Experimental Investigation of PHY Layer Rate Control and Frequency Selection in 802.11-based Ad-Hoc Networks

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ABSTRACT

This paper presents an experimental investigation of the performance impact of two important PHY layer design options that arise in 802.11 ad-hoc networks. In particular, throughput results are provided for multi-hop ad-hoc networks with and without PHY auto-rate control and for single vs. multiple frequencies. The study is motivated by the fact that default 802.11-based ad-hoc networks using commercially preset auto-rate PHY and a single frequency channel suffer from performance degradations caused by link quality fluctuations and MAC layer self-interference respectively. A baseline ad-hoc network scenario is set up on the ORBIT radio grid testbed at Rutgers and is used to determine end-to-end multi-hop flow throughput with default rate control and single channel operation. These results are then compared with those obtained with multiple channels and alternative PHY-rate selection methods demonstrating the potential for significant performance improvements. We observed significant improvements in end-to-end flow throughput, as much as ~4x for multiple channel vs. single channel and ~3x for optimally controlled PHY rate vs auto-rate.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design – *Wireless Networks*

General Terms

Experimentation, Measurement, Performance

Keywords

Ad-hoc Networks, Multi-hop networks, Experimental evaluation

1. INTRODUCTION

Over the past few years, there has been a great deal of interest in wireless ad-hoc networks and significant effort has been spent in designing better medium access protocols [1, 2, 14] or routing protocols [9, 10, 11]. Much of this work has been done in isolation either assuming an ideal MAC layer when designing routing protocols, or treating routing as an independent issue while designing certain enhancements to the MAC protocol. However, as noted in [4, 5], there is a tight coupling between the PHY, MAC and routing layers that needs to be understood in order to improve the overall performance of the network.

De Couto et al. [5] observed that using the well-known shortest path results in throughput degradation and proposed the expected transmission count metric (ETX) to handle the effects of link losses. Awerbuch et al. [4] explored the multi-rate functionality of the MAC protocol in route selection and suggested that in a fully interfering network, MTM (Mean Time Metric) is an optimal route-selection metric to maximize end-to-end flow throughput. Another metric proposed [7] was WCETT (Weighted Cumulative Expected Transmission Time) which combined both ETX and MTM metrics and extended to networks with devices having multiple radios. In [12], the authors proposed a load-aware metric to assign channels for each radio respectively. More recently in [6], a comparative study on some of current metrics for routing algorithms was reported.

In this paper, we experimentally evaluate two critical PHY layer design components and their impact on the performance of an 802.11-based ad-hoc network. In particular, we consider the impact of PHY auto-rate vs. alternative PHY rate selection methods, as well as single channel vs. multiple channel assignment in 802.11. Using the 64-node ORBIT radio grid testbed [13][1], we evaluate the performance of a multi-hop flow in terms of end-to-end throughput operating under noisy environment using a single channel and default PHY rate selection algorithm implemented on the commercial 802.11 hardware. This is used as a baseline case to compare the performance with the above-mentioned PHY design choices (i.e. alternative rate control methods and use of multiple channels).

The baseline experiment is extended to explore the use of multiple channel selection using "forwarding nodes" with two radios which are capable of operating at different frequencies to avoid MAC layer "self-inference" effects. We also investigate the impact of disabling auto-rate PHY, which is known to create performance problems by rapid rate switching in noisy environments, and using alternative methods to select suitable PHY bit rates on each link.

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It is noted that the purpose of these experiments is to identify potential improvements from the use of these two PHY design options by comparison with the default baseline. This contribution is to serve as an indication of achievable improvements with available PHY enhancements, rather than a complete cross-layer solution for ad-hoc networks. A specific topology discovery, rate control and routing strategy that takes advantage of the proposed PHY enhancements requires further work and will be reported in a future paper.

The remainder of the paper is organized as follows: Section 2 describes the experimental methodology including noise injection at desired frequencies and power levels using a raw waveform generator to create “noisy” links. We observe the effects of noise on the average PHY rates of some links under test. Section 3 discusses the three experiments described before and the performance enhancement obtained by selecting appropriate parameters. We conclude the paper in Section 4.

2. EXPERIMENTAL METHODOLOGY

2.1 The Testbed

All of our experiments were conducted using 64 wireless nodes arranged in an 8×8 grid as shown in Figure 1. The testbed also incorporates a raw waveform generator that is connected to specifiable antennas on the grid. This generator can be remotely controlled to inject AWGN noise at a desired power level and frequency band, thereby enabling the creation of arbitrary link quality levels and related ad-hoc network topologies.

Figure 1 Prototype 8×8 ORBIT radio grid

Each node has two 802.11 a/b/g cards that can be used to set up arbitrary topologies. By operating the second interface on a different channel, multi-channel forwarding can also be implemented. We also have supporting software libraries that allow us to extract useful information such as RSSI, PHY rate from the device driver on a per packet granularity. The reader is referred to [13] for further details on the ORBIT testbed used for these experiments.

2.2 Topology

We conducted initial experiments to observe the effect of noise on the average PHY rate of the links under test. Figure 2 illustrates the choice of nodes, links and the positions of the noise antennas. All the wireless cards for this experiment use 802.11a PHY. As mentioned before, the noise generator can be controlled to inject AWGN noise at a desired power level and frequency (from baseband to 6 GHz) [3].

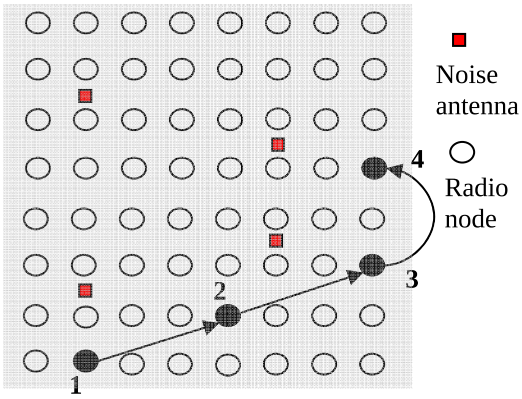

Figure 2 Experimental topology

In this experiment, we measured the average PHY rate of each link over a 120 second interval. A traffic flow of 512 bytes UDP datagrams at 50 packets per second is transported from one sender to one receiver under the influence of noise at -12 dBm. The transmit power of the sender was set to 20dBm. The PHY rate automatically adjusts to channel conditions using the default auto-rate adjustment algorithm implemented in the driver/firmware of the card (Atheros AR 5212 chipset)[2]. Figure 3 shows the fluctuation of the average PHY rate per second (averaged over 50 consecutive packets since we can report the selected PHY rate per packet) on one such link (1 to 2).

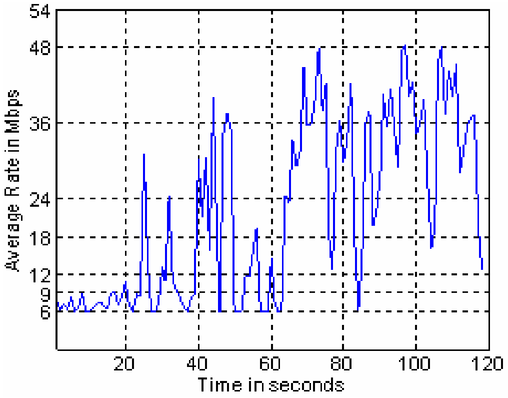

Figure 3 Fluctuation of the average PHY rate over the experiment duration at -12 dBm

This automatic PHY bit-rate adaptation feature is considered to be useful in WLAN systems because it permits end-users to take advantage of good-quality short-range links when available. However, one of the consequences of the automatic rate adaptation is the rapid rate fluctuation observed in Figure 3. Most auto-rate mechanisms adapt to the link quality based on packet loss measurements. Similar observations have been described in

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[2] THE IEEE 802.11 Standard [8] does not specify how auto-rate should be implemented. Therefore, manufacturers have their own proprietary algorithm for this scheme.

previous work [6], where the bandwidth of many links oscillates over a long time span, thereby making calibration necessary to determine the actual bandwidth. The fluctuations caused by auto-rate PHY algorithm may lead to an inefficient utilization of the link capacity resulting in a lower end-to-end throughput.

3. Experimental Results

In this section, we describe the three different scenarios that were studied. In the experiment, all hops on the same path always interfere with one another if they operate on the same channel. This assumption is usually true for small networks and short paths, resulting in links in the same "collision" domain.

3.1 Baseline Case: Single Channel with default Auto-Rate PHY

This is the baseline case that we used to compare with the PHY enhancements under consideration. In this scenario, as shown in Figure 4, all the wireless interfaces operate on the same 802.11a channel (channel 48, with center frequency at 5.24 GHz). Although the forwarding nodes use two radios, simultaneous transmission and reception is not possible since the radios are on the same channel. The transmit power of each radio is set at 20 dBm.

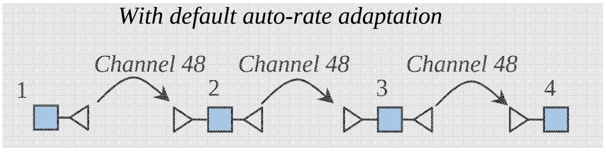

Figure 4 Single channel with default auto-rate

We injected noise at the center frequency of 5.24 GHz at different levels ranging from -18 dBm to -5 dBm. Also, the offered load was ramped up from 4.2 Mbps to 16.8 Mbps for each of these noise settings. Figure 5 shows the maximum throughput that was achieved under different noise power levels.

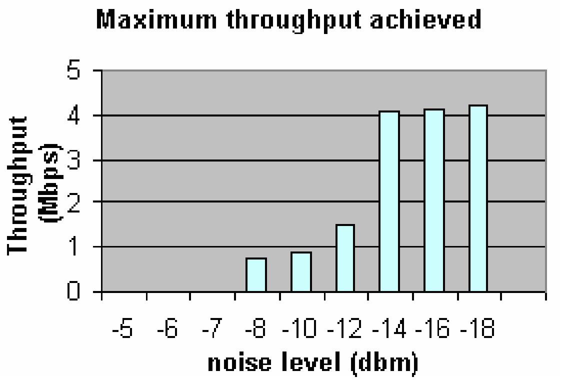

Figure 5 Maximum throughput at each noise power level

It can be seen that the throughput saturates around 4 Mbps irrespective of the offered load as we reduce the noise power levels. At higher noise levels (in the left side of the graph), the rate fluctuation causes the overall system throughput to decrease until it finally reaches zero where one (or more) of the links is completely cut off because of the noise. Note that the noise may affect each link differently based on the distance of the link from the noise source, yielding different average PHY rates on these links.

3.2 Channel Diversity with default Auto-Rate PHY

In this scenario as shown in Figure 6, the forwarding node operates on orthogonal frequencies and uses two radio interfaces. Thus, simultaneous transmission and reception is possible. The transmit power of each radio is set at 20 dBm. As before, noise was injected at the center frequency of 5.24 GHz (channel 48) at different power levels ranging from -18 dBm to -5 dBm. Note that in this case, the noise just affects one of the links (from 2 to 3)

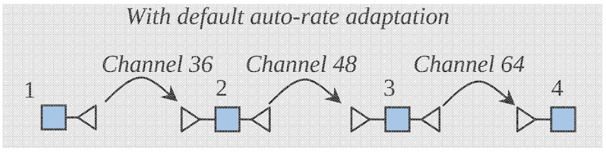

Figure 6 Orthogonal channels with default auto-rate

Figure 7 shows the end-to-end throughput under different offered loads and noise power levels.

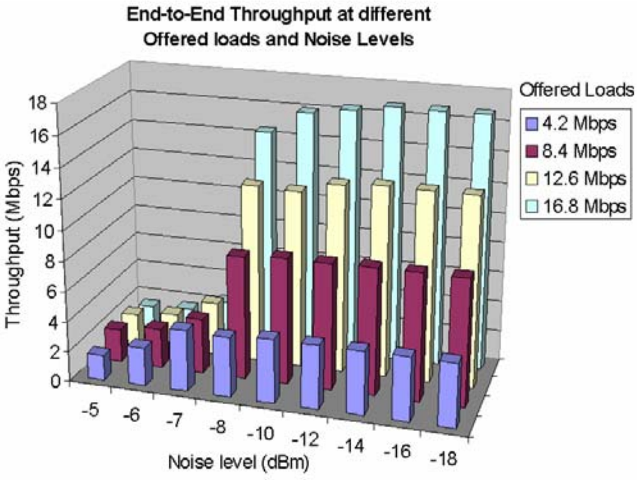

Figure 7 End-to-end throughput using orthogonal channels

In the previous case using single channel, the throughput saturates at around 4.2 Mbps. In this case, however, the throughput increases up to 16 Mbps by using three different channels, a gain of ~4x for the specific flow under consideration. This is because the noise affects only one of the links (from 2 to 3) in this case. In the previous case, there is zero throughput at -5 dBm, where as in this case, a low throughput (~2 Mbps) can still be sustained. We believe the reason for this is that the link between 1 and 2 is completely cut off in the first case, even though the other two links are still operational.

3.3 Channel Diversity with Selectable PHY Rates

In this case, as shown in Figure 8, the effect of auto-rate selection on the system throughput was evaluated using the same scenario as described in the previous case of orthogonal channels. However, in this experiment, instead of using the default rate adaptation algorithm, we tried out different combinations of PHY rate settings (R1, R2, R3) on the three links manually. Note that the cards support the capability to use fixed rates as specified by the user (using *iwconfig* [16] utility). Here, we fixed the noise level to -6 dBm on channel 48 such that it affected only link 2 to 3 as before.

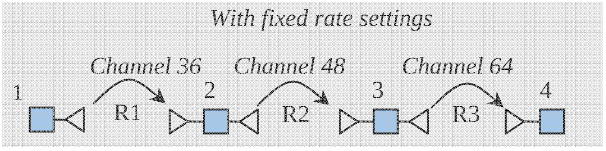

Figure 8 Orthogonal channels with auto-rate disabled

Different offered loads ramping up from 4.2 Mbps to 16.8 Mbps were tried for each of these 3-tuple rate settings and the corresponding throughput was measured. The results are shown in Figure 9 (e.g 6, 6, 6 means that R1 = R2 = R3 = 6 Mbps).

The experiment shows that because of the noise, there is zero throughput when rate is fixed at 48 Mbps and 54 Mbps because the PHY modulation schemes corresponding to those data rates experience a high packet loss rate. Auto-rate outperforms only two fixed-rate settings: (6, 6, 6) and (12, 6, 12). In all the other cases, up to (36, 36, 36), we see that setting reasonably chosen fixed rates on each link performs better than auto-rate adaptation. The improvement is as large as ~3x from auto-rate to the best rate selection case. This shows that auto-rate algorithm implemented on the driver/firmware is possibly too conservative because when the rate fallbacks to a lower level, it ramps up gradually thereby reducing the efficiency of the link utilization.

It is observed that the above experiment shows large potential gains when auto-rate is replaced with suitably selected PHY rates. Note that we do not actually provide an algorithm for selecting these rates. But the experiment show that a potential reasonably efficient algorithm can be implemented in a cross-layer ad-hoc protocol framework, which is the focus of our ongoing work. A specific topology discovery and routing protocol that exploits multiple frequencies and selectable PHY rate will be reported in further work.

Finally, we note that the performance evaluations here concentrate on a single multi-hop flow which would tend to overestimate the achievable gains when compared with a system level evaluation that takes into account multiple flows and routing in the network as a whole.

4. CONCLUSION AND FUTURE WORK

In this paper, we experimentally investigated two important PHY design options that arise in multi-hop wireless ad-hoc networks built with 802.11 radios. Our experiments suggest that using multiple radios working on orthogonal channel can significantly increase the system performance by a factor of as much as ~4x.

In addition, disabling auto-rate PHY and suitably selecting link bit-rates can provide additional performance gains in 802.11-based ad-hoc networks. In our current work, we are investigating other ad-hoc network enhancements at various layers including PHY power control, topology discovery, MAC scheduling and PHY/MAC aware routing [15]. A specific cross-layer design which exploits the proposed PHY enhancements along with other useful MAC and routing level mechanisms will be proposed and evaluated in future work.

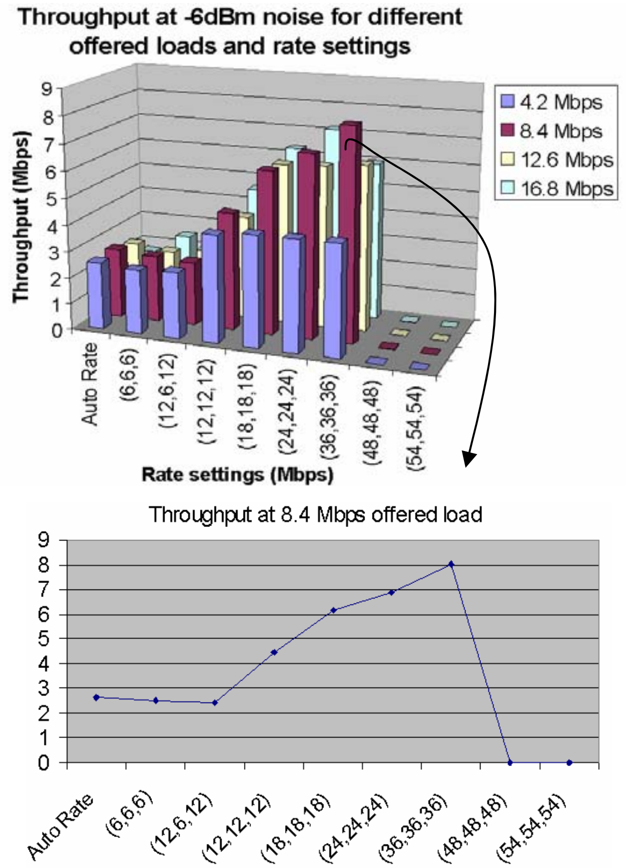

Figure 9 Auto-rate vs. fixed rate settings using orthogonal channels

5. ACKNOWLEDGEMENTS

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