802.11n Under the Microscope

Vivek Shrivastava, Shravan Rayanchu, Jongwon Yoon, Suman Banerjee
Department of Computer Sciences, University of Wisconsin, Madison, WI 53706, USA
{viveks, shravan, yoonj, suman}@cs.wisc.edu

ABSTRACT

We present an experimental study of IEEE 802.11n (high throughput extension to the 802.11 standard) using commodity wireless hardware. 802.11n introduces a variety of new mechanisms including physical layer diversity techniques, channel bonding and frame aggregation mechanisms. Using measurements from our testbed, we analyze the fundamental characteristics of 802.11n links and quantify the gains of each mechanism under diverse scenarios. We show that the throughput of an 802.11n link can be severely degraded (up to $\approx$ 85%) in presence of an 802.11g link. Our results also indicate that increased amount of interference due to wider channel bandwidths can lead to throughput degradation. To this end, we characterize the nature of interference due to variable channel widths in 802.11n and show that careful modeling of interference is imperative in such scenarios. Further, as a reappraisal of previous work, we evaluate the effectiveness of MAC level diversity in the presence of physical layer diversity mechanisms introduced by 802.11n.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

General Terms

Experimentation, Measurement, Performance

Keywords

802.11n, MIMO, Wireless, Frame Aggregation, Channel Bonding, MAC Diversity, PHY Diversity, Performance

1. INTRODUCTION

This paper presents an experimental study on the performance of the new IEEE 802.11n (draft) standard using a real testbed. IEEE 802.11n is a next generation wireless LAN technology that promises higher data rates, longer range and more reliable coverage than 802.11 a/b/g networks. In order to provide such gains, it introduces a variety of mechanisms such as physical layer diversity (using Multiple Input Multiple Output (MIMO) technology), channel bonding, and frame aggregation. The goal of this paper is twofold: (1) To provide a better understanding of 802.11n by experimentally evaluating the potential impact of each mechanism (and their combination) on client throughput under diverse scenarios (2) To re-evaluate the effectiveness of some prior wireless research in view of these new mechanisms (e.g., evaluating the benefits of MAC-diversity [5] in presence of physical layer diversity offered by MIMO).

We now briefly describe the different mechanisms used by 802.11n. These mechanisms are illustrated in Figure 1. For detailed information on these mechanisms, please refer to [7].

PHY-diversity (MIMO): IEEE 802.11n employs a variety of physical layer diversity mechanisms for achieving higher throughput and improved packet reception capabilities. In 802.11n, receiver diversity is implemented by using Maximum Ratio Combining (MRC), a technique which optimally combines signals from multiple antennas taking into account the signal-to-noise ratio (SNR) of the signals received at different antennas. The transmit diversity techniques used in 802.11n include Space Time Block Coding (STBC) and Cyclic Shift Diversity (CSD). These techniques improve the signal reception by spreading it over multiple transmit antennas using specialized coding (STBC) or phase shifting techniques (CSD).

Frame Aggregation: IEEE 802.11n provides an option of combining multiple data frames ready for transmission into an aggregate frame (Figure 1). Frame aggregation helps amortize the channel contention and backoff delays by transmitting the aggregated frame (i.e. multiple data frames) in a single transmission opportunity on the channel.

Channel Bonding: IEEE 802.11n also introduces two different channel bandwidths – 20 MHz and 40 MHz. Theoretically, using a 40 MHz band should double the amount of throughput achieved using a 20 MHz band. However, as shown in Figure 1, *all* the 40 MHz channels are *partially overlapping* in the 2.4 GHz band, as opposed to the 20 MHz channels 1, 6 and 11 which are non-overlapping. Thus using 40 MHz channels can also lead to degradation in the throughput due to increased interference with neighboring channels.

In this paper, we systematically evaluate the implications of using the aforementioned mechanisms and their impact on network throughput. Specifically, we evaluate the following:

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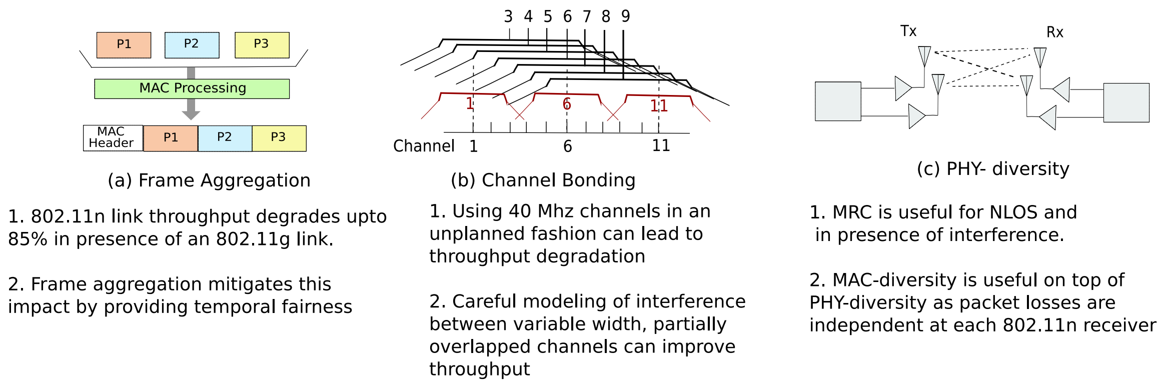

Figure 1: Different mechanisms used in the 802.11n standard. We summarize our findings regarding each mechanism.

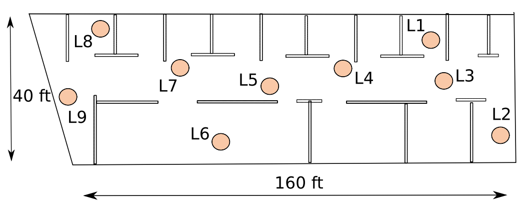

Figure 2: 802.11n testbed used for the experiments. The nodes are placed at locations L1-L9.

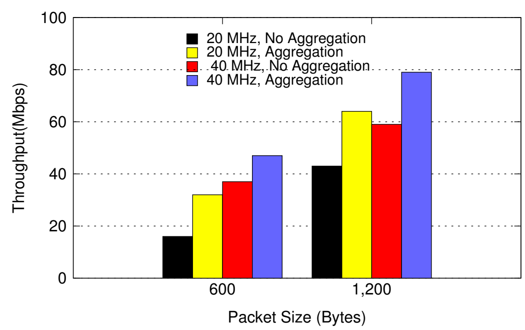

Figure 3: Average throughput achieved on a isolated 802.11n link under different combinations of channel width and aggregation mechanisms.

- What are the throughput gains of using each mechanism (MRC, frame aggregation, channel bonding) on an isolated 802.11n link? What are the factors affecting these gains?
- What is the performance penalty when a 802.11g link is operating near an 802.11n link? What mechanisms can be effective in such scenarios?
- What is the impact of using channel bonding on network design? Can we use 40 MHz channel efficiently in the 2.4 GHz band? When should we choose a 40 MHz channel vs. 20 MHz channel?
- What is the nature of packet losses in 802.11n? In presence of PHY-diversity, is MAC-diversity still beneficial? Will mechanisms exploiting MAC-diversity like MRD [5], ExOR [1], MORE [2] provide high throughput gains on 802.11n as well?

We answer these questions by performing targeted experiments on our 802.11n wireless testbed as shown in Figure 2. Our main observations from the experimental study are summarized in Figure 1. The rest of the paper answers these questions in detail. We first describe the impact of different components of 802.11n on client performance and also evaluate the performance of an 802.11n link in the presence of interference from a slower 802.11g transmitter.

2. UNDERSTANDING THE GAINS

In this section, we evaluate the three mechanisms used by 802.11n – frame aggregation, wider channel bandwidths and maximum ratio combining. We quantify the gains from each component in isolation and in presence of interference. Further, we also identify the scenarios under which a specific mechanism is more useful. First we detail our experimental methodology for the paper.

Experimental Methodology: All the experiments reported in this paper are performed on our 802.11n testbed (shown in Figure 2). The wireless nodes used in our experiments comprise of desktop machines (512 MB RAM, 1.2 GHz) equipped with the Edimax (EW-7728In) 802.11n (Draft 2.0) PCI wireless cards. These cards are based on Ralink chipset, support 3X3 MIMO operation, have three detachable antennas (of 3dBi gain) and operate in 2.4 GHz band. They support channel bandwidths of 20 MHz and 40 MHz. Unless otherwise stated, we run our experiments at the PHY-data rate of 300 Mbps, the maximum data rate supported by our card. The cards can also be configured to be used in 802.11b/g mode. We used RT2860 Wireless LAN Linux driver to configure the cards for our experiments. Please note that we intentionally use desktop machines with suitable processing power as we do not want our experiments to be impacted by the hardware limitations of the host machine. All our experiments were conducted at night to minimize interference from other wireless devices. We operate in a orthogonal channel from that being used by our department WLAN to prevent potential interference.

Performance of an 802.11n link in isolation: For this

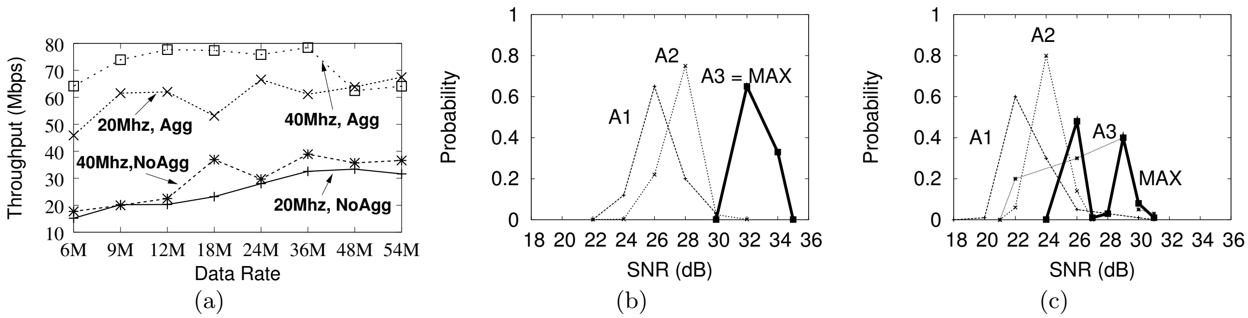

Figure 4: (a) Throughput of an 802.11n link severely degrades in presence of an 802.11g link operating on a lower data rate. Frame aggregation improves the throughput of the 802.11n link by providing *temporal fairness*.(b),(c) Lesser overlap in the PDFs of RSSI for three antennas indicate increased gains from MRC.

experiment, we fix the 802.11n transmitter at Location L1 in the testbed and vary the receiver location from L2 to L9 (as shown in Figure 2). At each receiver location, we perform a throughput test to the transmitter at location L1. Figure 3 shows the average throughput for two packet sizes, using both the channel bandwidths, with and without frame aggregation. For higher packet sizes, throughput improvements ranging from 33% upto $2x$ can be achieved using wider channel bandwidth (40 MHz), while frame aggregation results in throughput improvements ranging from 10% to 75%. Further we observe that the relative gains from aggregation are slightly higher in the case of 600 byte packets as compared to 1200 byte packets. This is expected as aggregation helps amortize the cost of header transmissions and is more effective for smaller packet sizes. We now study the impact of external interference on gains achieved from these two mechanisms.

Performance of an 802.11n link with interference: Previous research [3] in 802.11b multi-rate networks had highlighted a *performance anomaly* – If there is at least one host which operates at a lower rate, the throughput of all hosts transmitting at a higher rate is degraded below the level of the lower rate. We characterize the impact of this anomaly in 802.11n by evaluating the performance of a 802.11n link (transmitter at location L3 and receiver at location L4) and an 802.11g link (transmitter at location L5 and receiver at location L7) operating on the same channel. The packet size is fixed at 1200 bytes. Both the links are saturated, that is both the transmitters always have packets to send. The data rate of the 802.11g link was varied from 6 Mbps to 54 Mbps. We performed the experiments using different channel bandwidths and frame aggregation options for the 802.11n link. The 802.11n link operated on fixed data rate of 300 Mbps (when using 40 MHz) and 144.5 Mbps (when using 20 MHz).[1]

Figure 4(a) shows that performance anomaly indeed severely degrades the throughput of an 802.11n link to as low as 10 Mbps (a reduction of $\approx$ 84%) when an 802.11g link is operating at 6 Mbps on the same channel. We also observe that this *performance anomaly cannot be mitigated by using a wider channel bandwidth of* 40 *MHz*. However, using frame aggregation considerably improves the throughput and when used in combination with the 40 MHz channel width, frame aggregation provides further improvements. This improvement stems from the fact that frame aggregation helps an 802.11n link operating at a higher data rate attain a *similar temporal share* of the channel when compared to that of an 802.11g link operating on a lower rate by transmitting multiple data frames during each transmission opportunity on the channel.

Benefits of MRC: As mentioned before 802.11n uses MRC, a physical layer technique which exploits *antenna diversity* – signals from multiple receiver antenna chains are optimally combined to improve the packet delivery probability. Although we cannot accurately determine the exact amount of gains derived from this physical layer mechanism, we attempt to characterize the gains (as visible at the MAC layer) by looking at the RSSI of the signals on multiple receiver antennas. Analyzing the packet logs from our experiments, we were able to identify three scenarios which would result in varying gains from antenna diversity. In order to illustrate these scenarios, probability density (PDF) of SNR values at three antennas of the 802.11n receiver (A1, A2, and A3) are plotted along with PDF of the maximum SNR for each packet in the experiment (MAX). Figures 4(b) and 4(c) plot these values for two representative links belonging to two different scenarios. In the first scenario (shown in Figure 4(b)), the SNR of one of the antennas (A3) dominates the other two antennas all the time. In the second scenario (shown in Figure 4(c)), the MAX RSSI is derived from a combination of different antennas at different instants of time, indicating improved gains due to MRC under these conditions. We found the all the non line of sight 802.11n links in our testbed belong to one of the two aforementioned scenarios, showing the usefulness of MRC for such links. Finally, we found that for the line of sight link (transmitter at L1 and receiver at L3), the PDF of all the antennas overlapped, indicating little gains from MRC. The plot for this scenario is omitted for brevity.

3. CHANNEL WIDTHS AND INTERFERENCE

Although introduction of wider (40 MHz) channels can lead to increased throughputs, they also imply an increase in the observed interference. This is especially true in 2.4 GHz band where the boundaries of 40 MHz channels in 802.11n do not line up with the (1, 6, 11) 20 MHz channels of 802.11n

[1]These are the maximum possible data rates when using less than 4 spatial streams.

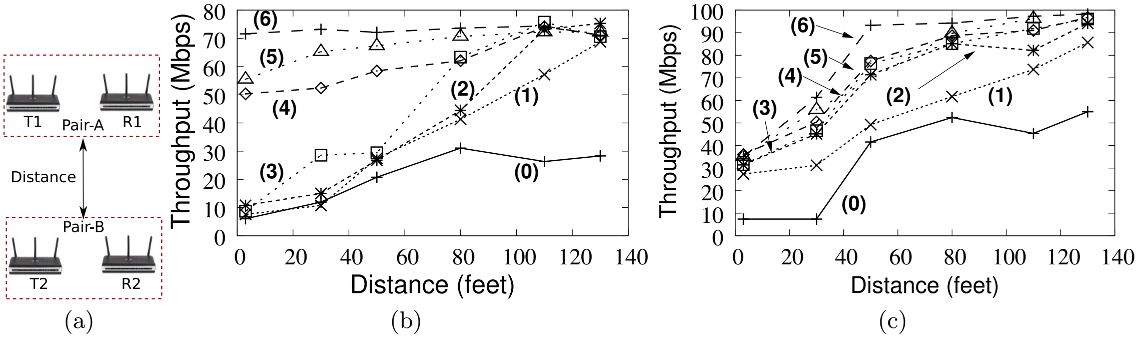

Figure 5: (a) Setup used for channel overlap experiments. The transmitter and the receiver are co-located while the separation (distance and channel) between the pairs is increased for each run. (b) UDP throughputs for a channel bandwidth of 20 MHz. (c) UDP throughputs for a channel bandwidth of 40 MHz.

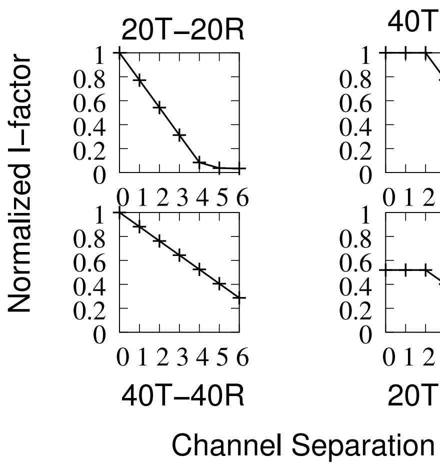

Figure 6: Theoretical I-factors for various interferer and receiver combinations.

and the traditional 22 MHz channels of 802.11 b/g. We illustrate this in Figure 1(b), which shows that: (1) *all* the 40 MHz channels are *partially-overlapping* (2) A 40 MHz channel might have a significant amount of spectral leakage on some of the 20 MHz channels. [2] While it is possible to use (non-overlapping) 20 MHz channels, it might reduce the maximum throughput that can be achieved with wider channel bandwidths. In this scenario, it becomes imperative to understand and characterize the nature of interference introduced due to these variable channel widths. To this end, we extend the model in [4] to characterize the interference on an 802.11n link due to partially overlapped channels and validate our model using experimental results which we present next.

Modeling 802.11n Interference: In order to characterize the amount of interference on an 802.11n link due to transmissions on other 802.11 channels (of 40 MHz or 20 MHz),

[2]Although 40MHz channels could be easily used in 5 GHz band but initial 802.11n deployments would also need to serve 802.11g clients for backward compatibility, forcing them to operate in a hybrid mode (both 11g and 11n) in 2.4 GHz band.

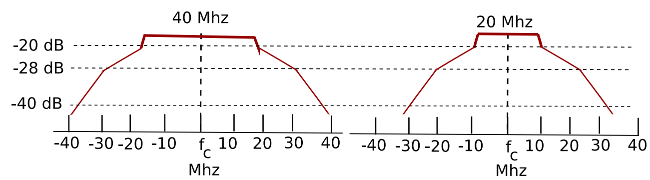

Figure 7: Transmit spectrum masks for 40 MHz and 20 MHz channels for the physical layer in IEEE 802.11n standard

we extend the model developed in [4] to calculate the *interference factor* (or I-factor) that captures the amount of overlap between a transmission on a certain frequency F_T and reception on a certain frequency F_R. The amount of overlap is captured quantitatively by calculating the area of intersection between a signal's spectrum and a receiver's band-pass filter. We incorporate the transmitter and receiver channel bandwidths, *bt* and *br* into this model to derive the I-factor:

$$IF_{(T,R)}(\tau) = \int_{-\infty}^{+\infty} S_{T,bt}(F) B_{R,br}(F-\tau)\, df$$

In above equation, the parameter τ represents the difference in the center frequencies of the channels i.e., $\tau = F_T - F_R$. The parameter $S_{T,bw}(f)$ denotes the transmitted signal's power distribution across the frequency spectrum when a channel bandwidth of *bt* MHz is used. As in [4] we approximate $S_{T,bw}(f)$ with the corresponding transmit spectrum mask. We illustrate the transmit spectrum masks for a 40 MHz channel and a 20 MHz channel of the 802.11n physical layer in Figure 7. Finally, $B_{R,br}(f)$ denotes the band-pass filter's frequency response when a channel of *br* MHz is used. Assuming the receive filter for a particular bandwidth to be same as the transmit spectrum mask [4], for 802.11n we get:

$$B_{R,bw}(f) = S_{T,bw}(f) =$$

$$\begin{cases} -45dB & \text{if } |f - F_c| \geq (1.5 * bw)\text{MHz} \\ -38dB & \text{if } (bw)\text{MHz} \leq |f - F_c| < (1.5 * bw)\text{MHz} \\ -20dB & \text{if } (0.55 * bw)\text{MHz} \leq |f - F_c| < (bw)\text{MHz} \\ 0dB & \text{otherwise} \end{cases}$$

where F_c denotes the channel center frequency and *bw* is the channel bandwidth (20 MHz or 40 MHz) used.

Figure 6 shows the I-factor calculated using the above model for four different scenarios – when the interferer and the receiver are both using 20 MHz channels (20T-20R), the interferer is using a 20 MHz channel and the receiver is using a 40 MHz channel (20T-40R), the interferer is using a 40 MHz channel and the receiver is using a 20 MHz channel (40T-20R), the interferer and receiver are both using a 40 MHz channel (40T-40R) [3].

Results: We used the set up shown in Figure 5(a) where four 802.11n nodes are used to form two transmitter-receiver pairs (Pair-A and Pair-B). The nodes in each pair we kept in close proximity of each other and we set up UDP flows from the transmitter to the receiver. We then measured the throughputs for at different physical distances, varying channel separation and bandwidths. Figures 5(b), 5(c) show the average throughput results across varying distances for two of the four configurations[4]. The numbers in the parenthesis correspond to the channel separation between the two pairs. We observe that as the physical separation between the pairs increases, the throughput improves due to decreased interference from the partially overlapped channels. Also, at a fixed distance, increase in channel separation from 0 to 6 leads to increase in throughput.

Further, we note that the observed throughputs correlate with the theoretical I-factor. It is interesting to note that linear increase in throughputs (due to increased channel separation) correspond to a linear decrease in the I-factor. We also note that at a distance of around 120 feet, the throughputs of the links reach the maximum for all the partially overlapped channels, indicating that the channels can be reused at this distance. For the (20T-20R) case shown in Figure 5(b), we observe that even at very small distances between the pairs (0-20 feet), the degradation in throughput is minimal when the channel separation is greater than 4 as the I-factor is close to zero for these cases. However, as observed in Figure 5(c), to achieve similar affect when 40 MHz channels are used, a separation of around at least 50 feet is needed even for the maximum channel separation of 6. This is due to the increased interference as a result of using wider channel bandwidths. Hence, there is a clear tradeoff in choosing a 20 MHz vs. a 40 MHz channel. This highlights the importance of careful *channel width assignment* in 802.11 networks by accurately modeling the amount of interference introduced due to variable channel widths.

4. PACKET LOSSES AND MAC-DIVERSITY

As previously mentioned in Section 1, IEEE 802.11n employs a variety of PHY-diversity mechanisms (MIMO) for improving network throughput. Maximum Ratio Combining (MRC) is one such technique which optimally combines signals from multiple antennas taking into account the signal-to-noise ratio (SNR) of the received signals. Mechanisms employing spatial diversity can also be implemented at the MAC layer [5] by combining frames from multiple receivers. We term this technique as MAC-diversity. In this section we first inspect the statistical dependence of packet losses in 802.11n MIMO receivers and then try to understand the impact of PHY-diversity mechanisms on MAC-diversity. More specifically, we answer the following question – *In presence of PHY diversity offered by 802.11n, what gains can we expect from MAC-diversity?*. The answer to this question has several important implications. Mechanisms such as MRD [5], ExOR [1] and MORE [2] depend on MAC-diversity to achieve throughput improvements and hence will be affected if the gains due to MAC-diversity decrease substantially when PHY-diversity is used.

We start with experiments which help us characterize the nature of packet losses in 802.11n and understand how they are different from packet losses in 802.11b/g. We then design experiments to understand the gains due to MAC-diversity in the presence of PHY diversity. Below, we describe the experimental set up used.

Experimental Setup: We perform broadcast experiments with a single transmitter (at L1) and we used two receivers which are co-located with each other. The position of this receiver pair was varied from location L2 - L9 during different runs of this experiment. For each run, a total of $100,000$ packets were transmitted in broadcast mode and the receivers captured the packets in the monitor mode. The packet size was set to 1024 bytes. We performed a total of 10 runs at each location. In order to compare the packet losses in 802.11n and 802.11g, we first performed the experiments with the transmitter set to 802.11n greenfield mode (using 40 MHz channel, at a PHY-data rate of 300 Mbps) and then repeated the experiments with the transmitter set to 802.11g mode (at a PHY-data rate of 54 Mbps). The captured packet logs at the receivers are then used to analyze the nature of packet losses in 802.11n.

Nature of Losses: In the experiments above, we observed packet losses ranging from 9% to as high as 80%. Further, we observed that the difference in delivery probabilities between the two receivers was *much higher* in 802.11g showing clear benefits of using MAC-diversity. On the other hand, packet delivery ratios for both the 802.11n receivers were *almost the same* for almost all the locations. The delivery ratios only differed at locations with very high loss rates ($\approx 70\%$). In order to investigate whether packet losses in 802.11n are independent at each 802.11n receiver, we take the following approach: For each set of $10,000$ packets in the above experiments, we measure $P_l(R_1)$ and $P_l(R_2)$ which are the packet loss rates observed at receivers R_1 and R_2. We also measure $P_l(R_1 \cap R_2)$ to represent the number of broadcast transmissions which were simultaneously lost at both the receivers. In Figure 8(a) we show the scatter plot of $P_l(R_1 \cap R_2)$ and the quantity $P_l(R_1) * P_l(R_2)$. If the losses at two receiver are independent, $P_l(R_1 \cap R_2) \approx P_l(R_1) * P_l(R_2)$, which implies that all the points in the scatter plot should lie on diagonal. As shown in the figure, the points are indeed scattered very close to the line $y = x$, which indicates that the packet losses in 802.11n are largely independent. This suggests that MAC-diversity can indeed be useful in improving the packet delivery ratio (even in the presence of PHY-diversity). This is further confirmed by our experiments that quantify the gains from MAC-diversity in 802.11n. Next we describe our results from the MAC-diversity experiments in detail.

Gains from MAC diversity: The idea of exploiting MAC level diversity was explored in [5], where authors showed that packet losses are independent at co-located 802.11g receivers. They also show that the losses on a single receiver are bursty in nature, which can be attributed to the short term channel fluctuations. We re-evaluate their findings in

[3]Please note that the I-factor model presented here provides a rough approximation of the amount of interference due to presence of guard bands, pilots etc. in OFDM.

[4]We omit the other two cases due to space constraints

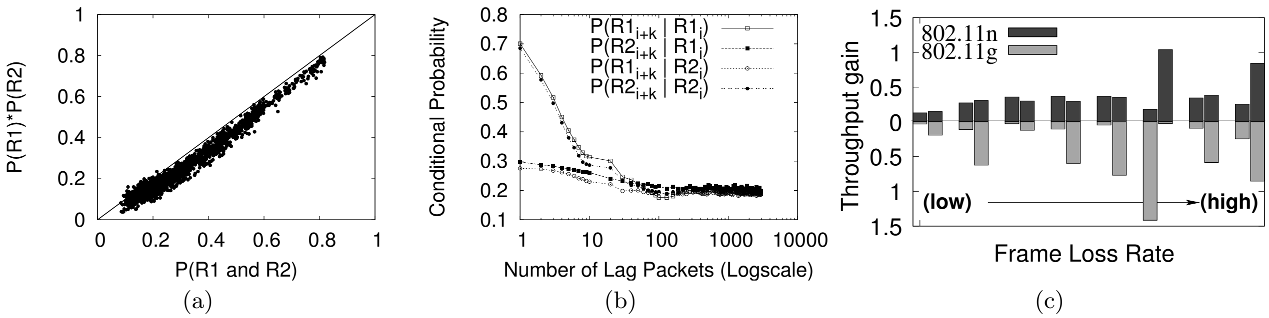

Figure 8: (a) $P_l(R_1 \cap R_2) \approx P_l(R_1) * P_l(R_2)$ indicates that the losses are largely independent across receivers R_1 and R_2. (b) Auto-conditional and cross-conditional packet error probabilities for broadcast experiments performed using two 802.11n receivers. (c) Throughput gains when using MAC-diversity with two receivers for 802.11n and 802.11g.

the context of 802.11n that already exploits diversity at the physical layer. In Figure 8(b) we plot the auto-conditional and cross-conditional packet error probabilities. The auto-conditional probability denotes the probability that packet $i+k$ was lost at receiver R_1 given that packet i was lost at receiver R_1. The cross-conditional probability on the other hand denotes the probability that packet $i+k$ was lost at receiver R_1 given that packet i was lost at receiver R_2. We draw two observations from the plot: (1) the conditional probability of error decreases with increase in the lag packets (k) and becomes constant (approaches the overall loss probability) for higher values of k. This clearly reflects the bursty nature of the losses as the conditional probability is higher than average for small values of k. Further, we note that after 100 lag packets ($k > 100$), the losses become completely independent of the previous packet loss. (2) the cross-conditional probability is much lower than the auto-conditional probability for smaller values of k. This shows that using MAC-diversity can still be beneficial.

To quantify the performance gains that can be achieved with MAC-diversity, we implemented a naive algorithm which would combine packet receptions from two receivers to improve the overall packet delivery ratio. Figure 8(c) shows the throughput gains achieved at different locations for both 802.11n and 802.11g. We observe that the gains for 802.11n vary from 12% to as high as 103%, while the corresponding gains for 802.11g reach upto 140%. It is important to note that *although similar loss rates were observed across both the 802.11n receivers, the losses were actually independent leading to improvements in throughput due to MAC-diversity.*

5. RELATED WORK

White papers from some of the companies have presented experimental results on their 802.11n products [7, 6]. However, to the best of our knowledge, ours is the first experimental study quantifying the gains of 802.11n under diverse conditions, modeling the interference due to variable width partially overlapped channels and evaluating benefits of MAC-diversity in presence of PHY-diversity offered by 802.11n. Further, MAC-diversity has also been exploited by prior research [5, 1] to achieve substantial throughput gains (upto 2.3x) over single radio systems. The I-factor model for partially-overlapped channels was initially proposed in [4]. In this paper, we extend the I-factor model to incorporate variable channel widths for characterizing the interference in 802.11n networks.

6. SUMMARY

Our work shows that the packet losses in 802.11n are indeed independent at each receiver and that MAC-diversity can still be beneficial in presence of the PHY-diversity mechanisms introduced by 802.11n. This has an important implication that mechanisms exploiting spatial diversity (e.g., MRD [5], ExoR [1]) can still provide high throughput gains for 802.11n links. We also observed that the throughput of an 802.11n link can severely degrade in presence of a lower rate 802.11g link and that frame aggregation can help mitigate this impact by providing temporal fairness among links. Further, we identified that gains from MRC are likely to be much higher in presence of interference and NLOS links. Finally, we extended the I-factor model to include variable channel widths and show that our model can be used to understand and characterize the nature of interference introduced due to the partially overlapping 40 MHz channels in 2.4 GHz band.

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