Wireless Reliability: Rethinking 802.11 Packet Loss

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Abstract

Wireless enabled devices are ubiquitous in today's computing environment. Businesses, universities, and home users alike are taking advantage of the easy deployment of wireless devices to provide network connectivity without the expense associated with wired connections. Unfortunately, the wireless medium is inherently unreliable resulting in significant work having been performed to better understand the characteristics of the wireless environment.

Notably, many works attribute the primary source of wireless losses to errors in the physical medium. In contrast, our work shows that the wireless device itself plays a significant role in 802.11 packet loss. In our experiments, we found that the correlation of loss between multiple closely located (within one λ) receivers is low with the majority of loss instances only occurring at one of the receivers. We conducted extensive experiments on the individual loss characteristics of five common wireless cards, showing that while the cards behave similarly on the macro-level (e.g. similar overall loss rates), the cards perform quite differently on the micro-level (e.g. burstiness, correlation, and consistency).

1 Introduction

802.11 wireless devices have become commonplace in today's computing environment. In both the home and in business, the easy deployment of wireless is leveraged in order to provide Internet connectivity to users. The potential applications for wireless communication are extensive ranging from Internet connectivity to games to military-based applications as well as numerous other applications.

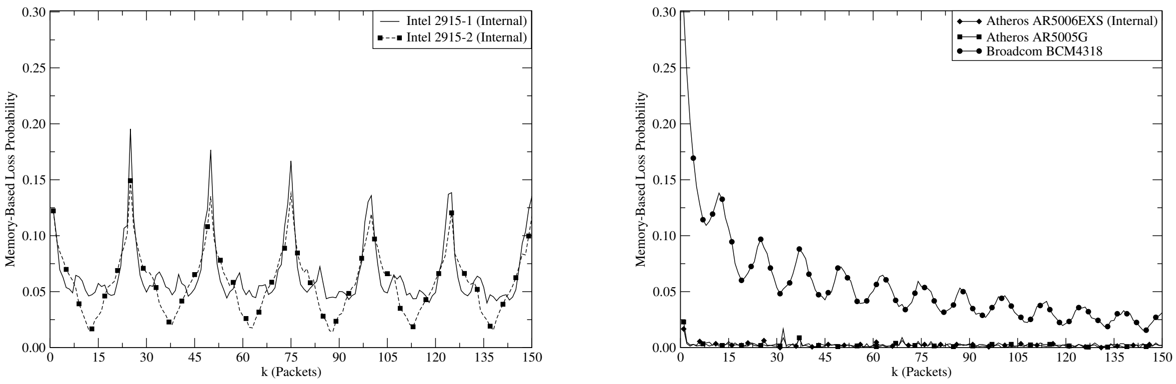
Considering the ubiquity of 802.11 devices, it is important to correctly understand the characteristics of the wireless medium in order to improve wireless performance [5, 6, 1, 2, 7]. Chief among the characteristics is an understanding of the underlying loss dynamics of the medium due to the significant implications for reliability and interaction with higher level network layers. Traditionally, errors in the physical medium have been viewed as the dominant factor in patterns of packet loss. In contrast to previous work, this paper points to a significant alternative source of error, the wireless device itself. We justify our findings through two key observations from our experiments:

- *Lack of Packet Loss Correlation:* It is expected that nodes in immediate proximity would exhibit highly correlated loss if loss is primarily determined by the physical medium. In our experiments, we show that the packet loss correlation between closely located nodes is low, indicating that a substantial portion of loss is due to localized errors at the receiving device. Moreover, the results occur consistently despite observations across different days, different positions, and different close proximities.
- *Varying Loss Burstiness:* It would be expected that different but closely located wireless devices should display similar patterns of loss burstiness if physical medium errors are the dominant source of packet loss. Conversely, we show how several popular wireless cards have significantly different loss patterns despite possessing a similar overall loss rate.

Our results indicate a benefit from having multiple antennas at the receiver. Such a concept is not new in that having multiple receiving antennas while only having a single sending antenna is simply a degenerate case of MIMO [4]. However, MIMO relies on the separation of antennas (normally large multiples of the wavelength) in order to provide increased performance or reliability [9]. This work notes differences in performance between closely spaced antennas (less then one wavelength), where MIMO is not expected to provide benefit.

While other works have attempted to understand the underlying sources of packet loss by dispersing numerous monitoring nodes throughout an environment [1, 3], the

978-1-4244-2100-8/08/$25.00



(a)

(b)

Figure 1. Memory-based loss performance of (a) Intel 2915 and (b) other wireless cards.

works make implicit assumptions regarding the accuracy of the devices. In contrast, our experiments took a skeptical view of the accuracy of a single device with regards to physical medium loss by placing multiple devices in close proximity. To that end, we investigated a variety of scenarios and configurations by validating our results over multiple monitoring periods, monitoring environments, device placement, and device orientations.

2 Experiments

The setup of our first experiment, conducted in our lab with a single sender and three closely located receivers which are 3.665 meters from the sending node. The hardware used in the experiment are identical in every way with the exception of their wireless cards. In Case 1 R_1 and R_2 use identical and use the same Intel 2915 wireless card and R_m uses an Atheros AR5006EXS. In Case 2 R_1 uses the Broadcom BCM4318 and R_2 uses an Atheros AR5005G, while R_m uses the same as in Case 1. The laptops were configured in Ad-Hoc mode using channel 1 with no overlapping wireless networks present. All cards were rate locked at 54 Mb/s for their transmission rate. Additionally, all systems and wireless cards had their power management features disabled. Finally, all systems were connected to power such that the battery would not play a role in packet reception [8].

In the experiment, nodes R_1 and R_2 received a broadcast stream from Node S. Node R_m was used to record all wireless traffic on the channel, including management frames via the MadWifi driver. Node S broadcasted a UDP, CBR stream of 16 Mb/s[1] with 1500 byte data packets (about 1400 packets per second) to both receivers and the monitoring node. Each experiment was performed several times, 15 minutes each, in order to verify results[2].

2.1 Instantaneous Loss Correlation

The loss correlation between the different receivers is shown in Table 1. In Table 1, each column shows the probability of loss with the given conditions where, for example, column two is $P(R_1|R_2)$, which is read as the "probability that node R_1 loses a packet given that nodes R_2 lost the packet". From Table 1, it can be seen that there is a very low correlation (< 0.50) of loss between the different devices. In fact, the only situation where there is a high correlation between losses is in Case 2 when any two of the three receivers loses the same packet, the third receiver is likely to lose the packet. The low correlation of loss may be justifiable if the receivers were using different hardware and had substantially different performance overall. However, nodes R_1 and R_2 in Case 1 are identical in every respect and have similar overall loss rates (as shown in Table 2). Moreover, the results are not merely an isolated incident. The results were repeated over different days, different laptop positions (swapping of R_1 and R_2), laptop rotations, and different close separations (within one λ) between R_1 and R_2.

In Case 2 each of the nodes experiences a low overall

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[1] 16 Mb/s was the maximum achievable rate of our equipment, before significant loss was seen due to send buffer overflow.

[2] The original data in addition to further analysis and results can be viewed at *http://netscale.cse.nd.edu/twiki/bin/view/Main/WirelessReliability*.

	Instantaneous Loss Correlation					
	$P(R_1\|R_2)$	$P(R_1\|R_m)$	$P(R_2\|R_1)$	$P(R_2\|R_m)$	$P(R_m\|R_1)$	$P(R_m\|R_2)$
Case 1	0.0354	0.1912	0.0323	0.1405	0.0053	0.0042
Case 2	0.2307	0.3083	0.2456	0.3057	0.2310	0.2129

Table 1. Instantaneous loss correlation.

	Node(s)	**Loss Rate (%)**
Case 1	R_1	3.886
	R_2	3.550
	R_m	0.107
	$R_1 + R_2$	0.126
	$R_1 + R_m$	0.020
	$R_2 + R_m$	0.015
	$R_1 + R_2 + R_m$	0.012
Case 2	R_1	0.152
	R_2	0.162
	R_m	0.114
	$R_1 + R_2$	0.037
	$R_1 + R_m$	0.035
	$R_2 + R_m$	0.035
	$R_1 + R_2 + R_m$	0.034

Table 2. Overall loss performance.

loss rate. At first we believed the lower loss rate for R_1 and R_2 was due to the fact that in Case 2 the wireless cards were external. However, we noted the cause for the discrepancy in loss rates as a property of the Intel card (results not shown). Overall, the results in Table 1 demonstrate that loss between the multiple receivers is not substantially correlated.

2.2 Burstiness of Loss

As the previous section indicated, wireless loss patterns can be substantially influenced by the wireless devices themselves and may not reflect the actual performance of the medium. Thus, we investigate the burstiness of the medium with respect to each device independently as well as the combined results of the cards in each case. Fig. 1 shows the memory-based loss properties of five different wireless cards. If loss is memory-based, it would be expected that for small values of k that the loss rate will be substantially higher than the overall average loss rate.

In Fig. 1(a) the memory-based loss properties are shown for the two Intel 2915 wireless cards. As can be seen, the two Intel cards have a very similar pattern as far as memory-based loss is concerned, even though the packets that are lost are not likely to be the same (broadcasts are not retried). Fig. 1(b) shows the memory-based loss performance of the other three wireless chipsets. In both graphs each card shows some tendency toward memory-based loss. However, the magnitude of the effect varies greatly from card to card. The Atheros based cards perform the best, with only a slight indication of memory-based loss. Both Intel cards demonstrate an oscillating pattern of loss probability after an initial loss even though the instantaneous loss correlation between the two systems was low. Thus, the low correlation of loss combined with similar loss rates and pattern of loss indicate a hardware or driver issue. This is not an OS issue, nor is it a property of the wireless medium as the Atheros cards do not exhibit such a pattern, and the Broadcom card has a different pattern.

2.3 Effect of Distance

The final result presented looks into the effect that distance has on the correlation of losses. An abbreviated result is shown in Table 3. In this experiment only two receivers are used, the distance is varied from 2 meters to 12 meters and a large lecture hall is the location. The results indicate that as the distance increases between the sending and the receiving nodes the loss correlation increases. When the distance is increased the signal strength becomes weaker, and increases the chances the packet will be lost to both receivers. However, even in this setting significant gain in loss performance can be had from multiple closely located receivers even at larger distances.

Once background traffic[3] is introduced (not shown), the loss correlation for the receiving nodes 12 meters from the sending node is substantial at 70% to 80%. For the three meter case significant reduction in loss can be obtained from using multiple receivers (74% loss eliminated), while at 12 meters only 15% of the loss could be eliminated.

3 Related Work

As previously stated, there have been multiple works investigating the loss performance of the wireless medium. Four such works are [5, 6, 1, 2]. In [5], Mui et al. present a study of the wireless medium, in a typical office environment. In their experiments two senders located in different locations transmit separate streams to a single receiver.

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[3] Background traffic is introduced via TCP connections between two additional nodes transmitting on the same channel.

	Instantaneous Loss Correlation		**Loss Rate (%)**		
Distance	$P(R_1\|R_2)$	$P(R_2\|R_1)$	R_1	R_2	$R_1 + R_2$
3 meters	0.1051	0.2683	1.9951	5.0910	0.5352
6 meters	0.1629	0.2158	6.1762	8.1833	1.3328
9 meters	0.2664	0.2860	8.6767	9.3145	2.4815
12 meters	0.3138	0.3585	8.6198	9.8501	3.0905

Table 3. Distance: Instantaneous loss correlation.

The authors investigate memory-loss based burstiness and demonstrate a high correlation between a packet being lost and subsequent packets from the same stream being lost. However, very little correlation of loss was shown across the two streams sent to the receiver. Thus, Mui et al. concluded that interference near the senders was not likely to be detected properly.

In [6], Reis et al, perform wireless measurements with fifteen stationary 802.11b wireless nodes spread throughout a floor of the building. As with [5], broadcasts were then transmitted between each of the clients. Using the data collected at each node, they drew conclusions about wireless loss and interference. The work did not explore the possibility of different observed loss rates, by similarly located devices.

The next two works [1, 2], investigated the loss characteristics on long-distance 802.11b wireless links. In [1], Aguayo et al, use the Allen Deviation to show that the wireless links have a slight tendency on burstiness. However, in [2], Chebrolu et al. determine that burstiness may not be an inherent property. Their result is likely due to the fact that they start with a low data rate, and the data rate is further decreased when looking at larger time windows. This causes the random generated loss to fluctuate significantly even at larger time intervals due to the low number of packets sent for each interval.

Finally, our work differs in that these works (and others) concentrate on large distances between nodes and typically the nodes are in a very noisy environment. Our results are similar to theirs in those situations, however when the signal strength between the sender and receiver is good, we note very little loss correlation between the nodes.

4 Conclusions and Future Directions

In conclusion, we have shown that under many conditions, instantaneous packet loss between two co-located identical nodes is not highly correlated as would be expected. However, the two identical nodes do exhibit similar patterns of loss (both memory-based and Allen Deviation measurements) indicating that the observed patterns of loss by an individual node may be a property of the wireless device itself and not the wireless medium.

While previous research has not revealed a similar behaviour in terms of loss, this is likely explained by the fact that that the experimental setups in these works have larger distances between sender and receiving nodes. Additionally, if there are multiple receiving nodes they are typically separated by a significant distance. For these reasons, similar results to ours would not have been observed. It is our belief that future work is needed to explore additional analysis of loss patterns. In light of our results we believe unique opportunities exist for smart localized recovery, especially for dense wireless networks.

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