Experimental Characterization of 802.11n Link Quality at High Rates *

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ABSTRACT

802.11n has made a quantum leap over legacy 802.11 systems by supporting extremely higher transmission rates at the physical layer. In this paper, we ask whether such high rates translate to high quality links in a real deployment. Our experimental investigation in an indoor wireless testbed reveals that the highest transmission rates advertised by the 802.11n standard typically produce losses (or even outages) even in interference-free environments. Such losses become more acute and persist at high SNR values, even at low interference intensity. We find that these problems are partly due to bad configurations that do not allow exploitation of spatial diversity, partly due to the wider 802.11n channels that expose these sensitive high rates to more interference. We show that these problems can be alleviated using the 802.11n MAC layer enhancements jointly with packet size adaptation.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Communication—*IEEE 802.11n*; C.4 [**Performance of Systems**]: Measurement Techniques

General Terms

Experimentation, Measurement, Performance

Keywords

MIMO, 802.11n, packet delivery ratio

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1. INTRODUCTION

The 802.11n draft is currently being finalized toward a high throughput 802.11 standard. 802.11n offers PHY layer and MAC layer enhancements over legacy 802.11 systems. First, it uses a MIMO PHY layer, where multiple antenna elements can be combined to achieve either higher PHY data rates (in Spatial Division Multiplexing (SDM) mode) or higher range (in Space Time Block Coding (STBC) mode). Second, it uses channel bonding, where two 20 MHz channels of legacy 802.11 can be combined to a single 40 MHz channel, thus increasing the PHY data rate. These features result in a maximum transmission rate of 300 Mbps, almost 6 times faster than the legacy 802.11a/g systems.

In this paper, we ask the question whether the high transmission rates advertised by 802.11n translate to links of high quality in real-world deployments. We characterize link quality using the Packet Delivery Ratio (PDR) experienced by the 802.11n MAC layer. Previous experimental studies with 802.11n hardware focus on link throughput performance [1, 2, 3, 4, 5]. Although throughput is an important measure of link quality, it may depend on factors such as hardware platform limitations, MAC parameter settings or implementation of the 802.11n draft (which is not yet fully standardized). For example, a 2x3 802.11n system can achieve 300 Mbps transmission data rate, but the maximum throughput reported in the above studies varies between 80 and 192 Mbps. Compared to throughput, PDR is a more direct metric of the link quality provided by the 802.11n PHY to the higher layers. It is also important for loss-sensitive applications. In addition, it can be easily measured at the network layer using probe packets and also forms the basis for link cost or routing metrics in 802.11-based WLANs or mesh networks [6, 7].

We perform experiments in an indoor testbed deployment using commercial 802.11n NICs operating in both ISM bands (2.4/5 GHz) [8]. In this testbed, we investigate the sensitivity of PDR of 802.11n links with regards to various parameters: the number of receiving antennas, the transmission rate, the received signal strength, the channel width and the packet size. Our findings can be summarized as follows:

- SDM at highest rates is very sensitive even in absence of interference. In particular the lack of rich multipath may result in zero PDR even at high Received Signal Strength (RSS) values.

- Receiver diversity can provide significant benefits when employed. In an 802.11n system with 2 transmit antennas, the usage of an additional receiving antenna can increase the PDR at the highest transmission rates.

- High rates are highly susceptible to external interference and/or noise. When operating in the same frequency with other co-located wireless networks, 802.11n links become lossy even when the RSS is high.
- The use of wider channels increases the peak transmission rate but can severely decrease PDR due to the increased levels of interference. For the highest rates, employing channel bonding reduces the observed PDR by approximately 35%.
- Reducing the packet size used at the high transmission rates can help towards improving the achieved PDR. In addition, by jointly tuning the MAC layer transmission parameters available with 802.11n, it is possible to avoid the throughput reduction introduced by the smaller packet sizes otherwise.

The rest of the paper is organized as follows. Section 2 presents related work. Section 3 provides background on the 802.11n MAC and MIMO PHY layer. Section 4 presents the testbed and experimental setup. Baseline experiments, impact of interference, impact of channel width and packet size are presented in Sections 5, 6, 7 and 8, respectively. Section 9 concludes.

2. RELATED WORK

In [1], Shrivastava *et al* show that the 802.11n CSMA/CA MAC protocol can significantly hurt achievable throughput, however, frame aggregation can reduce the hit. In addition, they use a previously introduced interference model [9] in order to capture the effects of channel bonding. In a similar fashion, the authors in [4], perform experiments with both isolated 802.11n links as well as competing links for medium access; the results reported align with the ones in [1]. In addition, they provide guidelines for the configuration of an experimental testbed that can realize the high throughput supported by commercial 802.11n wireless adapters.

Visoottiviseth *et al* [5] perform an empirical study on the achievable UDP and TCP throughput with various 802.11n NICs from different vendors. Their results indicate that the 40 MHz channel configuration only provides marginal performance improvement. Furthermore, they conclude that decisions with regards to how and when to use packet aggregation and block ACK, are hardware dependent. In [3] Minarsky measures throughput on individual links as a function of distance for office and home environments for various 802.11n products. Finally, in our previous work [2], we analyzed the impact of different PHY and MAC 802.11n features on the peak throughput of 802.11n lossless links. in an interference free environment (5 GHz).

All the studies up to now have focused on link performance in terms of throughput. In this work we are interested in the packet losses observed on an 802.11n link, as captured by the Packet Delivery Ratio (PDR). PDR is an important metric that has not attracted attention in the above experimental studies. In addition, we are experimenting with both SDM and STBC modes of operation, while most previous studies either do not clarify which mode they use or they focus only on one.

Finally, a few studies focus on MIMO PHY layer of 802.11n [10, 11]. These studies use low-level programmable platforms such as FPGAs (Field Programmable Gate Arrays) and characterize the performance of the MIMO technology in terms of PHY layer metrics such as Bit Error Rate (BER) [11] and wireless channel capacity [10]. In this work we do not focus on the PHY layer properties of MIMO communications but on the impact of MIMO PHY layer to the performance at higher layers.

3. BACKGROUND

802.11n uses MIMO communications at the PHY layer along with a number of MAC layer enhancements (e.g. channel bonding, block ACK, frame aggregation etc) [12]. In the following, we provide a brief description of these features.

3.1 MAC layer enhancements

Channel Bonding: Legacy 802.11 devices operate on 20 MHz channels [13]. In particular, each 802.11b/g channel is 22MHz wide, while each 802.11a channel is 20 MHz wide. In contrast, with 802.11n, a communication can use either a bandwidth of 20 MHz or a bandwidth of 40 MHz. The latter case corresponds to what is called ***channel bonding***. With channel bonding, two or more adjacent (native 802.11g) channels are united to form a new, wider channel. This expansion can help realize higher PHY data rates, and in particular to double the peak rate. However, as we will see in Section 7, this technique can have the opposite effect on the PDR.

Block Acknowledgment: In legacy 802.11 systems a single ACK packet is sent to confirm the correct decoding of each DATA packet. 802.11n supports a block acknowledgment mechanism where a single-block acknowledgment (ACK) frame is used to acknowledge several received frames, thus reducing overhead.

Packet Aggregation: In order to increase medium utilization and avoid the wasted time due to backoff and collisions of the 802.11 MAC protocol, 802.11n transmitters can send multiple back-to-back packets at each MAC access opportunity. 802.11n supports two different forms of aggregation, known as A-MSDU and A-MPDU. Under A-MSDU, multiple higher layer packets incoming to the MAC layer (termed MSDUs) are combined to a single MAC frame (MPDU). Under A-MPDU, multiple MAC frames (MPDUs) are combined to form an aggregate MAC frame. A-MSDU incurs less overhead than A-MPDU because the MSDU headers are smaller than the MPDU headers. However, all MSDUs must be destined to the same MAC address. A-MPDU does not have this limitation but requires the aforementioned Block Acknowledgement mechanism, in order to distinguish between lost and successful MPDUs.

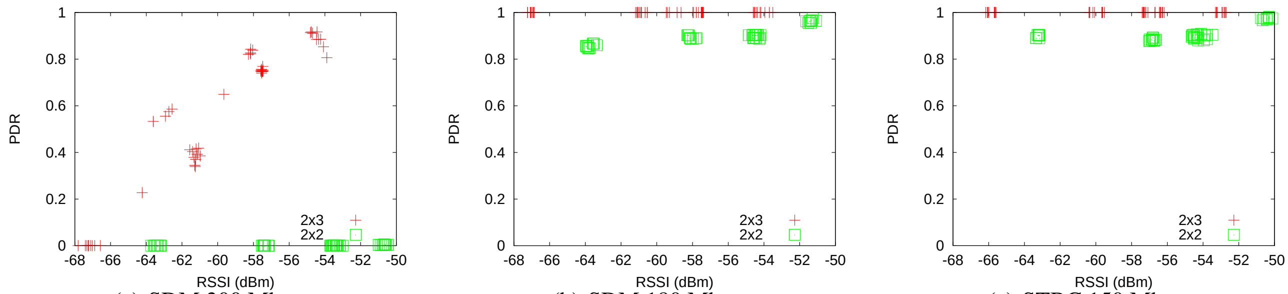
We emphasize that currently the 802.11n draft standard does not specify how the various MAC layer mechanisms (channel bonding, packet aggregation, block ACK etc.) will be implemented. It only makes provision for their usage. As a result, each vendor can implement a subset of the above mechanisms in a different way than other manufacturers, probably affecting the performance of the NIC in use. In the rest of the paper we will refer to the combination of Packet Aggregation and Block Acknowledgment mechanism as PABA.

3.2 PHY layer enhancements

Apart from the link layer enhancements introduced by 802.11n, the PHY layer of the new standard is enhanced by the use of MIMO communications. MIMO links can operate in two different modes described in what follows.

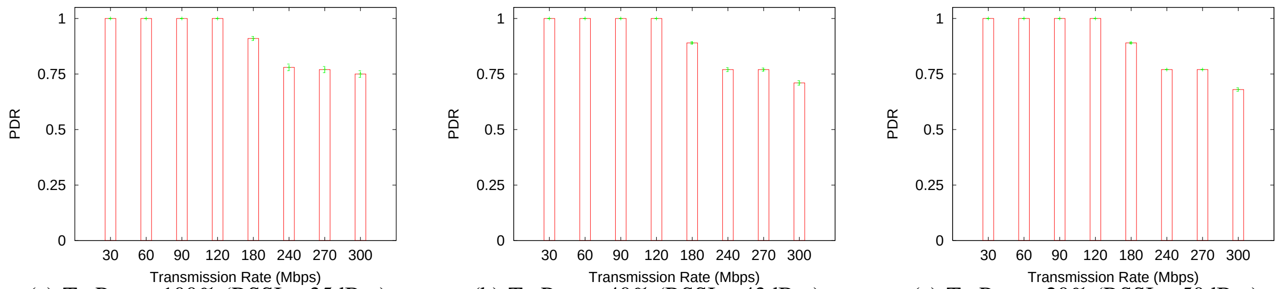
3.2.1 Spatial Division Multiplexing (SDM)

SDM utilizes multiple independent data streams in order to increase the PHY data rate and application throughput. These streams are being multiplexed and transmitted simultaneously from the multiple antenna elements, within one spectral channel. With SDM, each receiving antenna receives a superposition of the signals from the multiple transmit antennas at the sender. The multiple streams are separated and recovered using signal processing techniques. Current 802.11n products support a PHY data transmission rate of 300 Mbps when operating at the SDM mode [8]. While SDM may



(a) SDM 300 Mbps. (b) SDM 180 Mbps. (c) STBC 150 Mbps.

Figure 1: PDR vs. RSSI at highest 802.11n transmission rates in 40 MHz channels with 2 and 3 receiving antennas.



(a) Tx Power 100% (RSSI∼-35dBm). (b) Tx Power 40% (RSSI∼-43dBm). (c) Tx Power 20% (RSSI∼-50dBm).

Figure 2: PDR vs. transmission rate at SDM mode with 40 MHz channels for different Tx power levels.

increase PHY data rate and throughput, it does not yield more reliable communication than conventional SISO systems.

3.2.2 Space Time Block Coding (STBC)

When receiver diversity is being employed on a SISO system, two antennas are used in order to receive the transmitted signal that arrives at each of them after following independent fading characteristics. With special signal processing techniques the signal can be reproduced with higher probability. MIMO systems use more advanced techniques, called Space Time Block Codes. With STBC correlated blocks of the actual data are transmitted from each antenna, and several blocks are transmitted at separate times, thereby creating temporal diversity. The use of STBC can provide higher reliability and thus, can extend the effective transmission range. Alamouti Codes are the most popular coding schemes belonging to this category [14]. More details on STBC can be found in [15].

4. EXPERIMENTAL METHODOLOGY

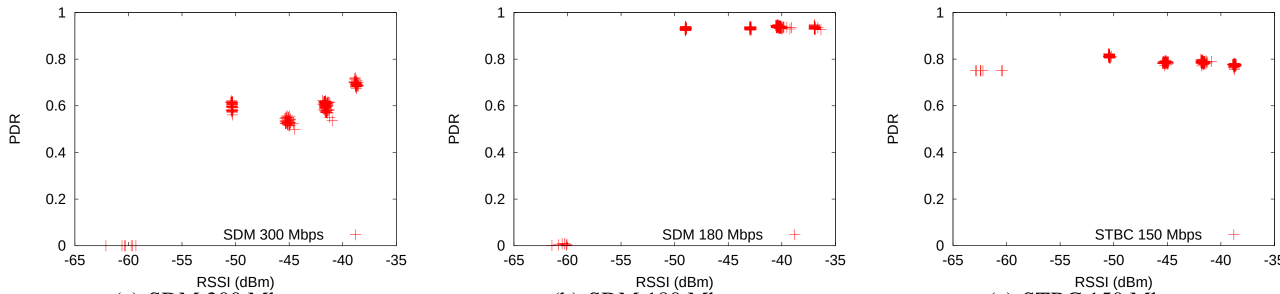
Our experimental testbed is deployed on the Technicolor premises. Each node is a mini-ITX form factor PC with 1.7GHz Intel CPU, 512MB RAM and 80GB HDD, running a Fedora Core Linux distribution with kernel version 2.6.18.5. This testbed node configuration does not impact measurement results or impose any limitations to our experimental study. It supports data transmissions at gigabit speed and generally follows the MIMO testbed deployment guidelines by Pelechrinis et al. [4].

Each device is equipped with one Ralink *RT2880* 802.11n card. *RT2880* is a dual-band chip able to operate in both 2.4 and 5 GHz bands, and supports up to 2x3 MIMO configurations. Each node carries three dual-band 5-dBi omnidirectional antennas mounted on the RT2880 card. The *RT2880* Linux driver [16] supports both STBC and SDM modes. The PHY data transmission rate is controlled by two parameters; the HT_BW which controls the channel width (20 MHz or 40 MHz), and the HT_MCS which controls the modulation scheme. For each mode (STBC or SDM), a higher HT_MCS corresponds to a denser modulation scheme and a higher transmission rate. For STBC, the HT_MCS parameter ranges from 1 to 7, and for SDM from 8 to 15.

For each 802.11n link, the transmitter card operates in AP mode and receiver card in client High Throughput (Greenfield) mode, both set with short Guard Interval for OFDM symbols (400μs). The first setting ensures that the cards do not operate in legacy 802.11 b/g mode, and the second setting yields the highest PHY data rates supported by 802.11n. We disable the card's automatic rate adaptation scheme and use fixed PHY data rates. This is done in order to achieve controlled and repeatable experiments at the highest PHY data rates which are of interest in our study. The HT_BW and HT_MCS settings are detailed for each experiment in conjunction with the results in subsequent sections.

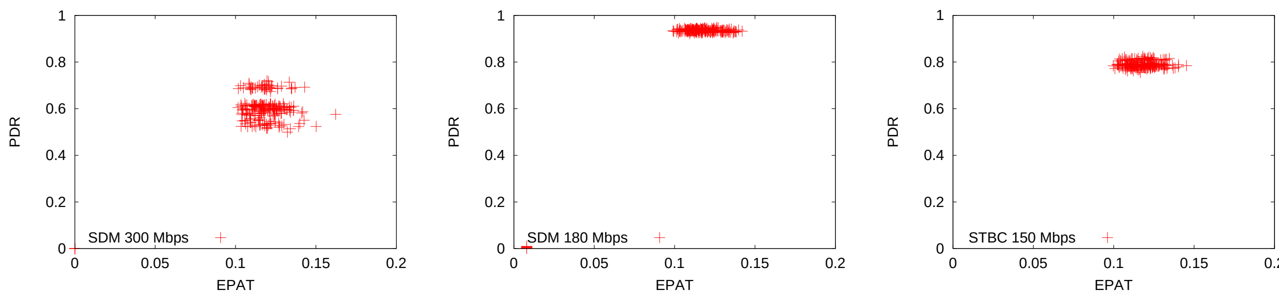
We vary transmission power levels and use different node positions to create a rich set of 802.11n links with different characteristics. We use the *iperf* [17] tool to generate UDP/TCP flows and, unless stated otherwise, use a packet size of 1500 bytes. To accurately measure the links' packet delivery ratio (PDR), we disable MAC layer retransmissions. We thus measure the PDR at the MAC layer (rather than at the IP layer), and avoid the need to count and account for per-packet retransmissions. UDP and TCP goodput are measured as the number of successfully received bytes over the experiment duration. Additional experimental configuration specific to individual experiments is given in conjunction with the results.

We experiment both at the 5 GHz and 2.4 GHz frequency bands. In the 5 GHz band we verified that there is no external interference. Our experiments in 2.4 GHz band are subject to interference due to co-located 802.11 networks. We quantify external interference using a new metric which we call EPAT (**E**xternal **P**acket **A**ir **T**ime). For each experiment, EPAT is defined as the ratio of sum of the



(a) SDM 300 Mbps. (b) SDM 180 Mbps. (c) STBC 150 Mbps.

Figure 3: PDR vs. RSSI at highest 802.11n transmission rates in 40 MHz channels.



(a) SDM 300 Mbps. (b) SDM 180 Mbps. (c) STBC 150 Mbps.

Figure 4: PDR vs EPAT at highest 802.11n transmission rates in 40 MHz channels.

measured air times of all external packets over the duration of the experiment.

$$EPAT = \frac{\sum_i Air\ Time\ of\ Packet\ i}{Experimental\ Duration} \quad (1)$$

where i is an external packet. EPAT takes values from zero to one. The higher the EPAT, the higher the level of external interference. An isolated link should have an EPAT of zero. We measure EPAT by running *tcpdump* on a separate node located next to the receiver. This node uses the same channel and configuration as the nodes in each experiment. During experiments with channel bonding enabled, both the 20 MHz channels are monitored using two separate wireless cards each operating on one of the channels. The monitor node can only record external 802.11 packets in the 2.4 GHz band, which it can decode based on its sensitivity threshold. Interference due to electromagnetic signals from non-802.11 sources, packets from far-away 802.11 interferers and packets that experience collisions are not captured. Thus, EPAT only provides a lower bound on the amount of external interference. Still, we found it a useful metric especially for *relative* comparisons between different experiments.

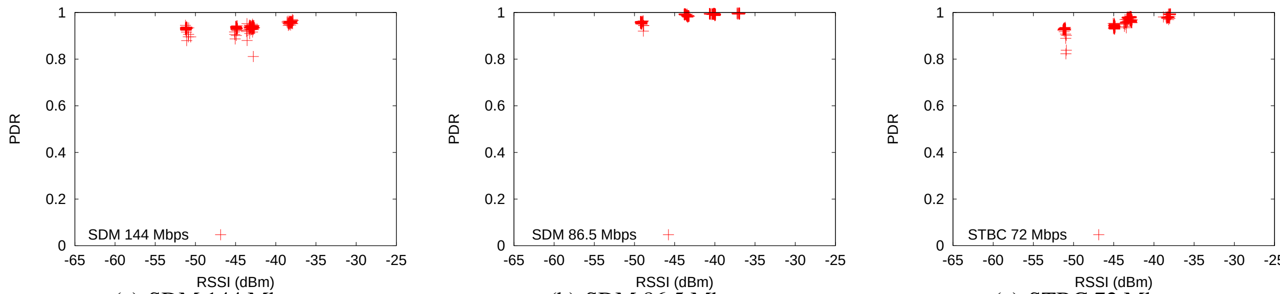
5. BASELINE EXPERIMENTS

We first establish a performance baseline by conducting controlled and interference-free experiments at the 5GHz band. This baseline will help to better understand the 802.11n performance for subsequent experiments where links are subject to interference. We also exploit these baseline experiments to explore the impact of receiver diversity.

To create a wide range of link qualities, we run several experiments where the node locations and transmission power levels are varied. For each set of node locations and transmission power, we run the different configurations back-to-back such that all experiments are performed under similar wireless link channel conditions. During each experiment, the transmitter sends 5000 unicast packets and we record the number of packets correctly captured at the receiver along with their RSSI on each antenna of the receiver. Finally, we explore receiver diversity by conducting two different set of experiments; one with 3 receiving antennas (i.e., 2x3 MIMO) and one with 2 receiving antennas (i.e., 2x2 MIMO).

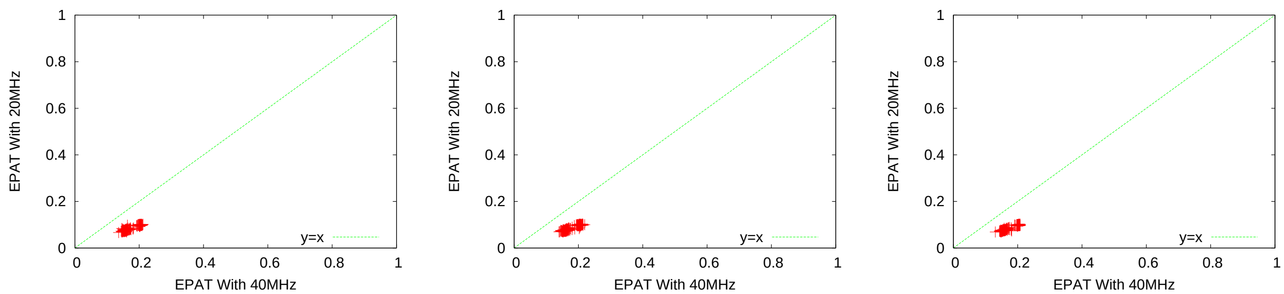
We are interested in the PDR performance at the highest transmission rates. We therefore set the HT_BW to use 40 MHz channel and study three different configurations of HT_MCS. In the first two, HT_MCS is set to 7 for STBC and 15 for SDM. This results in the maximum transmission rates supported by STBC and SDM: 150 Mbps in STBC mode (termed STBC150) and 300 Mbps in SDM mode (termed SDM300). The third configuration is used to compare SDM and STBC for approximately the same rate. This is achieved by setting HT_MCS=12 which yields 180 Mbps in SDM mode (termed SDM180).

Figure 1 depicts our results. For SDM300 (left-most graph), all 2x2 configurations result in zero PDR. This is because the 2x2 configuration did not offer sufficient spatial diversity for the dense modulation scheme used by SDM300. Adding a third receiver antenna, thus operating in 2x3, results in PDR increase and an operational link. However, achieving high PDR values ($>$ 0.8) at SDM300 required high RSSI ($>$ -54 dBm), even in the absence of interference. In contrast, for SDM180 and STBC150, we observe that 2x2 results in high PDR. Adding a third receiving antenna leads to 10-15% PDR increase (roughly from 0.85 to 1). It is interesting to note that even for the case of STBC, where theoretically the 2x2 system provides enough spatio-temporal diversity, the presence of an additional receiving antenna can further improve



(a) SDM 144 Mbps. (b) SDM 86.5 Mbps. (c) STBC 72 Mbps.

Figure 5: PDR vs. RSSI at highest 802.11n transmission rates in 20 MHz channels.



(a) SDM (180 Mbps - 86.5 Mbps). (b) SDM (300 Mbps - 144 Mbps). (c) STBC (150 Mbps - 72 Mbps).

Figure 6: Comparison of EPAT for 20 MHz and 40 Mhz channels for different modulation schemes.

performance[1]. Based on the above observations, we use only 2x3 MIMO configurations in the experiments presented in subsequent sections.

6. IMPACT OF TRANSMISSION RATE

Using similar experimental set up as in the previous section, we investigate to what extent transmission rates are affected by interference. We therefore conduct experiments in the 2.4 GHz band, which is subject to external interference from co-located networks. Figure 2 presents the average PDR with 95% confidence intervals versus transmission rate in SDM mode for three Tx power settings, spanning a high RSSI range of [-50 dBm,-35 dBm][2]. We observe that, for this high RSSI range, the PDR decreases for rates of SDM180 or higher. Notice that the PDR decrease of each rate is similar for all RSSI values. This indicates that the decrease is not due to weak signal but due to inability of the SDM high-rate modulation scheme to support error-free communication in this environment.

Based on the above observation, we delve into the same three configurations as in the previous section. Figure 3 plots the PDR versus the average of the RSSIs captured by the three antennas at the receiver. We observe that, for all configurations, the PDR is less than one even when the RSSI is as high as -37 dBm. Thus, a high RSSI is not an indication of a lossless link at high transmission rates when interference is present. In addition, in the higher RSSI range of [-50 dBm,-37 dBm], SDM300 receives lower PDR and has higher variability than the other two configurations. In contrast, the PDRs of STBC150 and SDM180 are stable. STBC150 receives slightly lower PDR and shows slightly higher variability than SDM180. However, at a lower RSSI of -60 dBm, STBC150 maintains its PDR around 0.8, while both SDM modes receive zero PDR. Thus, for comparable high PHY data rates, the higher robustness of STBC over SDM arises only at the lower RSSI range.

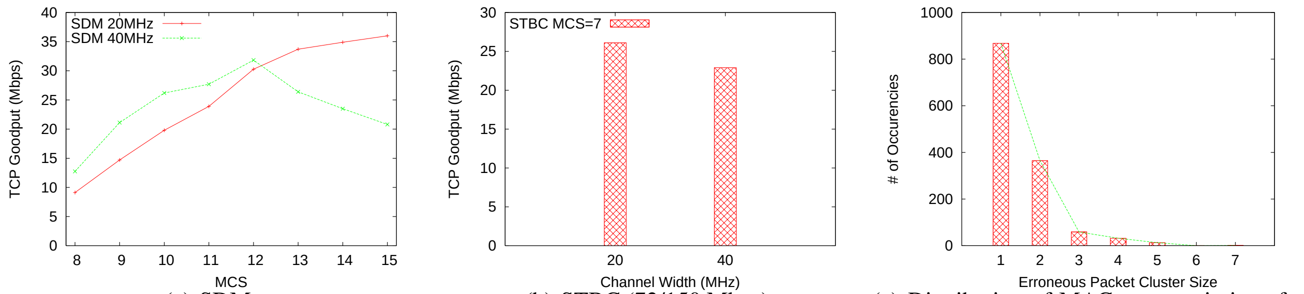
An interesting observation arises from the comparison of Figures 1 and 3. In particular, under the presence of interference (Figure 3), even at higher RSSI values compared to the interference-free settings (Figure 1), the PDR achieved is much lower. This result implies that *interference has a non-negligible impact at the highest transmission rates*.

Finally, Figure 4 plots the PDR vs. the EPAT for the above experiments. We observe that all experiments were subject to a similar amount of external interference, with a lower bound of 10-17% of the total experiment air-time. For such levels of interference, SDM 180 and STBC 150 show stable PDR around 0.9 and 0.8, respectively. On the other hand, we observe that for the same level of EPAT, the PDR of SDM 300 exhibit significant variability without clear relation to the EPAT metric. Thus, neither RSSI nor EPAT are good indicators of the PDR level at SDM 300.

We conclude that a high RSSI link is not a guarantee for lossless 802.11n communication at high PHY data rates. Modulation schemes used for the highest transmission rates are increasingly sensitive to interference, even under moderate interference and high RSSI links. Under equivalent high rate modulation schemes (similar HT_MCS values), STBC does not offer additional link robustness over SDM for high RSSI values. However, at lower RSSI values, STBC is able to sustain the same PDR as high RSSI values, while SDM yields zero PDR.

[1]Due to proprietary reasons, we did not have access on the exact operations of the receiver diversity in STBC mode. Given that STBC is strictly defined for 2x2 systems only, receiver antenna selection can be used.

[2]Note that for the same link and Tx-power, RSSI values observed during the 2.4 GHz experiments are slightly higher than those of the 5 GHz experiments, due to the different propagation characteristics at these frequencies.



(a) SDM. (b) STBC (72/150 Mbps). (c) Distribution of MAC retransmissions for SDM300 (HT_MCS=15, HT_BW=40 MHz).

Figure 7: TCP goodput for various modes of operation.

7. IMPACT OF CHANNEL WIDTH

In the previous section we saw that the highest modulation rates at 40 MHz channels exhibit low PDRs when interference is present even for high RSSI values. One question is whether this effect is due to the usage of wider 40 MHz channels offered by the channel bonding feature of 802.11n. Intuitively, a wider channel is susceptible to a larger amount of interference, thus reducing the achieved PDR.

To study the effect of channel bonding on the PDR, we perform experiments with the same set up and experimental methodology as in Section 6. The difference is that here we disable the channel bonding. In particular, we keep the values of HT_MCS fixed and same as the ones used in Section 6 but set HT_BW to use 20 MHz channels. The highest transmission rates at 20 MHz are almost halved compared to the rates at 40 MHz channels: SDM144 (instead of SDM300), SDM86.5 (instead of SDM150) and STBC72 (instead of STBC150).

Figure 5 plots the PDR versus the RSSI for the highest transmission rates of 20 MHz channels. For all three configurations, the PDRs are higher than the PDRs of the same modulation schemes at the 40 MHz channel in Figure 3. The improvement is most visible for the densest modulation scheme of SDM144: Compared to SDM300 in Figure 3 the PDRs for SDM144 are around 0.9 for the entire high RSSI region [-50 dBm,-35 dBm].

Figure 6 compares the EPAT measured at 20 MHz and 40 MHz channels from the experiments of every modulation scheme. In all cases, 20 MHz channels experience approximately 60% the EPAT of 40 MHz channels, which explains the increased PDR.

7.1 TCP Performance

The above observations show that although channel bonding doubles the transmission rate, it results in a PDR decrease. A valid question is whether such a PDR decrease also results in a throughput decrease. Previous work has shown that the 40 MHz channels offered by channel bonding can sometimes increase UDP throughput. However, the decrease of PDR in 40 MHz channels might have an effect on the throughput of applications that are more sensitive to packet losses than UDP.

In this section, we therefore study the TCP performance of an 802.11n link for different channel widths. Being sensitive to packet losses, TCP goodput might be negatively affected by the use of wider channels. We consider different modulation schemes, varying the channel width on back-to-back experiments. In these experiments we enable the MAC layer retransmissions, and we keep the nodes' positions and transmission power fixed.

Figure 7 plots TCP goodput versus the HT_MCS parameter. In the SDM case in Figure 7(a), at lower rates where PDR is high, TCP goodput is higher in 40 MHz channels than 20 MHz channels. This difference decreases as the modulation scheme HT_MCS increases. After HT_MCS=12, TCP goodput becomes increasingly lower at 40 MHz channels than 20 MHz channels. At the highest HT_MCS, the TCP goodput at 40 MHz is almost half the TCP goodput at 20 MHz. In the STBC case (Figure 7(b)), the TCP goodput is less at 40 MHz than 20 MHz at the highest HT_MCS, but the decrease is not as pronounced as in SDM.

The low TCP goodput at high rates can be due to two reasons. Either PDR is very low that translates to IP losses seen at TCP, or there are no IP losses but the overhead due to the binary exponential backoff of MAC retransmissions is high. Figure 7(c) shows the distribution of MAC retransmissions at the SDM300 case. We see that the 802.11 retransmission threshold of 8 packets is not exceeded, hence TCP does not see packet losses. However, even a few retransmissions are enough to spend air time due to the 802.11 binary exponential backoff. From the graph we conclude that the overhead due to binary exponential backoff can lead to high throughput degradation.

We conclude that the decision whether to use 20 MHz or 40 Mhz channels is not straightforward, especially at the highest rates. We proceed to investigate whether we can increase both PDR and throughput by adjusting the packet size.

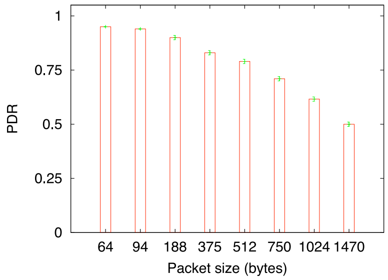
8. IMPACT OF PACKET SIZE

In previous sections we saw that the 802.11n PDR performance degradation can be significant at high transmission rates. We now investigate whether it is possible to exploit 802.11n MAC features in addition to packet size adjustment to overcome this problem.

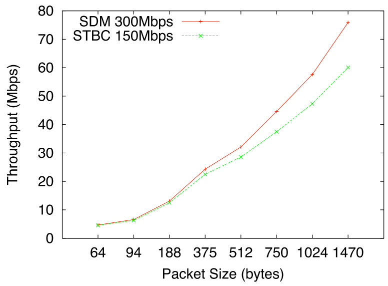
As described in Section 3, 802.11n supports the channel bonding feature to increase the transmission rate and PABA to reduce MAC protocol overhead. In order to gain a better understanding of the impact of packet size and different 802.11n's features on packet loss, we first perform controlled experiments at 5 GHz in the absence of interference.

We start with the SDM300 configuration on a lossy link, where the Tx power has been set to 9 dBm so that the PDR with a packet size of 1470 bytes is roughly 0.5. Keeping the same Tx power, we perform back-to-back interleaved experiments with 8 different packet sizes. Figure 8(a) shows that reducing packet size increases the PDR on this lossy link: starting from 0.5 PDR for a 1470-byte packet, it increases to 0.9 for a 64-byte packet. The lower packet size is expected to increase PDR because less bits are likely to be in error in each packet[3].

[3] A simple model where success of a P-bit packet is modeled as independent bit successes under a fixed bit error rate (BER), gives



(a) PDR vs. Packet size



(b) Throughput vs. Packet size.

Figure 8: Impact of packet size on PDR and UDP throughput for SDM300. (a) Lossy link at 9 dBm Tx Power. (b) Lossless link at 18 dBm Tx power.

To isolate and quantify the impact of packet size on throughput, we run back-to-back experiments with 8 different packet sizes on the same link using SDM300 and STBC150 configurations and maximum Tx power of 18 dBm. For that Tx power we confirmed that the link was lossless for both modes and all packet sizes. Figure 8(b) shows the UDP throughput vs. packet size. We observe that the throughput shows modest increase until 375 bytes. In this range it also does not matter whether SDM300 or STBC150 mode is used. The reason is that the packet size is too small and MAC protocol overhead dominates throughput. After 375 bytes the throughput increases linearly with packet size. The increase is higher for SDM300. The reason is that SDM300 has a higher peak lossless throughput at 1470 bytes than STBC150 [2].

Are there cases where reducing the packet size improves both PDR and link throughput as compared to a larger packet size? In the following experiments we evaluate the impact of packet size adjustment on lossy SDM 300 links when PABA is enabled and disabled. For each case, we tune the transmission power on different links in order to create different link qualities and we measure the PDR and the corresponding throughput with different packet sizes. Figure 9(a) shows the results when PABA is disabled for a representative trial. The maximum throughput curve corresponds to the maximum transmission power, which results in PDR values equal to 1 for all the packet sizes. Reducing the transmission power results in packet losses on the link. From our results, it is evident that in all cases with lossy links (PDR < 1), the improvement on the PDR caused by the smaller packet size introduces a throughput reduction. As an example, when using a packet size of 1470 bytes, the PDR is the smallest observed among the lossy links whereas the achieved throughput is the highest ($\sim 40 Mbps$). Figure 9(b) presents experimental results for PABA enabled. We observe that PABA in combination with smaller packet sizes on lossy links can lead to PDR increase, and avoid at the same time the throughput

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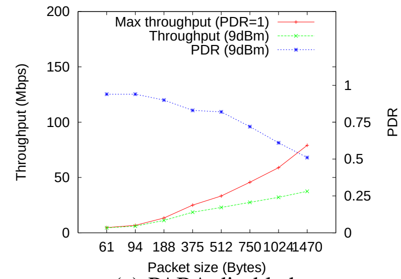
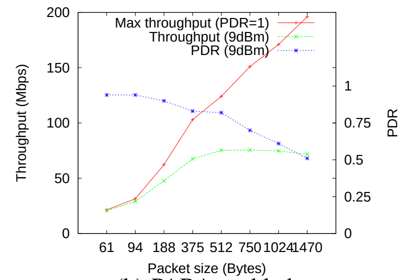
$PDR = (1 - BER)^P$. Assuming PDR=0.5 at P=1470 bytes, this model predicts PDR=0.97 at 64 bytes, close to the measured 0.9.



(a) PABA disabled.



(b) PABA enabled.

Figure 9: Throughput vs. Packet size for lossy links in SDM300 mode. (a) For PABA disabled, reduced packet size increases PDR but hits throughput. (b) For PABA enabled, packet size reduction may increase PDR without introducing throughput decrease.

reduction due to the increased overhead. On top of that, throughput is also slightly increased in some of the cases.

Table 1 shows a subset of Figure 9(b) data. For 750-byte packets, the PDR increases by 40% over that of 1470-byte packets. This packet size exhibits the maximum throughput, which is 5% higher than the throughput with the 1470 bytes packets. These results show that tuning the packet size along with PABA can help towards improving PDR while preventing the throughput degradation due to the increased overhead.

Packet Size (Bytes)	PDR	Throughput (Mbps)
1470	0.51	71.8
1024	0.61	74.7
750	0.7	75.5
512	0.82	75.3

Table 1: 750-byte packet size and PABA can improve the link throughput by 5% compared to 1470-byte packet size.

9. CONCLUSIONS AND FUTURE WORK

In this study, we evaluated the PDR performance of 802.11n links when operating at the highest supported PHY data transmission rates. We conducted an 802.11n measurement campaign in both 2.4 GHz and 5 GHz bands with carefully designed and controlled experiments in an indoor testbed. Our analysis concentrated on the impact of interference and various 802.11n settings on link PDR.

Our findings can be summarized as follows. *(i)* 802.11n configurations (combinations of modulation schemes and channel widths) that achieve high transmission rates (e.g. greater than 180 Mbps with SDM mode), are highly susceptible to noise and interference, delivering a low PDR even for high RSSI values. In addition, the number of receiving antennas can significantly affect the performance. *(ii)* While channel bonding can increase the observed UDP throughput, it can have a negative effect on the packet losses and consequently to applications sensitive to packet drops. In particular, the TCP goodput appears to be lower for the dense modulation schemes when 40 MHz channels are employed. *(iii)* Reducing the packet size for the (above mentioned) high transmission rates can increase the PDR of a lossy 802.11n link. Nevertheless a throughput hit is observed due to the increased overhead. *(iv)* Carefully combining MAC layer enhancements with packet size adaptation can provide improvement in PDR, avoiding at the same time the throughput degradation.

In future work, we plan to further explore the interference sensitivity of 802.11n. Our results indicate that future dense 802.11n network deployments may suffer from low performance due to interference and 802.11n configuration complexity. We believe that accurate interference estimation and efficient interference mitigation will become key differentiators. Furthermore, the PDR will be increasingly important in future wireless networks, as wireless technologies are expected to support many existing and future heterogeneous contents and services.

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11. REFERENCES

[1] V. Shrivastava, S. Rayanchu, J. Yoon, and S. Banerjee. 802.11n Under the Microscope. In *Proc. ACM Internet Measurement Conference (IMC)*, Vouliagmeni, Greece, 2008.

[2] K. Pelechrinis, T. Salonidis, H. Lundgren, and N. Vaidya. Analyzing 802.11n Performance Gains. In *Proc. ACM MobiCom (poster session)*, Beijing, China, 2009.

[3] F. Minarsky. Competitive test of draft 802.11n products. http://www.octoscope.com.

[4] K. Pelechrinis, I. Broustis, T. Salonidis, S.V. Krisnamurthy, and P. Mohapatra. Design and Deployment Considerations for High Performance MIMO Testbeds. In *Proc. International Wireless Internet Conference (WICON)*, Maui, Hawaii, USA, 2008.

[5] V. Visoottiviseth, T. Piroonsith, and S. Siwamogsatham. An Empirical Study on Achievable Throughputs of IEEE 802.11n Devices. In *Proc. International workshop on Wireless Network Measurements (WinMee)*, Seoul, Korea, 2009.

[6] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris. A High Throughput Path Metric for Multihop Wireless Routing. In *Proc. ACM MobiCom*, San Diego, CA, 2003.

[7] J. Bicket, D. Aguayo, S. Biswas, and R. Morris. Architecture and Evaluation of an Unplanned 802.11b Mesh Network. In *Proc. ACM MobiCom*, Cologne, Germany, 2005.

[8] Ralink: MIMO technology. http://www.ralinktech.com.

[9] A. Mishra, V. Shrivastava, S.'Banerjee, and W. Arbaugh. Partially Overlapped Channels not Considered Harmful. In *Proc. ACM SIGMETRICS*, Saint Malo, France, 2006.

[10] P. Goud Jr, R. Hang, D. Truhachen, and C. Schlegel. A Portable MIMO Testbed and Selected Channel Measurements. *EURASIP Journal on Applied Signal Processing*, 2006:141–151, 2006.

[11] C. Mehlfuhrer, S. Geirhofer, S. Caban, and M. Rupp. A Flexible MIMO Testbed with Remote Access. In *In Proc. European Signal Processing Conference (EUSIPCO)*, Antalya, Turkey, 2005.

[12] B. O'hara and A. Petrick. *IEEE 802.11 Handbook, a Designer's Companion*. IEEE Press, Second Edition, ISBN 0-73-814449-5.

[13] ANSI/IEEE 802.11-Standard. 1999 edition.

[14] S.M. Alamouti. A simple transmit diversity technique for wireless communications. *IEEE Journal on Selected Areas in Communications*, 16(8):1451–1458, 1998.

[15] H. Jafarkhani. *Space-Time Coding: Theory and Practice*. Cambridge University Press, 2005.

[16] RT2860 wireless driver. http://www.ralinktech.com/ralink/Home /Support/Linux.html.

[17] iperf. http://dast.nlanr.net/projects/iperf.