed the data from these traces in order to see if we could find an explanation for asymmetric throughput result in the non-routing case (see Section IV). Therefore, we analyzed the tcpdump traces of a single measurement with respect to packet loss and round trip time (RTT) and throughput. These traces correspond to the measurement described in Section IV-A for the case of a separation of one channel. Comparing the losses at both link 1 and 2 shows that they are on average only 9% higher for link 1 in the case of a separation of one channel. Thus, packet losses are not a significant cause for the much lower throughput on link 1 which lead us to further analyze the traces for links 1 and 2 with respect to RTT. Figure 11 shows the round trip times for links 1 and 2 while Figures 12 and 13 show the throughput (averaged over 10 segments) for links 1 and 2, respectively. The results for the throughput are consistent with the results shown in Figure 3; the throughput on link 2 is significantly higher than on link 1. The results from the RTT analysis show that the RTTs on link 1 are much higher than on link 2 (the average RTT for link 1 is 43.6 ms while the average RTT for link 2 is 14.4 ms). We assume that the increased RTT is caused by two effects on the MAC layer. First, there might be packet losses on the MAC layer which will not be seen at the network layer due to the retransmission mechanism in 802.11 [9]. But these retransmissions increase the RTT as seen by TCP. Second, the sender on link 1 might

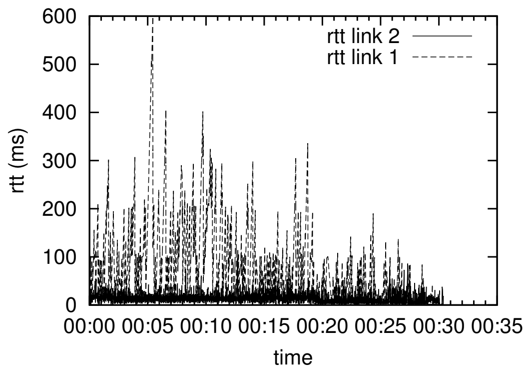

Fig. 11. RTT for link 1 and 2

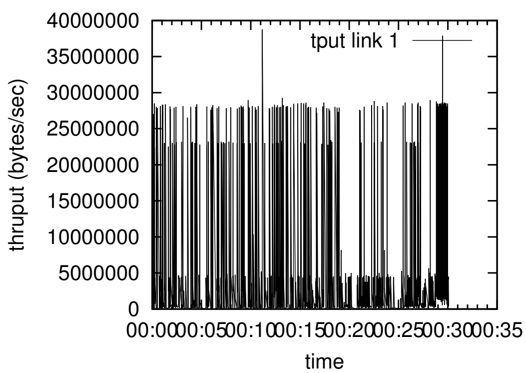

Fig. 12. Throughput on link 1 (average over 10 segments)

not sense the channel to be idle due to interference on the multi-hop node caused by the transmission on link 2. By taking a closer look at Figure 13 one can see that the transmission rate is very high (around 24 Mbps) and interference at the multi-hop node could cause the fact that the channel at link 1 seems to be occupied. In future work, we plan on repeating this measurement with an additional measurement device that allows the capturing and analyzing of 802.11g traffic. We hope that traces from this measurement will allow us to find the exact cause of of the asymmetric throughput results for the non-routing case. We also plan on performing a UDP-based measurement in order to see if we can verify the simulator-based results from [10].

VI. Conclusions and Future Work

Our measurements have shown that the placement (orientation and distance) of antennas on a multi-hop node can have a significant impact on the overall throughput. Some of this behavior finds its explanation in the beam patterns of the directional antennas used in the measurement. In addition, we see an interesting effect on the throughput based on data handling at the multi-hop node. The results show that when routing is enabled interference at the multi-hop node is reduced.

In future work, we plan to investigate impact of weather

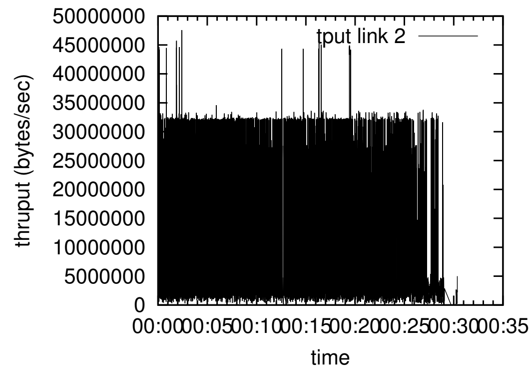

Fig. 13. Throughput on link 2 (average over 10 segments)

and terrain on link quality. This will be possible with the long-distance link between the university campus and a fire tower on a mountain that is 7 Miles apart and in the coverage area of two research weather radars. In addition, we also plan on analyzing the MAC layer behavior in more detail in order to try to find more specific answers for phenomena as the one described in Section IV-A

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