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Throughput and PER estimates harnessing link-layer measurements for indoor 802.11n WLAN

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The research work reported in this paper investigates if a Markov chain can model the throughput and packet error rate (PER) performance of off-the-shelf IEEE 802.11n wireless LAN network interface cards (NICs). We draw together uplink -downlink information from the NIC with a Markov chain to examine the performance of 802.11n within an indoor environment. Site measurements and point-estimates are taken and compared with the model predictions. Errors of less than 4% were recorded for the Markov model estimates while point-estimates recorded average errors of 9% both compared to site-measured throughput.

1. Introduction

Increasing demands for multimedia services and high-speed wireless communications have led to great interest in the 802.11n variant of the popular 802.11 WLAN standard. Going by the draft revisions itself, the 802.11n drafts have so far seen five revisions for year 2009 [1]. This hive of activity is expected to be further intensified fuelled by the maturing of the standard itself as more 802.11n-enabled NICs appear in the market.

The 802.11n standard offers ten-fold increase in physical data rates plus increased reliability over existing 802.11a/g networks. Previous research has noted that the high physical data rates promised by the 802.11n not necessarily translate to the throughput attained by an application such as a video streaming session or a voice call [2–4]. The throughput attained by an application fluctuates due to the changes in physical data rate in response to signal strength (SS) variations. Fluctuating SS values, sometimes as high as 10 dBm, force switchovers between data rates several times within a short time-span. This is further complicated by the numerous data rates made available in 802.11n. Under such dynamic conditions, predicting throughput on the basis of up-to-date link layer measurements would provide better accuracy.

Another unexplored dimension in the literature is the effect of SS asymmetry on throughput and PER estimation. In typical 802.11 WLANs, access points (APs) have a significantly higher transmit power compared to stations (STAs). It is common practice to set the transmit power level in the range 20–23 dBm. This serves to maximize AP coverage, which minimizes the number and overall deployment cost through reducing the associated financial outlay for AP's. Wireless STAs, though, tend to conserve power by stabilizing the transmit power thus contributing to asymmetric SS profiles between uplink and downlink. Despite many papers on physical and theoretical aspects of 802.11n link characteristics [5–7], there have been very little studies on how asymmetry information may be exploited for estimating throughput and error-rate.

Recognizing the aforementioned issues, this paper presents a model harnessing link-layer measurements for estimating throughput and PER. The research reported in this paper is unique in the following aspects:

- A hybrid approach is adopted by incorporating link-layer measurements into an analytical (Markov) model for improved throughput and PER prediction.
- The model takes into consideration both uplink and downlink SS changes to ascertain transitions between different data rates dictated by the modulation and coding scheme (MCS).
- There is a very limited set of indoor throughput and PER measurements on 802.11n. Reported site measurements in this paper expand existing results on indoor 802.11n throughput and PER.

The rest of the paper is organized as follows. Section 2 describes the role of the MCS and the channel model in estimating the throughput and PER. Our proposed system model for capturing throughput and PER performance is detailed in Section 3 together with the simplifying

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assumptions leading to their derivations. The site measurement configuration is explained in Section 4 followed by experimental validation of the proposed Markov model in Section 5. The final section reviews the contributions of the paper and suggests directions for further improvement.

2. Indoor wireless environment and 802.11n WLAN

The MCS and the operating environment are the primary factors that affect the throughput and PER in 802.11n WLAN. An accurate model for throughput and PER must consider the MCS selection, indoor channel characteristics and the interactive nature between these two factors. We will first examine the concept of MCS in relation to receiver sensitivity, followed with explanation on suitable channel models for indoor WLANs.

2.1. Modulation and coding scheme (MCS)

The MCS determines how data is sent over the air. 802.11n APs and STAs negotiate capabilities such as the number of spatial streams (N_{ss}) and channel width (CW) and they must agree upon the type of radio frequency (RF) modulation, coding rate, and guard interval (GI) to be used. The combination of all these factors determines the actual physical data rate, ranging from a minimum 6.5 Mbps to a maximum 600 Mbps (achieved by leveraging all possible high throughput options).

A simple integer assigned to every permutation of modulation, coding rate, GI, CW, and N_{ss} defines the MCS number (MCS#) in the 802.11n standard. It is a precise and efficient way to communicate the 77 possible permutations of the factors that determine the physical data rate [1]. However, not all MCS#s are supported by WLAN NIC manufacturers. Some broadly supported 802.11n MCS values are selected and numbered sequentially in Table 1. Note that the MCS# entries in Table 1 do not correspond directly to the MCS# in the standard specification [1].

To relate the MCS#, SNR and bit-error rate (BER), a BER versus signal-to-noise ratio (SNR) curve such as the one shown in Fig. 1 is most suitable and widely understood. As an example, the contours delineating the MCS# and the corresponding BER–SNR range shown in Fig. 1 is based on the closed form expressions derived in [8].

The wireless NIC uses the SNR levels to select an MCS# among the available transmission rates. Both SNR and SS are used interchangeably and are related by:

$$\mathrm{SNR(dB)} = \mathrm{SS(dBm)} - \left\{N_{\mathrm{floor}}(\mathrm{dBm}) + N_{\mathrm{fig}}(\mathrm{dBm})\right\} \quad (1)$$

where the noise floor (N_{floor}) typically ranges from −93 dBm to −96 dBm for the 40 MHz channel width, and N_{fig} (measured in dBm) is the signal impairment due to losses in the RF signal chain. Conforming to the behavior of the standard 802.11n NIC, the basic rate selection mechanism outlined in Section 9.6 of the 802.11n standard [1] is assumed throughout this paper.

Table 1
Modulation and coding scheme for data transmission in IEEE 802.11n (CW = 40 MHZ, N_{SS} = 2).

MCS#	Modulation	N_{ss}	PHY rate (Mb/s)	GI
0	BPSK	2	27	800ns
1	QPSK	2	54	800ns
2	16-QAM(3/4)	2	162.0	800ns
3	64-QAM(5/6)	2	270.0	800ns

2.2. Path loss and Rician fading environment

In addition to the range of supported MCS, the throughput also depends on the local channel conditions. Wireless communication channels experience significant losses through the environment mostly due to free space losses and fading. These losses alter the SS and SNR, which in turn elicits a change in MCS#. We start this section by examining two types of losses in wireless channels: path loss and small-scale fading. Finally, we discuss fading rates and its effect on PER.

The most widely used path loss model for 802.11n is the breakpoint model [9]. For different scenarios described in [9], different break-point distance (d_{BP}) were chosen to differentiate scenarios such as indoor, outdoor and path clearance. The path loss $L(d)$in dB is defined as,

$$L(d) = \begin{cases} 20\log_{10}(d) + 20\log_{10}\left(f_{op}\right) - 144.75 & \text{if} \quad d \le d_{BP} \\ 20\log_{10}(d_{BP}) + 20\log_{10}\left(f_{op}\right) - 144.75 + \left(35\log_{10}\dfrac{d}{d_{BP}}\right) & \text{if} \quad d > d_{BP} \end{cases} \quad (2)$$

where f_{op} is the operating frequency of 5.2 GHz (the one in which the IEEE 802.11n operates) and d is the distance separating the transmitter and receiver. However, the path loss model cannot account for the shorter and steep changes in SS, and thus relies on a small-scale model.

The Rician distribution is widely used to model small-scale SS variation in the presence of a strong dominant line of sight (LOS) path. Rician fading models have been successfully applied in numerous indoor WLAN studies [10–12]. Denote by f_p the fading envelope of a signal p, thus,

$$f_p\left(\mu, \sigma^2\right) = \frac{p}{\sigma^2} e^{\frac{-\mu^2 + p^2}{2\cdot\sigma^2}} \cdot I_0(k \cdot p)\ ;\ k = \frac{\mu}{\sigma^2} \quad (3)$$

where μ is the first moment, σ^2 represents the variance of the random components and $I_0(\cdot)$ is the modified Bessel function of the first kind. Usually, the factor k is used to identify the Rician distribution function for a specific fading environment. Values of k of approximately 6 dB is typical in modeling indoor radio channel amplitude fluctuations [13,14].

Besides the SS attenuation, another aspect of fading is slow or fast varying fades. The rate of amplitude change with respect to the symbol duration defines what is called the fading rate. If we consider a typical human movement within indoor environment with maximum velocity (ν) of 1.5 m/s and f_{op} of 5.2 GHz, the maximum Doppler frequency is calculated as,

$$fd_{max} = \frac{f_{op} \cdot \nu}{c} = \frac{\left(5.2 \times 10^9\right) \times 1.5\mathrm{m/s}}{3 \times 10^8} = 16\mathrm{Hz} \quad (4)$$

while the coherence time T_c is related to $fd_{\max}$through,

$$T_c = \frac{9}{16\pi \times fd_{max}} = \frac{9}{16\pi \times 16} = 11.2 \times 10^{-3}\mathrm{s} \quad (5)$$

Comparing T_c with an 802.11n symbol whose duration spans 4μs [1], it is evident that T_c is much larger compared to the symbol duration. Thus, we may assume that the Rician fading is slow varying and affects the channel for durations spanning several symbols. The slow varying characteristics allow us to approximate PER expressions which would otherwise be intractable.