ANALYSIS OF PHYSICAL LAYER PERFORMANCE OF IEEE 802.11A IN AN AD-HOC NETWORK

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ABSTRACT

The IEEE 802.11a standard using Orthogonal Frequency Division Multiplexing (OFDM) can provide data rates up to 54 Mbps, which makes it a good candidate for high-speed communications in wireless local area networks (WLANs). Although the standard is meant for indoor applications, we tested its performance in a city environment. Our measurements indicated that the users experience a significantly lower throughput than that promised by the standard, with the performance becoming worse as the speed of the users increased. To better understand the reasons for this behavior, we measured outdoor channels, corresponding to stationary and mobile users. Analysis of experimental data showed that the channel could vary even within the duration of one data frame. Thus, the training-based scheme used in 802.11a, which estimates the channel once during the initial part of the frame and then uses it to equalize the entire frame, results in imperfect channel equalization. This results in high bit-error rate (BER), causing packets to be discarded and increasing the probability of outage. The paper presents experimental results demonstrating the 802.11a weaknesses when operating in an outdoors mobile environment, and provides some recommendations for improving its performance.

1. INTRODUCTION

Wireless Local Area Networks (WLANs) provide for the desired cable-free access to the information highway. The high capacity 802.11a protocol deploying Orthogonal Frequency Division Multiplexing (OFDM) at the physical layer (operating in the 5 GHz range) promises data rates as high as 54 Mbps.

At high transmission rates, the communications channel becomes a limiting factor. Signal pulses are broadened in time as they travel through the channel (multipath effect), leading to intersymbol interference (ISI). The pulse spread limits the speed at which adjacent data pulses can be sent without overlap, thus, limiting the maximum information rate of the wireless system. OFDM ([1, 2, 3]) is a multicarrier modulation technique [4], that mitigates multipath effects, without sacrificing transmission. The overall frequency band is divided into a number of subbands with separate subcarriers. On each subcarrier, the modulated symbol rate is low in comparison to the channel delay spread, thus ISI can be prevented. Besides 802.11a, OFDM has been implemented in HiperLAN [5] and has been adopted by the European digital audio and video broadcasting standards ([6] and DVB [7]).

OFDM modulation is performed using the following steps. First, the information-bearing symbol, modulated via any type of constellation (e.g., BPSK, QAM) is segmented into blocks of length N. An N-point IDFT (Inverse Discrete Fourier Transform) is then performed on each block (more precisely, as supported by the 802.11a standard, the total number of carriers equals N=64, but only 48 of them are used to transmit the information bearing signal), and a preamble, consisting of the last N_{cp} IDFT samples, called cyclic prefix (CP), is appended in front of the IDFT block. The augmented blocks are sent one after the other through the communications channel. As long as the channel length is smaller than the length of the cyclic prefix, the spreading of the block, caused by the convolution with the channel, affects less than N_{cp} symbols. Thus, interference occurs between two adjacent blocks only. At the receiver, the cyclic prefix part is discarded, and an N-point DFT is performed on the remaining N-symbol segment of the block. It can be shown that the received symbol at the k-th carrier equals the transmitted one scaled by the channel frequency response at frequency k. Thus, multicarrier modulation armed with cyclic prefix effectively turns the wideband frequency-selective channel into a number of parallel narrowband frequencyflat subchannels. Although ISI can be avoided, via the use of cyclic prefix, the phase and gain of each subchannel is needed for coherent symbol detection.

2. USING 802.11A IN AN OUTDOORS MOBILE SCENARIO

In the 802.11a standards, estimation of the channel is done via training symbols. Figures 1 and 2 show the PLCP Protocol Data Unit (PPDU) frame format and OFDM training structure, respectively, as described by the IEEE 802.11a standard.

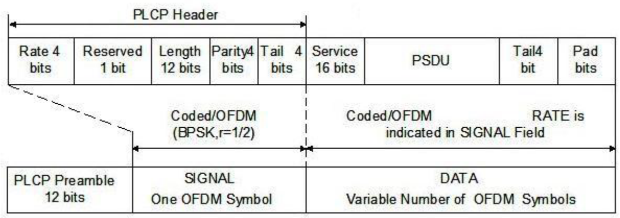

Figure 1. PPDU frame format (from [9])

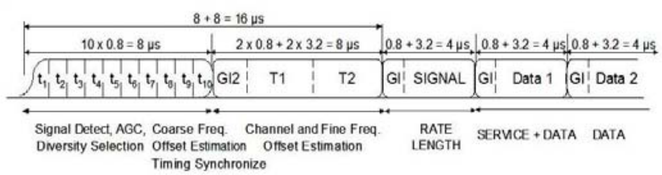

Figure 2. OFDM training structure (from [9])

As can be seen from the Figure 2, the OFDM training structure (or more precisely, its 8 microseconds long segment denoted with GI2:T1:T2) is used for fine frequency offset estimation and channel estimation. What is of interest to us is that this is the only segment of the OFDM frame that is used for estimating the multipath effects. The channel estimates obtained during this period are used to compensate for multipath effects for the entire frame.

The idea of using the training symbols for estimating the channel relies on the assumption that the channel will stay the same for the duration of the entire OFDM frame. The guidelines suggest that the 802.11a cards should be used for indoor applications and under low mobility conditions, so that the latter condition is guaranteed. However, if 802.11a was to be used in an outdoors mobile scenario, the performance might be affected. The reasons for this could be the fast-varying channels that are not equalized adequately based on the available training symbols, and/or the Doppler shifts that translate to carrier frequency offset, giving rise to higher bit-error rates and increasing outage probabilities.

Indeed, as will be illustrated in the next section, experimental results with laptops employing 802.11a wireless cards showed that throughput decreases with increase in mobility of any of two nodes in an ad-hoc configuration and decreases significantly when both the nodes are mobile at high speeds. The probability of outage increases with increase in mobility. Field measurements were made using our wireless test-bed to characterize these mobile channels.

3. EXPERIMENTS AND RESULTS

In the sequel, we:

- Report the results that we obtained on the behavior of the 802.11a cards.
- Experimentally measure channel under the above conditions.
- Experimentally measure Doppler effects.
- Conduct Monte Carlo simulations based on the above measured channels to study the effectiveness of the channel equalization approach used in the 802.11a standard.

3.1 Report on the results that we obtained on the behavior of the 802.11a cards

Primary experiments were set-up to study the performance of the 802.11a cards under mobile conditions. The experiment was set-up in the outskirts of the city of Philadelphia. The 802.11a cards were used with laptops working with Windows 2000 as the operating system at 1 GHz processor speed. The cards were arranged to work in the ad-hoc mode where one of the nodes acted as the server that was set-up using the Windows IIS Service and the other acted as the host. Data transfer from the server was initiated by the host node, using 'GNU wget', a software package used to retrieve files using the HTTP transfer protocol and logs the data transfer progress with time, noting the instants when outages occur. Data of at least 950 MB in size was downloaded for each set of readings. The cards were set-up to work at raw data rates (excluding the preamble of the data frames) that could vary from 6 Mbps to 54 Mbps (as defined by the standards). One of the nodes was kept stationary; while the other was mobile with speeds varying from walking speeds up to 20mph. Performance was measured in terms of 'goodput' or user throughput and the outage probability. Results were used for comparative study of performance with increasing mobility of the nodes. Results are shown in Figures 3 and 4.

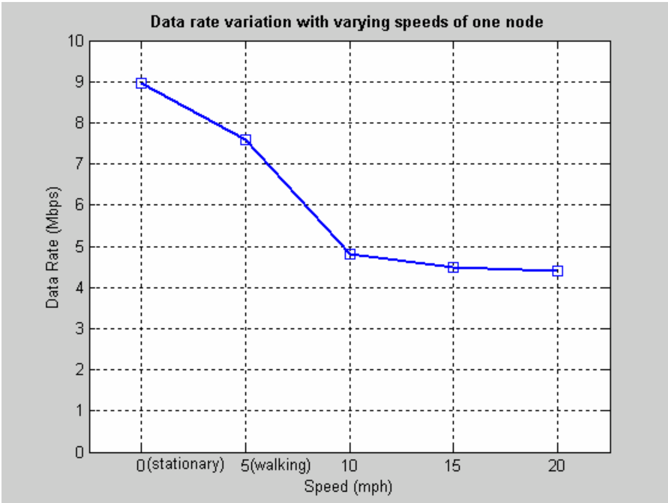

Figure 3. Data rate

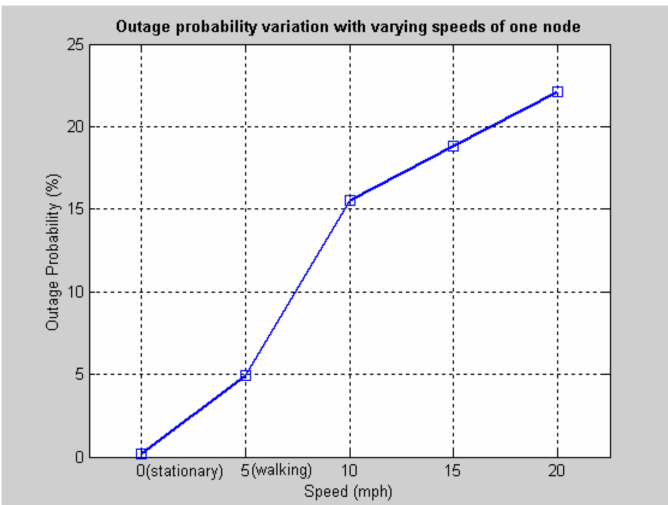

Figure 4. Outage probability

Performance further deteriorated when both the nodes were placed in moving vehicles at about 50 mph on the highway, while distance between the two was maintained within 40 feet.

3.2 Experimental measurement of the channel characteristics under the above conditions

Field tests were further carried out to investigate the cause for the observed performance. Channels were measured at a transmission frequency of 5.2 GHz with the receiver (Agilent - Vector Signal Analyzer 89600 series) stationary while the transmitter (Agilent - ESG 4438C) was placed on a car moving at a perpendicular distance of about 40 feet and moving at a speed of 10mph. The technique used for obtaining the channel estimates was the spread-spectrum channel sounding technique. This channel sounding method can be summarized as follows. At the transmitter a signal is modulated with a pseudo-random sequence (with the period longer than the length of the channel), while at the receiver, the same pseudo-random code is used to demodulate the transmitted signal using the cross correlation between the received signal and the known code. The idea behind this approach is as follows. Let us consider one period T of the transmitted signal after it is modulated with the pseudo-random sequence and denote it with $s(t)$, $0 \le t \le T$. Then, if the pseudo-random sequence is properly designed and long enough the following holds:

$$\int s(t)s^*(t-\tau)dt \approx A\delta(\tau)$$

where $\delta(t)$ is the Dirac delta function, and A is a constant that describes the energy of the transmitted signal. After the signal is passed through the channel $h(t)$ that we would like to determine it becomes:

$$r(t) = \int h(\xi)s(t-\xi)d\xi$$

The received signal is then cross-correlated with the known signal $s(t)$ at the receiver to obtain:

$$\begin{aligned} p(\tau) &= \int\int h(\xi)s(t-\xi)s^*(t-\tau)d\xi dt \\ &= \int\int h(\xi)s(\eta)s^*(\eta+\xi-\tau)d\xi d\eta \\ &= \int h(\xi)\int s(\eta)s^*(\eta+\xi-\tau)d\eta d\xi \\ &= \int h(\xi)A\delta(\tau-\xi)d\xi \\ &= Ah(\tau) \end{aligned}$$

Thus, as a result, a channel impulse response is obtained. The experimental setting is shown in Figure 5.

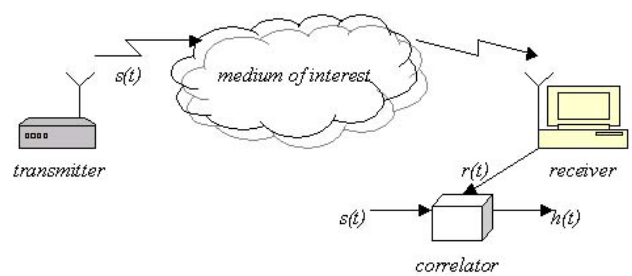

Figure 5. Experimental setting for channel measurements

In our experiments the pseudo-random signal $s(t)$ was selected to be a periodic BPSK sequence transmitted at the symbol rate 18 Msps, with the period being 1024 symbols long. The BPSK sequence was additionally convolved with the shaping filter (raised cosine filter) which is the standard technique to limit the bandwidth of the transmitted signal. The spread-spectrum channel sounding technique allows us to estimate the impulse response of the channel every T seconds (where T is the duration of the pseudo-random sequence and in our case equals approximately 57 microseconds). This further allows us to, by going into the frequency domain and taking into consideration the spacing between the subcarriers, model each subchannel with its estimated gain and phase (see the Introduction part), follow their variations in time and use the recorded results for future analysis. Let us recall the OFDM frame format from Figs. 1 and 2. If the DATA part of the frame were to be occupied by the maximum possible Ethernet frame size of 1518 bytes and data were transmitted (using 48 out of 52 as data carriers [9]) at the minimum rate of 6 Mbps, transmission would require 506 OFDM symbols taking 2.024 ms of transmission time, whereas the same amount of data being transmitted at the rate of 54 Mbps would need about 57 OFDM symbols requiring 228 microseconds to transmit. If channels were to vary faster than the time used to transmit the OFDM frame, the channel calculated using the training sequence at the start of the frame will not accurately equalize the entire frame and may cause the frame to be discarded. This not only increases the probability of outage but consequently also decreases the throughput. In this case, as is logical, the data rate at the transmitting node is decreased (lesser bits per carrier) and the coding rates are also decreased. Though this reduces the raw data throughput, outage probability decreases at least keeping the transfer going. However, due to mobility of any of the nodes, the channel continues to change and in fact changes even more often in this longer duration taken for transmission of 1518 bytes. The transmission frames facing varying channels may again be subject to discarding if channel variations are large. The channels measured every 500 microseconds at the speed of 10 mph showed significant variations. As the mobile user's speed increases further, the time variations in the channel causes more significant bit-error rates.

3.3 Doppler effects

Carrier frequency offset (CFO) is caused by the tuning oscillator instabilities and Doppler effects induced by the channel. Tuning oscillator instabilities are inevitable, occur in both indoor and outdoor environments and are not related to the movement of the units. Doppler effects are caused by the movement of the transmitters and/or receivers and need to be investigated. In order to measure Doppler frequency shifts we transmitted the simple sine wave at 5.2 GHz and recorded the spectrogram of the received signal. The receiver was moving towards and from the receiver with the maximal speed of 20 mph. The results are shown in Figure 6.

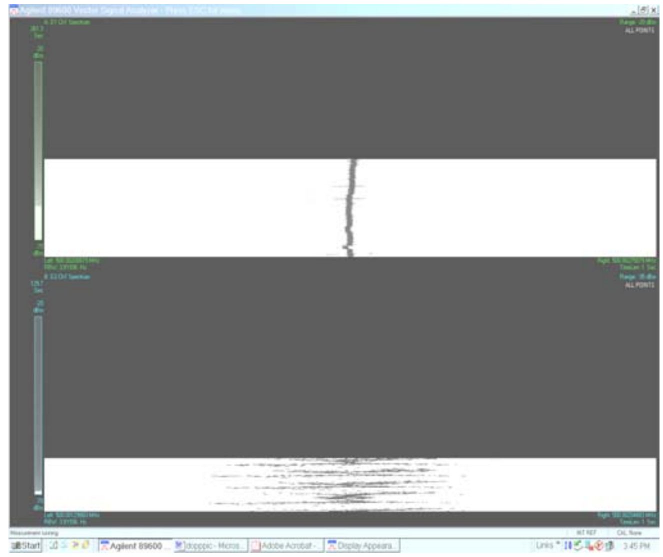

Figure 6. Location of the strongest spectral component

The upper part of the figure is the spectrogram that corresponds to the signal received in the indoor environment with stationary units. It is shown here for comparison. We have concentrated only on the strongest spectral component that is shown with the dark line. As it can be seen, the received signal has very stable frequency (center frequency is 500 MHz (downconverted from 5.2 GHz) and horizontal span is 750 Hz). The lower spectrogram corresponds to the signal recorded outside in the same environment and under the same conditions as for the multipath measurements. This time, due to the Doppler effects, the position of the strongest spectral component varied in time. The horizontal span shown in the lower spectrogram was also 750 Hz, thus the variation in the location of the strongest spectral component was approximately $2f_d = 300$ Hz.

To simulate and analyze the effects of this offset on the quality of the reception is a difficult task, mainly due the difficulties in reproducing the exact way of measuring and compensating the Doppler effects as implemented by the wireless cards. In addition, it is possible that the channels errors at the receiver could prevent the PLL to determine the correct phase shift, resulting in poor CFO estimation.

In the discussion that follows we will assume that the estimated CFO is, as per the standard requirements, taken care of by the wireless cards, and analyze the effects of the errors in the channel estimates alone on the quality of the transmission.

3.4 Study of the effectiveness of the channel equalization approach used in the 802.11a standard based on the above measured channels

Simulations were carried out to estimate the bit-error rate variation for the different modulation schemes used for the OFDM transmission. The effect of the channel estimated for a block of data corresponding to 500 microseconds when used with the following block of data where the channel has changed is seen to cause large orders of BER variations as compared to if perfect/adaptive equalization was employed. Figures 7-9 show the effects of varying channels on both unencoded and encoded OFDM symbols for three different modulation schemes used for the transmission. The encoding was performed using the same convolutional encoder as recommended by the 802.11a standard (see [9]), with the coding rates $R=1/2$ for *4-QAM* and *16-QAM* constellations, and $R=2/3$ for *64-QAM* constellation. At the receiver the convolutionally encoded data were decoded using the Viterbi algorithm with the decoding depth $d=10$ (our experiments showed that increasing this depth yields only negligible improvement).

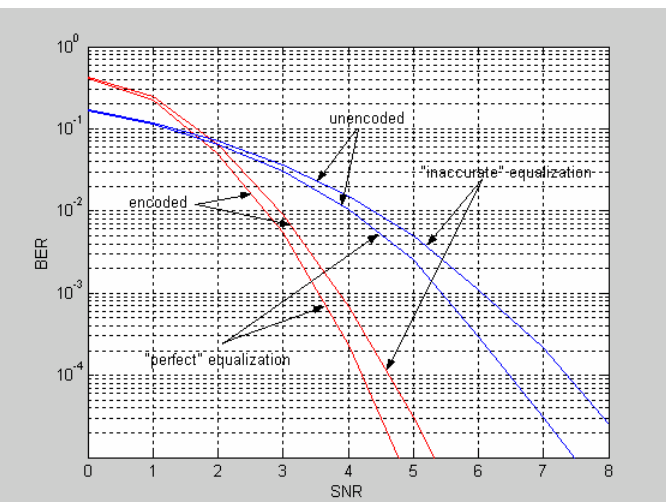

Figure 7. BER for *4-QAM* constellation

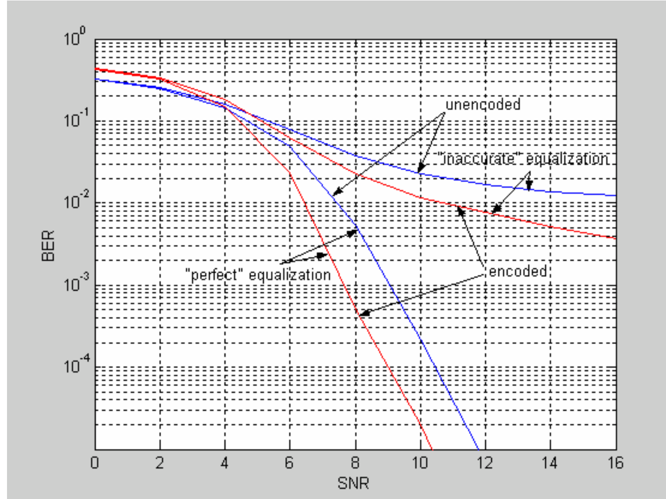

Figure 8. BER for *16-QAM* constellation

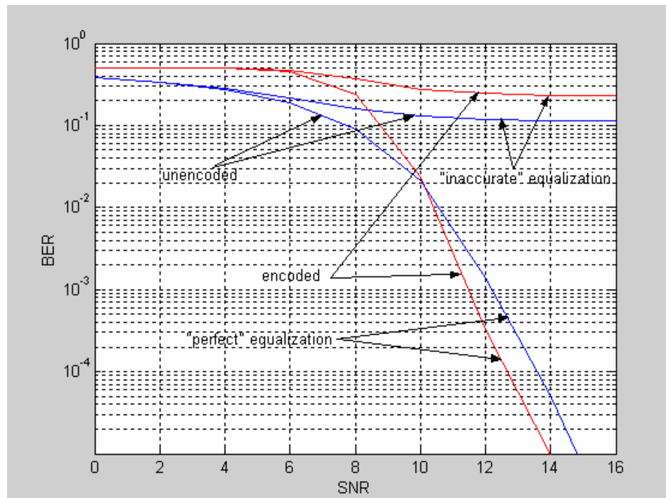

Figure 9. BER for *64-QAM* constellation

Figures show the variation of BER with signal to noise ratio (SNR). It can be seen that the inaccurate channel equalization at the receiver, which is due to the time varying nature of the multipath characteristics, significantly damages the quality of the connection, especially if multilevel modulation schemes (such as *16-QAM* and *64-QAM*) are used.

4. CONCLUSIONS

From the obtained experimental and simulation results, one can see that the outdoor multipath characteristics at 5.2 GHz with moving units cannot be considered constant over the one OFDM frame and, consequently, updating the channel estimates at the beginning of each frame, as currently recommended by the IEEE 802.11a standard, is not enough to accurately compensate multipath effects.

Two possible approaches can be implemented to cope with the problem of inadequate channel compensation in 802.11a.

The first approach calls for more advanced channel estimation/equalization technique as compared to what is currently implemented in the commercially available 802.11a wireless cards. Several works have been proposed along these lines, [10, 11, 12, 13] which are bandwidth efficient and robust to fast channel variations.

The second approach involves modifications at the upper layers of the OSI model. In particular, the MAC layer could consider channel conditions when determining the frame size. As currently supported, the DATA segment in the OFDM frame carries exactly one packet formed by the upper layers. The only mechanism for coping with the bad transmission environment at the physical layer is to reduce the data transmission rate. However, reducing the transmission rate also increases the OFDM packet size and, consequently, further slows down the rate at which the channel is estimated. Having the MAC layer be able to operate in *a channel aware mode* would allow the reduction of the OFDM DATA segment size when the channel is bad, so that the channels can be estimated more frequently.

5. REFERENCES

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