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 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 (eg. similar overall loss rates), the cards perform quite differently on the micro-level (eg. burstiness, correlation, and consistency).

I. 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 [1]–[5]. 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.

While other works have attempted to understand the underlying sources of packet loss by dispersing numerous monitoring nodes throughout an environment [3], [6], the 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.

The remainder of our work is organized as follows: Section II presents measurements and techniques of measurements used in order to find the underlying loss performance of the wireless medium. Next, Section III through Section V discuss the experiments performed and their results. Related work is presented in Section VI. Finally, Section VII presents conclusions based upon our experiments and discussions regarding future research directions.

II. Metrics for Patterns of Loss

While the overall loss rate of wireless networks is important, the underlying patterns of the loss have significantly greater implications to overall protocol design. Critically, the ability to observe the patterns of loss is predicated on the accuracy of the observation device itself. Hence, the first aspect of loss we investigate is instantaneous loss correlation which refers to the likelihood of multiple closely located receivers losing the same packet. It would be expected that two closely located receivers receiving the same broadcast packets would experience similar dropped packets if loss comes primarily from the physical medium, i.e. the packet is corrupted before it reaches the device. However, our experiments show that there is a low correlation between the losses of co-located receivers, indicating that the receiving device may have a significant role in the pattern of loss. Moreover, the results are not isolated as they occur despite multiple combinations of wireless cards and settings (homogeneous, heterogeneous, orientation, position, etc.).

Conversely, many previous works have focused on the burstiness of loss [1]–[4] rather than localized loss performance. A common method, also known memory-based loss, as presented in [1], [2] is defined as:

$$P(l_{i+k}|l_i) \tag{1}$$

where the above is read: the probability of dropping the $(i+k)^{th}$ packet given that the i^{th} packet is lost. For small values of k, if Eq. 1 is greater than the overall loss ($P(l_i)$), than the loss can be said to be bursty. For larger values of k, if the $P(l_{i+k}|l_i) > P(l_i)$, then that likely indicates a periodic source of interference (ex. beacon interval), not an inherent property of the wireless medium.

Conversely, the works in [3], [4] propose using a modified Allen Deviation to capture burstiness. The modified Allen Deviation measures the average change in loss between adjacent, fixed time intervals as defined by:

$$\sigma_n = \sqrt{\frac{\sum_{i=2}^{N}\left(y_i - y_{i-1}\right)^2}{2(N-1)}} \tag{2}$$

where y_i is the loss at time interval i, and N is the number of time intervals. It is important to note, that unlike the original Allen Deviation, the modified Allen Deviation is not dimensionless and provides an exact measurement of the average variation in loss[1]. In order to determine if loss is bursty, results are graphed against data generated from a uniform pseudo-random number generator. If the two plots overlap significantly, the loss is not bursty. If the two plots are distinct, then the loss shows a trend towards burstiness.

The interactions of the wireless medium with upper level network layers (eg. TCP), the burstiness of the wireless medium cannot be ignored. However, an incorrect measurement of the level of burstiness or the incorrect identification of the source of the burstiness can have profound implications for protocol design. It is our position that while both measures (memory-based loss, modified Allen Deviation) claim to measure burstiness, the measures in fact capture two distinct characteristics. The memory-based loss gives a measurement of how likely subsequent packets are to be lost after an initial loss has occurred. This is useful in determining how much time should pass between attempting a retransmission of a previously failed packet. For longer time intervals, the modified Allen Deviation can be used to determine the time intervals where the loss rate fluctuates substantially. The extraction of such time intervals is useful for dynamic protocols [1], [7] to prevent thrashing due to insufficient monitoring windows.

Critically, a device performing well in one measure does not imply that it will perform well in the other. For example, we show in Section III that the Intel chipsets perform better in terms of memory-based loss than the tested Broadcom chipset, allowing for more aggressive error recovery. However, the Intel chipsets vary more from one time interval to the next in terms of the modified Allen Deviation, necessitating longer monitoring windows for adaptation. To that end, we present results in our experiments using both the memory-based loss measure as well as the modified Allen Deviation measure to better illustrate the performance of the underlying medium. When coupled with instantaneous loss correlation, we believe our experimental results clearly point to the wireless device itself as a potentially significant source of packet loss.

III. Experiment 1: Lab

The setup of our first experiment, conducted in our lab, is shown in Fig. 1. The hardware used in the experiment is shown in Table I. As noted in Table I, R_1 and R_2 were identical systems for Case 1 and all systems were running Fedora Core 6. 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[2] 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[3].

[1]To convert the modified Allen Deviation into the true Allen Deviation, then $y_i = y_i/avg_{loss}$. This results in a measurement indicating the relative magnitude of change in loss from one interval to the next as compared to the overall average loss rate.

[2]16 Mb/s was the maximum achievable rate of our equipment, before significant loss was seen due to send buffer overflow.

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

	Node	Wireless Card Chipset	Driver	Machine	OS
Case 1	S	Intel 2200 (Internal)	Intel 2200/2915 Linux Driver	IBM/Lenovo T43	Fedora Core 6
	R_1	Intel 2915 (Internal)	Intel 2200/2915 Linux Driver	IBM/Lenovo X41	Fedora Core 6
	R_2	Intel 2915 (Internal)	Intel 2200/2915 Linux Driver	IBM/Lenovo X41	Fedora Core 6
	R_m	Atheros AR5006EXS (Internal)	MadWifi Driver	Apple Mac Mini	Fedora Core 6
Case 2	S	Intel 2200 (Internal)	Intel 2200/2915 Linux Driver	IBM/Lenovo T43	Fedora Core 6
	R_1	Broadcom BCM4318 (External)	NdisWrapper	IBM/Lenovo X41	Fedora Core 6
	R_2	Atheros AR5005G (External)	MadWifi Driver	IBM/Lenovo X41	Fedora Core 6
	R_m	Atheros AR5006EXS (Internal)	MadWifi Driver	Apple Mac Mini	Fedora Core 6

TABLE I
HARDWARE USED FOR THE FIRST SET OF EXPERIMENTS.

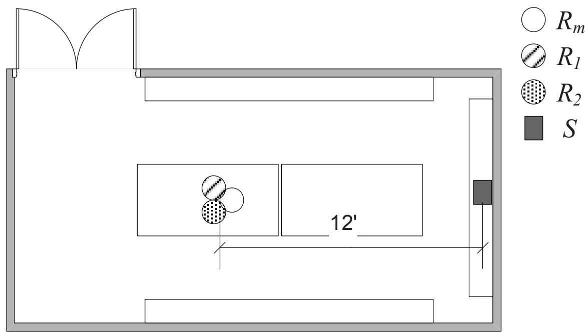


Fig. 1. Experiment 1: Setup

A. Multiple Receivers: Instantaneous Loss Correlation

The loss correlation between the different receivers is shown in Table II. In Table II, each column shows the probability of loss with the given conditions where, for example, column two is $P(R_1|R_{2,m})$, which is read as the "probability that node R_1 loses a packet given that nodes R_2 and R_m lost the packet". From Table II, 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 III). 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 between R_1 and R_2.

In Case 2 each of the nodes experiences a low overall 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, in Section V, we note the cause for the discrepancy in loss rates as a property of the Intel card. Overall, the results in Table II demonstrate that loss between the multiple receivers is not substantially correlated.

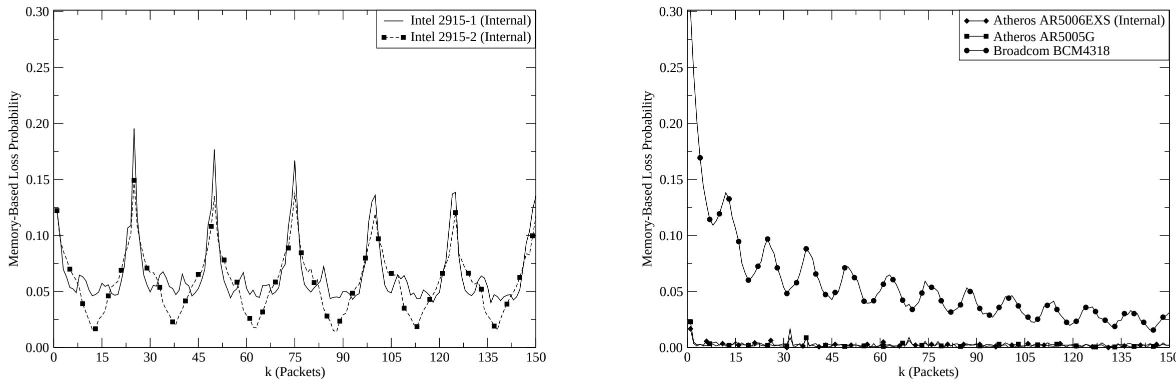
B. Multiple Receivers: Burstiness of Loss

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. 2 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. 2(a) the memory-based loss properties are shown for the two Intel 2915 wireless cards. As can be seen, the two Intel

	Instantaneous Loss Correlation								
	$P(R_1|R_2)$	$P(R_1|R_m)$	$P(R_1|R_{2,m})$	$P(R_2|R_1)$	$P(R_2|R_m)$	$P(R_2|R_{1,m})$	$P(R_m|R_1)$	$P(R_m|R_2)$	$P(R_m|R_{1,2})$
Case 1	0.0354	0.1912	0.4632	0.0323	0.1405	0.5673	0.0053	0.0042	0.0922
Case 2	0.2307	0.3083	0.9750	0.2456	0.3057	0.9852	0.2310	0.2129	0.9225

TABLE II
EXPERIMENT 1: INSTANTANEOUS LOSS CORRELATION.



(a) (b)

Fig. 2. Experiment 1: Memory-based loss performance of (a) Intel 2915 and (b) other wireless cards.

	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

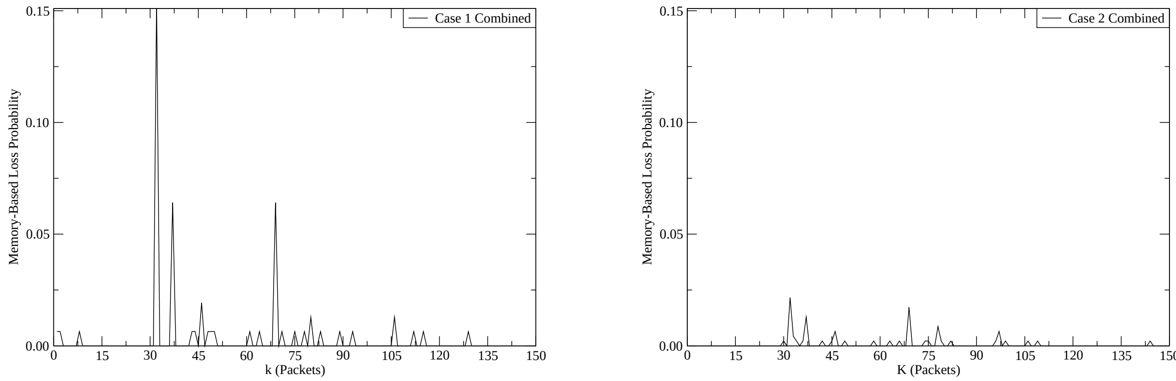
TABLE III
EXPERIMENT 1: OVERALL LOSS PERFORMANCE.

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. 2(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.

In Fig. 3, the memory-based loss characteristics of the combination of the cards in Case 1 and in Case 2 of the first experiment are shown. Notably, the results indicate there is not a significant memory-based aspect to the wireless channel, as the packets immediately following a loss are likely to be successfully transmitted.

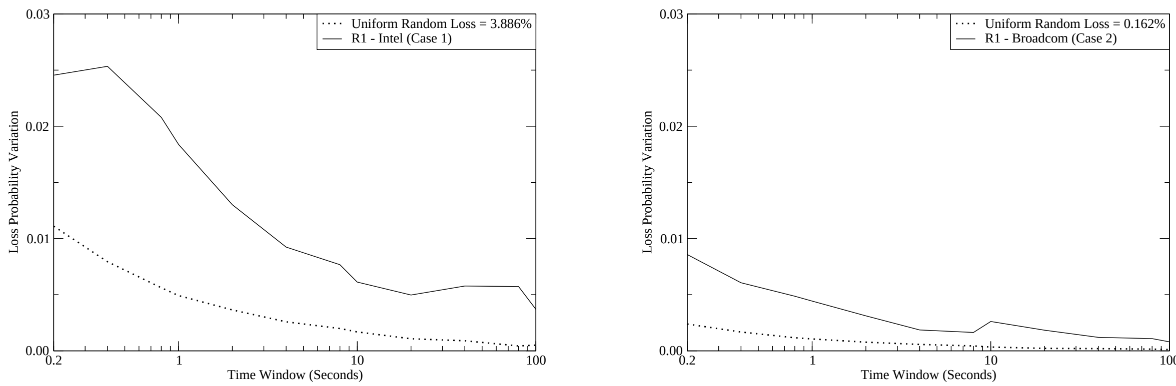
The Allen Deviations of the two nodes, R_1 and R_m (R_2 is similar to R_1), are shown in Fig. 4. In each graph, the plot from a generated uniformly random loss pattern is shown (the loss rate for the generated data matches the overall loss rate of the device it is being compared to). As can be seen, the Intel card has a loss rate that varies more than the uniform random data for smaller time window intervals, while the Broadcom card (shown in Fig. 4(b)) varies less. The fact that the Intel card varies more in terms of average loss is quite notable as the memory-based loss measurement painted a different picture.

In Fig. 5, the Allen Deviation for the combined received packets of Case 1 and Case 2 is shown. With the combined data set, the difference in variation between the generated random data set and the obtained data is less than 0.1% for both cases of the experiments. Again, the minor difference in the generated data from the experimental data implies that much of the non-randomness detected by the wireless receivers may actually be dependant upon the wireless card and not a substantial inherent



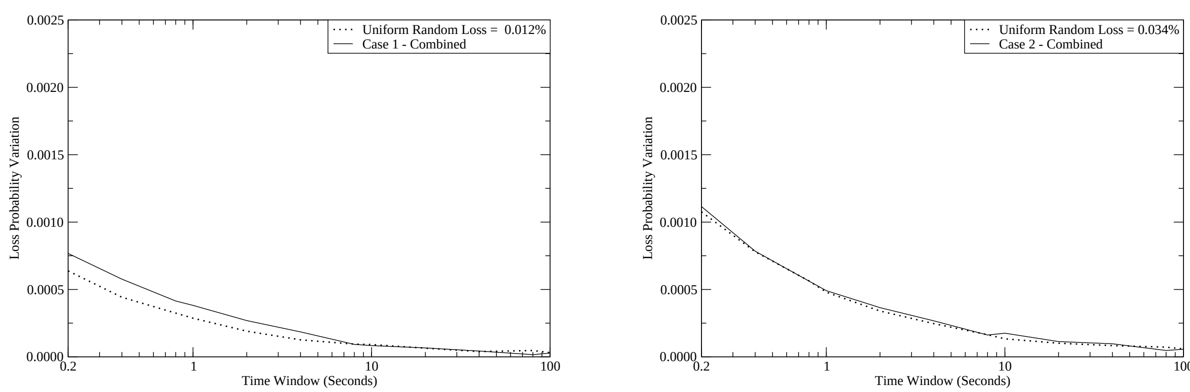
(a) (b)

Fig. 3. Experiment 1: Combined Memory-based loss performance for (a) Case 1 (b) Case 2.



(a) (b)

Fig. 4. Experiment 1: Allen Deviation of (a) Case 1 Node R_1 (b) Case 2 Node R_1.



(a) (b)

Fig. 5. Experiment 1: The Allen Deviation of all the combined results from the combination of results in (a) Case 1 (b) Case 2

Node	Loss Correlation With Beacon
R_1	0.0848
R_2	0.0328
R_m	0.0049

TABLE IV
EXPERIMENT 1: LOSS CORRELATION WITH THE BEACON INTERVAL.

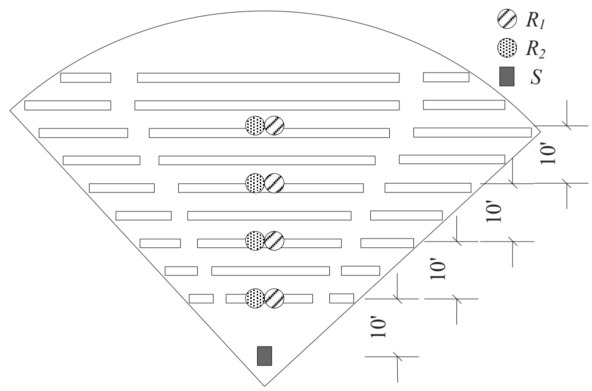


Fig. 6. Experiment 2: Setup.

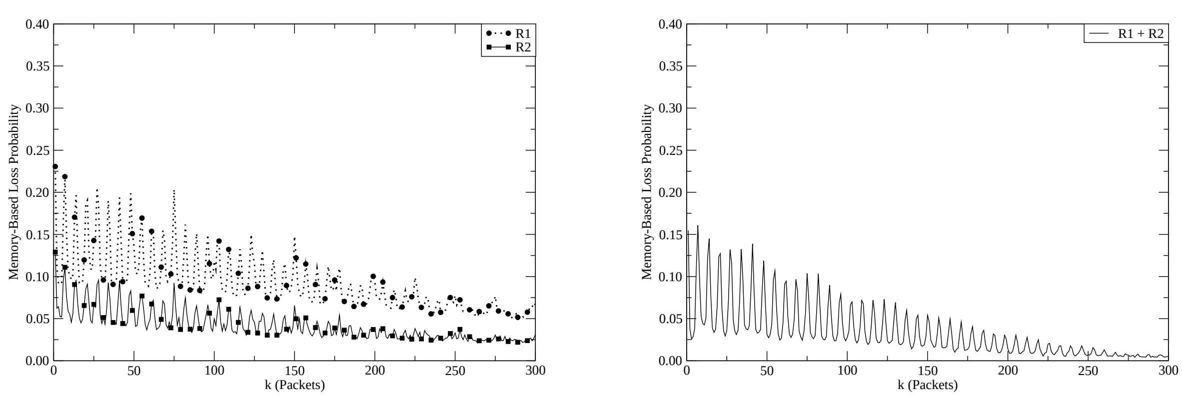
property of the medium.

C. Multiple Receivers: Beacon Loss Correlation

Previous research has noted a potential correlation between packet loss and the beacon interval of the wireless network [1]. Thus, with node R_m all link level events were recorded in order to investigate the correlation between packet loss and these events. In Table IV the correlation between packet loss and the wireless network beacon is shown. Nodes R_1 and R_2, both using the Intel-based wireless cards, show differing amounts of correlation between the beacon interval and packet loss. However, neither node shows significant correlation, with R_1 showing the most significant correlation at 8%.

IV. EXPERIMENT 2: CLASSROOM

In the second experiment, situated in a classroom, the same settings as in the first experiment are used with the specific hardware used listed in Table V. The layout of the experiment is shown in Fig. 6 which is a standard lecture room. The most significant difference in the classroom experiment is the consideration of the effect of distance and hence signal strength.



(a) (b)

Fig. 7. Experiment 2: Distance: Memory-based loss correlation (10 Feet, 16 Mb/s) of R_1 and R_2 (a) separately (b) together.

Node	Wireless Card Chipset	Driver
S	Intel 2200 (Internal)	Intel 2200/2915 Linux Driver
R_1	Intel 2915 (Internal)	Intel 2200/2915 Linux Driver
R_2	Intel 2915 (Internal)	Intel 2200/2915 Linux Driver

TABLE V
EXPERIMENT 2: HARDWARE.

	Instantaneous Loss Correlation		Loss Rate (%)		
Distance	$P(R_1\|R_2)$	$P(R_2\|R_1)$	R_1	R_2	$R_1 + R_2$
10 feet	0.1051	0.2683	1.9951	5.0910	0.5352
20 feet	0.1629	0.2158	6.1762	8.1833	1.3328
30 feet	0.2664	0.2860	8.6767	9.3145	2.4815
40 feet	0.3138	0.3585	8.6198	9.8501	3.0905

TABLE VI
EXPERIMENT 2: DISTANCE: INSTANTANEOUS LOSS CORRELATION.

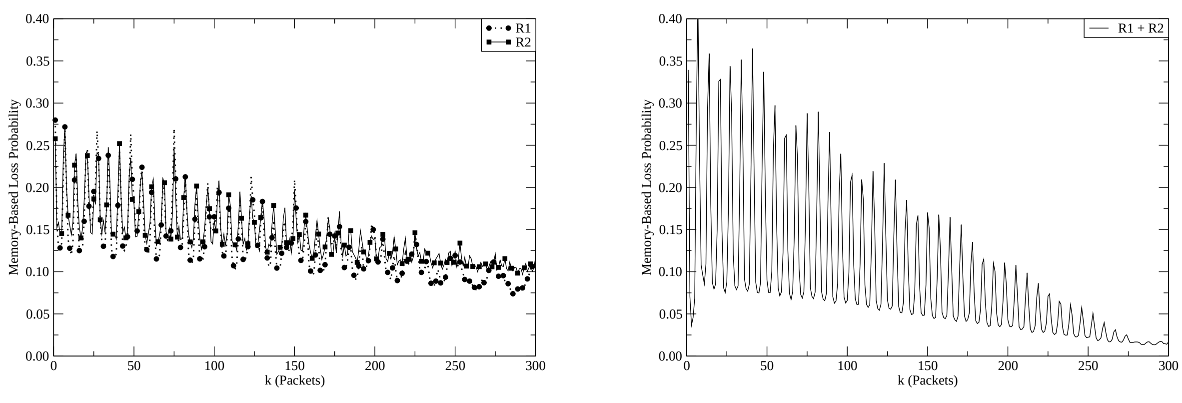
Additionally, external interference is more prominent, as the university uses channels 1, 6, and 11, with channel 3 being used for the experiment. With the selection of channel 3, wireless traffic on channel 1 will provide noise interference that cannot be interpreted as packet transmission by the senders or receivers in the experiment [5]. This provides a more realistic setting, for further validation of the previous results.

The distances of 10, 20, 30, and 40 feet were used; longer distances were not tested, due to the relatively weak transmitting station, loss rates increase greatly at distances significantly more than 40 feet[4]. As with the first experiment, several runs of 15 minutes each were performed in order to validate the results. The main premise of this experiment is to determine if the previous results stand with the introduction of distance and background interference.

A. Effect of Distance

In Table VI, the instantaneous loss correlation between the two receivers and overall loss is shown as distance is increased. As can be seen, as the distance increases, the instantaneous loss correlation also increases. This is expected, because as the distance increases, the signal to noise ratio will decrease for each transmission. However, the instantaneous loss correlation between the two nodes is less than 50% for all distances, implying that at least half of the losses are due to localized errors and not an actual transmission failure. While there is a higher instantaneous loss correlation than what was observed in the first experiment, the overall result remains the same. As is shown, the overall loss can be reduced to less than $1/3$ the loss of either of the two receiving nodes taken independently.

[4]Base stations can be expected to generate a stronger signal than the laptop we use for our experiments, allowing for longer ranges. However, that range is still limited to the wireless devices' ability to transmit back to the base station.



(a) (b)

Fig. 8. Experiment 2: Distance: Memory-based loss correlation (40 Feet, 16 Mb/s) of R_1 and R_2 (a) separately (b) together.

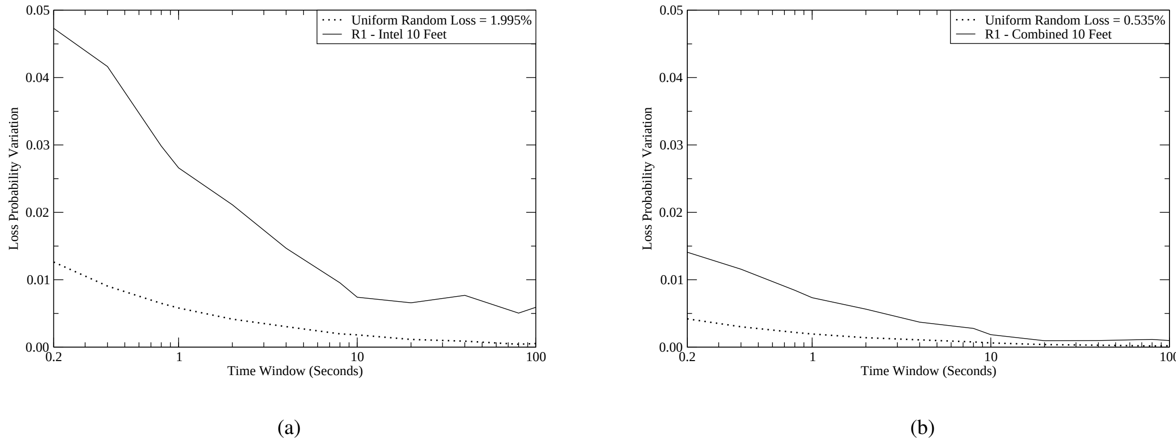


Fig. 9. Experiment 2: Distance: modified Allen Deviation (10 Feet, 16 Mb/s) of (a) R_1 (b) R_1 + R_2

	Instantaneous Loss Correlation		**Loss Rate (%)**		
Distance	$P(R_1\|R_2)$	$P(R_2\|R_1)$	R_1	R_2	$R_1 + R_2$
10 feet No TCP BG	0.0065	0.2141	0.139	4.570	0.030
10 feet TCP BG	0.1969	0.2419	5.509	6.771	1.333
40 feet No TCP BG	0.3082	0.5878	4.696	8.958	2.761
40 feet TCP BG	0.7663	0.8649	10.207	11.519	8.827

TABLE VII
EXPERIMENT 2: BACKGROUND TCP: INSTANTANEOUS LOSS CORRELATION BY DISTANCE AND PRESENCE OF BACKGROUND TRAFFIC (2 MB/S).

The next aspect to be investigated for the distance experiments is the burstiness of loss. Fig. 7(a) shows the memory-based loss performance of the two receivers at ten feet from the sending node. Both receivers show that packets transmitted immediately after a loss are more likely to be lost than other packets. In Fig. 7(b), the memory-based aspect of loss is shown for when the data from the two receivers is combined. In the case where the packets from the two receivers are combined, it can be seen that loss probability still shows some aspects of being memory-based. However, the magnitude of the memory-based aspects is considerably decreased versus the single receiver case even though the duration of the impact of a loss remains constant at 300 packets, or 200 ms.

In Fig. 8, the memory-based loss characteristics at 40 feet is shown. Fig. 8(a) shows the memory-based loss performance of the two different receivers. As with the 10 foot distance, a degree of memory-based loss is shown most significantly for the first 300 packets (roughly 200 ms). Fig. 8(b) shows the memory-based loss performance of the combined results. Again, the graph indicates that previous losses can affect subsequent packets most greatly for the first 300 packets. The only substantial difference between the results of the 10 foot and 40 foot distance is that the magnitude of the memory-based loss increases with the distance, even though the duration of the effect remains the same.

The Allen Deviation of R_1 in the 10 foot distance experiment is shown in Fig. 9(a) and the Allen Deviation of the combined results is shown in Fig. 9(b). As can be seen, as with the memory-based aspect of loss, the Allen Deviation improves significantly when the received packets from the two nodes are combined. When the distance is extended to 40 feet, the Allen Deviation of the individual nodes indicates a slightly higher variation then when the distance between the receiver and sender is 10 feet (not shown). Additionally, there is little improvement in the Allen Deviation when the results are combined at a distance of 40 feet, indicating that the true wireless loss pattern more closely resembles the loss pattern of a single node when the signal is weak (as shown in Fig. 10).

B. Effect of Background Traffic

Using the same setup as shown in Fig. 6 and adding background traffic, we aimed to determine the effect two competing TCP streams have on the loss patterns of the receivers[5]. Specifically, Node S sent a 2.0 Mb/s UDP stream with 1500 byte packets to

[5]Adding additional TCP streams actually provided less contention, due to the fact that the TCP streams will throttle each other such that the overall bandwidth consumed by the TCP stream is less than when only a couple of streams are used.

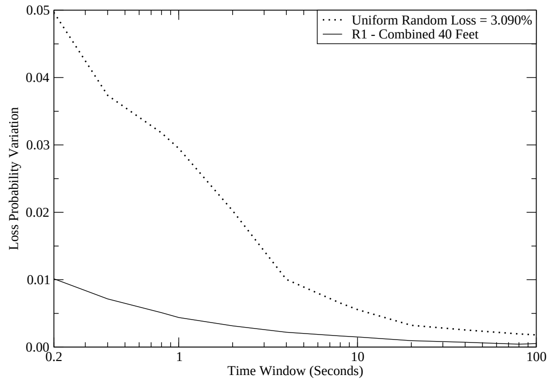


Fig. 10. Experiment 2: Distance: modified Allen Deviation (40 Feet, 16 Mb/s) of R_1 + R_2.

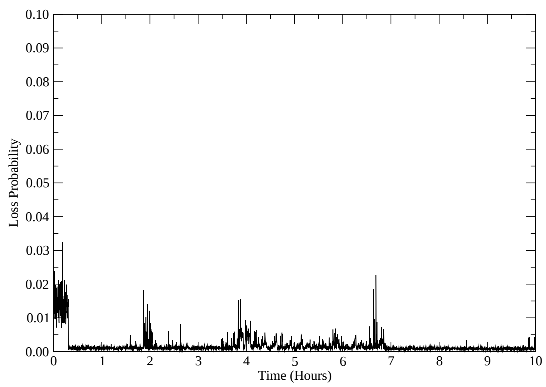


Fig. 11. Experiment 4: Average Loss percentage.

nodes R_1 and R_2[6]. Two additional nodes, BG_1 and BG_2 (using Broadcom wireless chipsets) were placed equidistant between the sending and receiving nodes at a distance of 20 feet from each other. These two nodes each transmitted one long-term TCP flow to the other providing competition for the medium.

In Table VII, the correlation between loss between the two receivers is shown. For the distance of 10 feet, the results are similar, with less than a 25% correlation of losses between the two receivers. However, for the lower data rate, the correlation of losses increases substantially when the distance is increased to 40 feet. At a distance of 40 feet, the loss correlation between R_1 and R_2 is higher than the previous experiment with a higher data rate. This implies that a higher data rate will cause some randomness in the loss as each device will behave slightly differently with the higher rate of packet reception. Thus, for lower data rates, the losses are about as likely to occur from background noise as from a local error in reception at the receiver.

V. Experiments 3 and 4

Our final two experiments were performed in order to help validate our conclusions. In our third experiment, we studied the effect of a physical barrier on the pattern of loss between the two receivers. The setup of the experiment is the same as listed in Table 1, however, only the nodes S, R_1, and R_2 are used. The two receivers are co-located, and are a total distance of 20 feet from the sender. Between the sender and the receivers is a six-inch brick wall. This experiment ran for 15 minutes and was run multiple times to verify the results. Similar to our other results, little correlation between losses was found when introducing a physical barrier between the sender and receivers as $P(R_1|R_2) = .1168$ and $P(R_2|R_1) = .1504$.

[6]Rates much higher than 2 Mb/s resulted in degraded performance of the TCP flows such that the two flows would eventually terminate during the experiment.

In the final experiment, a long term study of the wireless loss pattern was performed. The same setup as Case 1 in Experiment 1 was used, except that R_m is not present and the experiment was run for 10 hours. In Fig. 11 (measured in 10 second intervals), the observed average loss rate over the time is shown. During the first twenty minutes of the experiment, the average observed loss rate is higher than for the rest of the experiment. Subsequent runs of the experiment also showed the higher period of loss. The pattern remained the same across reboots in addition to restarts of the experiment.

Removing the initial period of higher loss for the Intel cards, the results resembled those of Case 2 in Experiment 1. Thus, the initial period of higher loss is not likely to affect our conclusions. However, in order to verify that the initial period of higher loss did not significantly impact our other results, portions of experiment two were re-run with a 30 minute test length. The last ten minutes of the experiment (where the change in average loss occurs), were isolated and the various loss properties were calculated again. While the instantaneous loss correlation between nodes did increase, for distances less than 30 feet, the instantaneous loss correlation remained < 0.30. For the 40 foot case the instantaneous loss correlation increases to 0.54, which still shows significant un-correlated loss.

VI. Related Work

As previously stated, there have been multiple works investigating the loss performance of the wireless medium. Four such works are [1]–[4]. In [1], 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. 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 [2], Reis et al, perform wireless measurements with fifteen stationary 802.11b wireless nodes spread throughout a floor of the building. As with [1], 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 [3], [4], investigated the loss characteristics on long-distance 802.11b wireless links. In [3], Aguayo et al, use the modified Allen Deviation to show that the wireless links have a slight tendency on burstiness. However, in [4], 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.

Another more recent work by Sheth et al. [5], investigated the reasons for packet loss in a long distance 802.11b network. The authors note a significant source of loss for their experiments is external WiFi traffic. Specifically, they find that adjacent channels with a separation of one can receive each other's packets, however, with a separation of two the competing stations can not understand each other's packets and are thus more likely to interfere with each other.

Other works, such as [9]–[11], have also investigated the overall performance of a wireless network in different settings. In [9], Eckhardt and Steenkiste examine the overall effect of walls, cordless phones, and other common office items has on the signal level and error rate of the wireless network. Reason and Rabaey investigate the performance of a Bluetooth multi-hop network in [10]. The main area investigated in [10] was the energy consumption of various activities of Bluetooth communication. While overall loss rate is presented, the work does not investigate loss or delay patterns. In [12], Karrer et al. present an evaluation of the Magnets (WiFi backbone in Berlin, Germany) network was performed. While all of these works investigate particular aspects of various wireless networks, none investigate the influence of the wireless device itself on the observed pattern of loss. Conversely, our work specifically investigates how different wireless cards report various loss patterns, and how even identical nodes will have a low correlation between losses.

Finally, in [13], Bianchi et al. investigate the back-off behavior of different wireless cards and find substantial differences. While their work is concerned with the back-off behavior, our work investigates packet loss characteristics of different wireless cards under various conditions.

VII. Conclusions and Future Directions

In conclusion, we have shown that under many conditions, instantaneous packet loss between two co-located identical nodes are not highly correlated as would be expected. However, the two identical nodes do exhibit similar patterns of loss (both memory-based and modified 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. By combining results from multiple co-located receivers we demonstrate how the wireless chipset itself can play a substantial role in determining patterns of loss. Importantly, we show that while one device may display large amounts of burstiness in loss, when the results are combined from the receivers, the burstiness of loss is significantly reduced. This work demonstrates the importance of not assuming that the pattern of loss received at a single node indicates the true performance of the wireless medium.

It is our belief that future work is needed to explore alternative analyses of loss patterns. In light of our results, we believe unique opportunities exist for smart localized recovery, especially for dense wireless networks. Technologies such as MIMO [14] and beyond should be studied for not only exploiting the lack of loss correlation but also for their implicit properties during ordinary usage.

REFERENCES

[1] A. Miu, G. Tan, H. Balakrishnan, and J. Apostolopoulos, "Divert: fine-grained path selection for wireless LANs," in *Proc. of MobiSys 2004*, New York, NY, USA, 2004, pp. 203–216, ACM Press.

[2] C. Reis, R. Mahajan, M. Rodrig, D. Wetherall, and J. Zahorjan, "Measurement-based models of delivery and interference in static wireless networks," in *Proc. of SIGCOMM 2006*, New York, NY, USA, 2006, pp. 51–62, ACM Press.

[3] D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris, "Link-level measurements from an 802.11b mesh network," in *Proc. of SIGCOMM 2004*, New York, NY, USA, 2004, pp. 121–132, ACM Press.

[4] K. Chebrolu, B. Raman, and S. Sen, "Long-distance 802.11b links: performance measurements and experience," in *Proc. of MobiCom 2006*, New York, NY, USA, 2006, pp. 74–85, ACM Press.

[5] A. Sheth, S. Nedevschi, R. Patra, S. Surana, E. Brewer, and L. Subramanian, "Packet Loss Characterization in WiFi-Based Long Distance Networks," in *Proc. of IEEE INFOCOM 2007*, May 2007, pp. 321–320.

[6] Y.-C. Cheng, J. Bellardo, P. Benko, A. C. Snoeren, G. M. Voelker, and S. Savage, "Jigsaw: solving the puzzle of enterprise 802.11 analysis," in *Proc. of SIGCOMM 2006*, New York, NY, USA, 2006, pp. 39–50, ACM Press.

[7] J. W. Byers, M. G. Luby, M. Mitzenmacher, and A. Rege, "A digital fountain approach to reliable distribution of bulk data," *ACM Computer Communication Review*, vol. 28, no. 4, pp. 56–67, 1998.

[8] J. Zhao and R. Govindan, "Understanding packet delivery performance in dense wireless sensor networks," in *SenSys 2003*, New York, NY, USA, 2003, pp. 1–13, ACM Press.

[9] D. Eckhardt and P. Steenkiste, "Measurement and analysis of the error characteristics of an in-building wireless network," in *SIGCOMM 1996*, New York, NY, USA, 1996, pp. 243–254, ACM Press.

[10] J. M. Reason and J. M. Rabaey, "A study of energy consumption and reliability in a multi-hop sensor network," *SIGMOBILE 2004*, vol. 8, no. 1, pp. 84–97, 2004.

[11] A. P. Jardosh, K. N. Ramachandran, K. C. Almeroth, and E. M. Belding-Royer, "Understanding link-layer behavior in highly congested ieee 802.11b wireless networks," in *E-WIND 2005*, New York, NY, USA, 2005, pp. 11–16, ACM Press.

[12] R. P. Karrer, I. Matyasovszki, A. Botta, and A. Pescapé, "Experimental evaluation and characterization of the magnets wireless backbone," in *WiNTECH 2006*, New York, NY, USA, 2006, pp. 26–33, ACM Press.

[13] G. Bianchi, A. Di Stefano, C. Giaconia, L. Scalia, G. Terrazzino, and I. Tinnirello, "Experimental Assessment of the Backoff Behavior of Commercial IEEE 802.11b Network Cards," in *Proc. of IEEE INFOCOM 2007*, May 2007, pp. 1181–1189.

[14] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311–335, 1998.