The 802.11g 11 Mb/s rate is more robust than 6 Mb/s

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Abstract— **The robustness to noise of the 802.11b/g 5.5 Mb/s and 11 Mb/s rates must be investigated experimentally as they cannot be predicted theoretically. In this paper we report on detailed outdoor and indoor measurements that lead us to the surprising conclusion that the 11 Mb/s 802.11g rate experiences fewer packet losses than the 6 Mb/s 802.11g rate at any given (symbol) SNR. This occurs due to the combination of modulation and physical layer coding schemes used by these rates and has serious implications for rate control algorithms. The practical implications of this, factoring in the interaction between packet loss and 802.11 MAC retries, is that 6 Mb/s is effectively redundant as a packet transmission rate if the 11 Mb/s rate is available.**

Index Terms— **WLAN, IEEE 802.11, Packet Loss Rate.**

I. INTRODUCTION

In wireless devices, it is well-known that higher transmission rates can lead to lower throughput due to reduced robustness to channel noise [1]. Consequently the IEEE 802.11a/b/g/n WLAN protocol-suite provide a range of transmission rates determined by distinct physical layer modulation and Forward Error Correction (FEC) schemes. Each station is equipped with a rate control algorithm that aims to select the rate that gives the highest throughput based on current channel conditions [2][3].

The 802.11a rates are amenable to theoretical analysis in both Additive White Gaussian Noise (AWGN) and Rayleigh fading channels [4][5]. This analysis has shown, surprisingly, that at all signal to noise ratios the 802.11a 9 Mb/s rate experiences higher Packet Loss Ratio (PLR)[1] and hence less throughput than the 12 Mb/s rate. The observation of this engineering error, which as a supplementary point we provide experimental support for, has serious implications for rate control algorithms, which should, consequently, never use the 9 Mb/s rate.

Due to the modulation scheme employed (CCK), the 802.11b/g 5.5 Mb/s and 11 Mb/s rates are not amenable to theoretical evaluation and their performance must be investigated through simulations or experiments. Experiments are particularly desirable as they reflect the experience of end-users without approximation. In this article we undertake this task and arrive at a surprising conclusion: the 6 Mb/s 802.11a/g rate experiences a higher PLR than the 11 Mb/s 802.11b/g rate in both outdoor and indoor environments. As the 6 Mb/s rate has a shorter preamble than the 11 Mb/s rate ($20\mu s$ instead of 96 or $192\mu s$ [6]), this does not *a priori* mean that its throughput is always lower than that of the 11 Mb/s rate. We show, however, that the advantage conferred by the shorter preamble at 6 Mb/s is negligible when there is noise on the medium and thus the 6 Mb/s rate is effectively redundant[2].

In Section II we briefly discuss related work. A pseudo-theory investigation of the 5.5 and 11 Mb/s rates in the presence of noise, based on experimentally fit curves, is presented in Section III. In Section IV we report our experimental results. In Section V we deduce that 11 Mb/s will offer better performance than 6 Mb/s in practical situations. We note that a number of papers have highlighted that care is needed to conduct 802.11 measurements as the hardware may not implement the standard correctly [7], it can have undocumented features such as antenna selection [8] or interference mitigation [9]. For our experiments to be repeatable, in the Appendix we describe in detail the measurement setup that we used to assess the available 802.11g rates, as substantial care is required to avoid complications of the 802.11 protocol and its implementation. By avoiding problems identified by these authors, we ensure that our results are not an artifact of known issues such as antenna selection and Atheros's ANI.

II. RELATED WORK

There has been a considerable volume of previous work on 802.11 rates, particularly when considering rate control, e.g. [1], [2], [10], [11]. Some authors have considered the packet-loss performance of rates alone, e.g. [12], [13] considers the performance of 11b rates outdoors, or in terms of bit-level error patterns [14], [15]. The recent article [16] provides an analysis for a modulation scheme, BOK, related to CCK in a AWGN channel, but no analytic method is available for CCK itself.

We also provide experimental results supporting our claims, as noted above, care is required because cards may have undocumented features [8], [9] which result in unexpected experimental results [17]. We have gone to some length to learn from these previous studies and to avoid potential pitfalls. Consequently, we are confident our results show new effects, supported by both theoretical predictions and experimental results.

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[1] We define the PLR to be the fraction of frames that cannot be successfully decoded; on failure to decode the MAC layer may re-send the frame and for PLR we consider this to be a new transmission.

[2] We note that 6Mbps can be used as the basic rate, rather than a data rate used for payload. In this context 11 Mbps is not a direct substitute for 6 Mbps.

III. PSEUDO-THEORY FOR 802.11B/G 5.5 & 11 MB/S RATES

The 802.11b protocol operates at approximately 2.4 GHz and has 4 transmission rates. The 802.11a protocol operates at approximately 5 GHz and has 8 distinct transmission rates. As with 802.11b, 802.11g operates at 2.4 GHz, but possesses all 12 of the 802.11b and 802.11a rates. The 802.11b rates employ Direct-Sequence Spread Spectrum, while the 802.11a/g rates employ Orthogonal Frequency-Division Multiplexing (OFDM). All of the 802.11a/b/g rates are summarized, including their Forward Error Correction Rates, in Table I.

TABLE I

802.11A/B/G TRANSMISSION RATES

Rate (Mb/s)	Modulation Scheme	FEC Rate	In 802.11a/b/g
1	DBPSK	1/11	b/g
2	DQPSK	1/11	b/g
5.5	CCK	4/8	b/g
6	BPSK	1/2	a/g
9	BPSK	3/4	a/g
11	CCK	8/8	b/g
12	QPSK	1/2	a/g
18	QPSK	3/4	a/g
24	16QAM	1/2	a/g
36	16QAM	3/4	a/g
48	64QAM	2/3	a/g
54	64QAM	3/4	a/g

While the 802.11b/g 5.5 Mb/s and 11 Mb/s rates are not amenable to theoretical investigation, they are susceptible to pseudo-theory using experimentally determined relationships. The following empirical equations are taken from [18] and provide a relationship between Bit Error Rate (BER) at the PHY layer and the bit SNR (S_{bit}) in a channel that is assumed to resemble AWGN: for 5.5 Mb/s,

$$BER_{PHY_{5.5}}(S_{bit}) \leq \frac{8}{15}(14Q(\sqrt{8S_{bit}}) + Q(\sqrt{16S_{bit}})) \quad (1)$$

and for 11 Mb/s,

$$\begin{aligned} BER_{PHY_{11}}(S_{bit}) \leq\ & 24Q(\sqrt{4S_{bit}}) + 16Q(\sqrt{6S_{bit}}) \\ & + 174Q(\sqrt{8S_{bit}}) + 16Q(\sqrt{10S_{bit}}) \\ & + 24Q(\sqrt{12S_{bit}}) + Q(\sqrt{16S_{bit}}), \quad (2) \end{aligned}$$

where $Q(x) = \mathcal{P}(N(0,1) > x)$ and $N(0,1)$ is a mean zero unit variance Gaussian. It is common to use the symbol SNR instead of the bit SNR, S_{bit}, to describe the received signal. The function relating symbol SNR and S_{bit}, as given in [19], is:

$$S_{bit} = \text{SNR}\frac{B}{R}, \quad (3)$$

where B is the bandwidth (20 MHz) and R is bit-rate (R Mb/s). We will reserve SNR for the symbol SNR.

To calculate the BER at the MAC layer it is necessary to take account of the coding gain. The 5.5 Mb/s and 11 Mb/s rates use 8-bit CCK which has a gain of 8 dB [18]. Using equations (1) through (3) and this coding gain, the following equations give the pseudo-theory relationship between the BER at the MAC layer and the symbol SNR in the AWGN channel model of rates 5.5 Mb/s and 11 Mb/s:

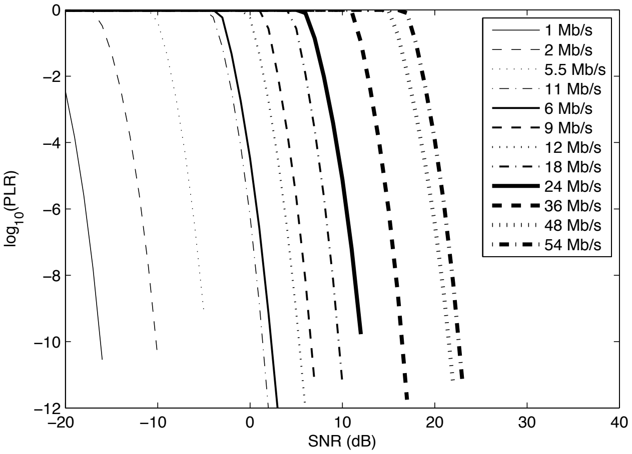

Fig. 1. PLR vs. SNR for all 802.11g rates in an AWGN channel and $1,000$ byte packets (similar graphs are observed for a wide range of packet sizes). Pseudo-theory for 5.5 and 11 Mb/s, theory for all other rates

$$5.5 \text{ Mb/s}, \ BER_{MAC_{5.5}}(\text{SNR}) = BER_{PHY_{5.5}}(\text{SNR}\frac{B}{R}10^{0.8});$$

$$11 \text{ Mb/s}, \ BER_{MAC_{11}}(\text{SNR}) = BER_{PHY_{11}}(\text{SNR}\frac{B}{R}10^{0.8}).$$

Based on these formulae, and assuming all bits in the packet are independent of each other, we calculate the packet loss rate as $1-(1-BER_{MAC})^L$, where L is the payload length in bits. Combining this with standard theory for all other 802.11a/b/g rates in an AWGN channel [20][21][22] we obtain Fig. 1 for $L = 1000 \times 8$ bits. This figure, based on pseudo-theory for the 5.5 and 11 Mb/s rates in the AWGN channel, provides the first suggestion that the 11 Mb/s rate could be more robust than 6 Mb/s for all SNR. At every SNR, the 6 Mb/s rate experiences higher PLR than the 11 Mb/s rate. As this deduction is based on pseudo-theory, fit curves and a channel model that may not be representative of practical circumstances, before concluding the 6 Mb/s rate is redundant in the 802.11g rate set used for data transmission, experimental evidence is required.

IV. EXPERIMENTAL RESULTS

Using the experimental apparatus described in the Appendix, we performed extensive measurements in two distinct environments, outdoor experiments on a sports field and indoor experiments in an office environment. We expect the outdoor environment to be representative of a relatively simple channel, with line-of-sight being the primary signal path. We expect the indoor environment to be more complex with significant multipath propagation and so conduct tests at night when the environment is relatively static and during the day when people, doors and other objects move frequently. As described in the Appendix, significant effort was made to check that we are testing low-layer performance of the system, before retransmissions etc. Each point on a graph in this section

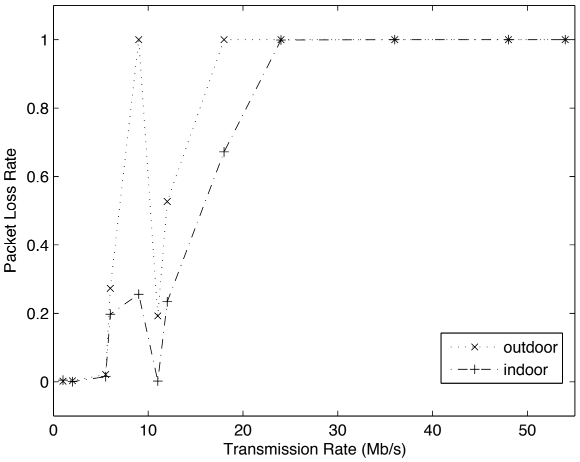

Fig. 2. Measured PLR vs. Transmission Rates in day-time outdoor environment at 160m separation and in night-time indoor environment at 10m separation. Experiment

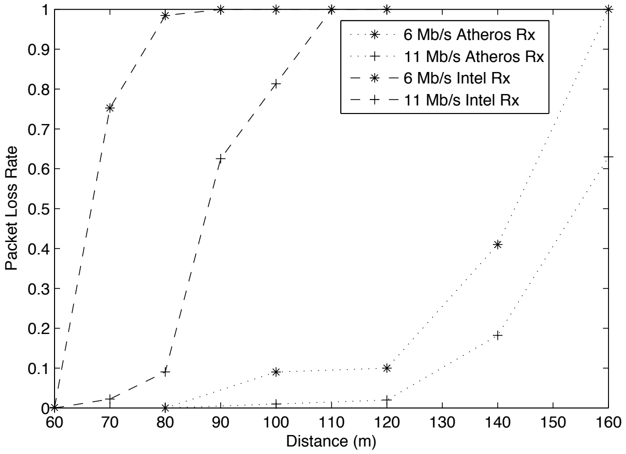

Fig. 3. Measured PLR vs. distance in day-time outdoor environment. Experiment

represents a measurement outcome from an experiment with 20,000 packets with length 1000 bytes. The error bars based on a Central Limit Theorem approximation for the mean PLR are, consequently, too small to be shown.

Fig. 2 shows PLR vs. Transmission Rate for the outdoor experiments at a separation of 160 meters and the indoor environment in the night-time at 10m separation. Focusing initially on the outdoor experiments, there are two significant deductions from this graph. Firstly, the 6 Mb/s 802.11a/g rate experiences more packet loss than the 11 Mb/s 802.11b/g rate (roughly 25% against 20%). Thus, while one expects that by design the lower rates will be more robust, this is not the case. Secondly, the 9 Mb/s 802.11a/g rate gets no throughput while the 12 Mb/s 802.11a/g rate experiences packet loss of approximately 50%. This supports analytical work [4][5] suggesting that the 9 Mb/s rate will have a higher loss rate than the 12 Mb/s rate.

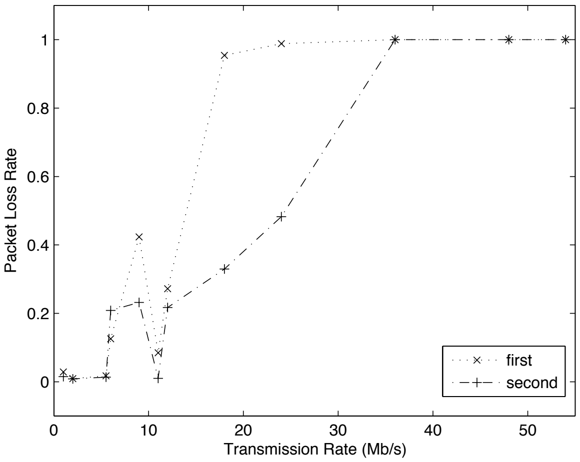

Fig. 4. Measured PLR vs. Transmission Rates in day-time indoor environment at 10m separation. Experiment

As shown using pseudo-theory in Fig. 1, the 6 Mb/s rate suffers a bigger PLR than 11 Mb/s at any given SNR. To verify this prediction, a sequence of outdoor experiments were performed to measure PLR exclusively for the 6 Mb/s and 11 Mb/s rates. Fig. 3 shows PLR for 6 Mb/s and 11 Mb/s for two different receiver chipsets as the distance between the sender and receiver is varied. It is clear that SNR is a monotonically decreasing function of distance in stable environments. These data were obtained on a different day from those in Fig. 2, so that absolute loss rates are different, but the trend is the same. Apart from at distances where neither rate experiences any packet losses, the clear conclusion is that 6 Mb/s loses more packets than 11 Mb/s at all the distances.

The indoor night time experiments were carried out at midnight to limit the impact of human motion, which can cause variation in channel conditions [23]. Fig. 2 also reports PLR vs. Transmission Rate for these experiments. For these results, the transmitter and receiver laptops were placed in separate offices approximately 10 meters apart, with several partition walls between them. In the plot it can be seen that the 9 Mb/s 802.11a/g rate suffers a similar PLR to the 12 Mb/s 802.11a/g rate. The 11 Mb/s 802.11b/g rate experiences no loss at this distance, but the 6 Mb/s 802.11a/g rate experiences approximately 20% loss.

A second collection of indoor experiments were performed at noon during a working day to investigate the impact of channel conditions driven by human motion as well as the switching on and off of equipment with wireless cards. For two distinct runs, Fig. 4 reports typical measurements of PLR vs. Transmission Rate. This plot illustrates that although the absolute level of loss changes based on environmental conditions, the undesirable PLR ordering seen in the mid-day measurements remains present.

Our final observation is that for 802.11 packets can be lost because of noise, interference or collisions with other 802.11 packets. In our outdoor experiments, we aimed to eliminate interference and collisions. However, in our indoor measurements, we expect that some of the losses may be due to collisions or interference from devices other than our test devices. Thus the PLR values shown encompass all three possibilities.

V. PRACTICAL IMPLICATIONS FOR RATE CONTROL

Our experiments demonstrate that the 11 Mb/s rate is more robust than the 6 Mb/s rate as the 6 Mb/s rate experiences higher PLR at any given SNR, but this does not mean its throughput is lower. The 6 Mb/s has an advantage over 11 Mb/s as the preamble associated with the 802.11 OFDM rates (20 μs) is considerably shorter than the one for the 802.11b rates (96/192 μs for the short/long preamble) [6]. We can perform a simple calculation to determine if this advantage is significant; we conclude it is not.

With packet payloads taken from a distribution with mean $E(\text{payload})$, the average time that a frame takes on the medium, not including MAC failed transmissions and MAC layer retries, at rate R Mb/s is

$$\begin{aligned} E(T_R) =& \text{Preamble + E(Payload)/R + SIFS} \\ & + \text{Preamble + ACK} + \text{DIFS}, \end{aligned} \tag{4}$$

where, in the absence of legacy 802.11b cards, SIFS $= 10\mu s$ is the short inter-frame spacing, the ACK takes $112\mu s$ and DIFS $= 28\mu s$ is the distributed inter-frame spacing. Thus, in the absence of any losses, for average payloads of less than 250 bytes the 6 Mb/s rate gives higher throughput than 11 Mb/s with the short preamble, which is already smaller than the average packet size likely to be seen on a typical network. With the long preamble, the cross over $(E(T_6) = E(T_{11}))$ is at an expected payload of 566 bytes, but this back-of-envelope calculation does not tell the full story.

Failed transmissions due to noise or collision induce MAC layer retries with binary-exponential-back-off periods. For a station that always has packets to send in a noise-free and collision-free environment, between transmissions there is a uniformly chosen back-off period of between 0 and $W - 1$ idle slots ($9\mu s$ in 802.11g), where the base back-off window is $W = 32$ in 802.11g. For a given packet, a failure to receive a positive acknowledgment of a transmission results in the back-off window being doubled before the next attempted transmission up to a maximum size of $2^m W$, with $m = 5$ in 802.11g. Should any given packet experience more than M collisions, 11 in 802.11g, the packet is discarded. After a successful transmission or a discard, the next packet uses the base window size W.

For a lone station transmitting packets in a noisy environment where packets are lost with probability p, the mean time until successful transmission or discard of a packet, including retries and back-off periods, is

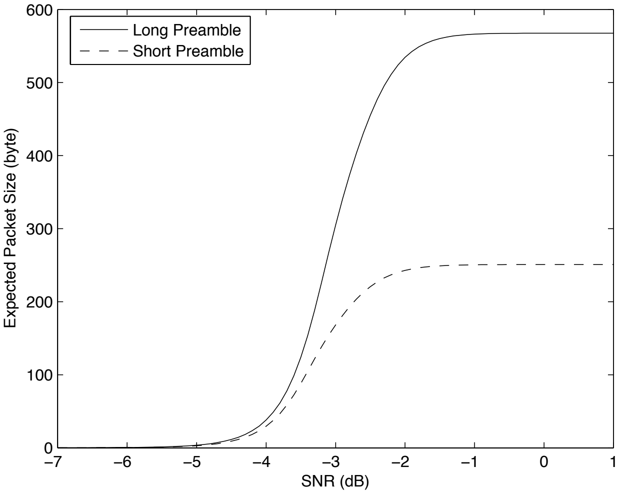

Fig. 5. Single station. Largest expected payload at which the 6 Mb/s rate at given SNR obtains higher throughput than the 11 Mb/s rate. Results based on 6 Mb/s theory and 11 Mb/s pseudo-theory

$$\begin{aligned} E(T_S) =& E(T_R) \sum_{i=0}^{M} p^i \\ & + \sigma \left(\sum_{i=0}^{m} p^i \frac{2^i W - 1}{2} + \sum_{i=m+1}^{M} p^i \frac{2^m W - 1}{2} \right) \\ =& E(T_R) \frac{1 - p^{M+1}}{1 - p} \\ & + \sigma \left(\frac{W}{2} \frac{1 - (2p)^{m+1}}{1 - 2p} - \frac{1}{2} \frac{1 - p^{m+1}}{1 - p} \right. \\ & \left. + \frac{2^m W - 1}{2} \frac{p^{m+1} - p^{M+1}}{1 - p} \right), \end{aligned} \tag{5}$$

where $\sigma = 9\mu s$ is the idle slot length. Accounting for discards, the throughput of a station will be $(1 - p^M)/E(T_S)$.

We have seen that the 6 Mb/s rate experiences more noise based losses than the 11 Mb/s rate. For a network consisting of a single station that always has packets to send we use theory to determine p as a function of SNR for the 6 Mb/s rate in an AWGN channel and the pseudo-theory described in Section III for the 11 Mb/s rate. We then use $(1 - p^M)/E(T_S)$ to identify the threshold expected payload size in bytes at which the 6 Mb/s rate stops having higher throughput than the 11 Mb/s rate. The result is plotted in Fig. 5 for both the long and short preamble. With any difference in noise characteristics, in order for throughput at the 6 Mb/s rate to be higher than the 11 Mb/s rate due to its shorter preamble, the average packet size would have to be smaller than found in a typical network, particularly with the short preamble being used for the 11 Mb/s rate. Thus we conclude that the when the 6 Mb/s and 11Mbps rates are both available, then 11 Mb/s is a better choice.

VI. CONCLUSIONS

Using an experimental approach that directly reflects the end-user's experience we have shown that the joint effect of modulation and physical layer encoding schemes of the 802.11g transmission rates results in a surprising, undesirable feature that could not have been predicted theoretically: robustness of PLR to SNR is *not* a monotonic decreasing function of the rate. Detailed outdoor and indoor experiments, over a range of conditions, show that the 6 Mb/s 802.11g rate experiences more packet loss than the 11 Mb/s 802.11g rate at the same SNR.

Substantial care, as described in the Appendix, was taken in the design and testing of our experimental apparatus to guarantee that meaningful, reproducible results were obtained. This is essential in ensuring our deductions are accurate and can be used with confidence by device manufacturers so that their products can meet their customers' expectations.

The 11 Mb/s rate has a physical layer preamble of $96\mu s$ or $192\mu s$ for each transmitted packet, while the 6 Mb/s rate has a preamble of $20\mu s$. Thus, despite the higher loss rate, this does not necessarily mean that the 6 Mb/s rate gets less throughput. By considering the number of retries and the amount of time a station spends in back-off, however, we can quantify the conditions under which 6 Mb/s will offer better throughput. For practically realistic mean payload sizes the rate with the lowest PLR will offer the highest throughput and lowest transmission delays. Thus, while the 6 Mb/s 802.11g rate is not necessarily redundant in all situations, it is in most practical ones. Thus both the 6 and 9 Mb/s 802.11g rates are effectively redundant and should not be considered by rate control algorithms for data transmission.

APPENDIX

Using our experimental setup, we wish to determine the performance of the IEEE 802.11g rates. We use multicast 802.11 packets for a number of reasons. Firstly, multicast packets are not acknowledged in the IEEE 802.11 protocol and therefore they are not subject to MAC level retries. This is an advantage because each packet will be transmitted exactly once, making tallying which packets are lost easier than with the unicast case. It also means that we do not have to concern ourselves with lost ACK packets, which might result in successfully transmitted packets being retransmitted. Since we plan to operate across a wide range of SNR values, lost ACKs could have been an issue.

In each packet the first 80 bytes of payload were used to record experiment sequence number and transmission rate. The full payload was 1000 bytes and the remaining payload bits were chosen randomly for each packet using a Bernoulli 1/2 process. We do this in order to ensure that a wide variety of symbols are used at the physical layer. While 802.11 does XOR with a scrambling sequence before transmission, there are only 127 possible scrambling sequences. By using a random payload we avoid any risk of repeatedly testing the transmission of the same bit sequences. Packet transmissions are spaced so that there is sufficient time to send each packet before the next is queued, thus avoiding losses due to buffer overflows.

Two laptops equipped with Atheros 802.11b/g cards were used, one employed as a transmitter and one as a receiver. Both were equipped with a modified version of MadWifi driver (details below, with modifications available on request). One laptop was configured to act as an access point (using host AP mode) while the other was configured as a station. Our multicast frames are sent from the AP to the station. Note that sending in the other direction would result in the frame being unicast to the AP and then multicast from the AP. To check that our deductions were not chip-set dependent, we also used a laptop equipped with an Intel 2915abg card as a receiver, as reported in Fig. 3.

To ensure that each packet was transmitted in the same manner, so we fixed transmission power at the sender and fixed which antenna was used for transmission. The driver was modified to enable the selection of a fixed transmission rate for multicast data packets. At the receiver, a certain amount of adaptation cannot be avoided (for example, hardware signal equalization), however we did modify the driver to disabled disassociation due to missed beacons. This prevents the driver from scanning for new access points when the signal level to the current access point is so low that beacon frames cannot be successfully decoded. We also disabled Atheros's Ambient Noise Immunity (ANI) feature, which has been reported to cause unwanted side effects [9]; it has been observed that ANI can disable the reception of packets at 6 Mb/s with low signal strength, while not impacting on the reception of packets transmitted at 11Mb/s. This can result in large differences in PLR due to ANI.

While validating our setup, we sent sequences of packets and recorded if each packet was successfully received or not. We initially conducted tests in a playing field some distance from any buildings, roads and other sources of interference, as confirmed using a spectrum analyzer. For all validation runs and experiments reported on in this paper, we investigated the resulting sequences for evidence of correlation by examining the autocovariance of the loss sequence and inspecting the PLR smoothed with an exponential sliding average. In a simple memoryless channel without interfering devices, packet losses are expected to be independent, so we regarded non-zero covariance as evidence of interference, higher-layer adaptation, etc. that should be eliminated from clean-environment performance.

These investigations confirmed previous results that the human motion heavily influences measurement outcomes [23] and so for our clean-environment results we aim to minimize the impact of moving people. The impact of moving people is often an important part of the WiFi environment and our office-based results include this. It is, however, useful to study the behavior of our equipment in a static environment in order to ensure that we are testing the low layer channel performance and not observing a changing environment or a higher layer adaptation mechanism.

Our measurements were repeated with the laptops separated by increasing distances to vary the path SNR in a stable environment. The ground was not level and if the laptops were close to the ground then line-of-sight could be obscured. To avoid this, we placed each laptop on a 75cm tall plastic pedestal, to ensure that the direct path was not obscured. Further aspects of this experimental apparatus are discussed in [24].

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