Measurement Based Outdoor Link Level Investigation on IEEE 802.11 channels

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Abstract—**The awareness of channel conditions is critical to routing and MAC protocols. But, it is challenging to assess channel conditions due to the highly dynamic nature of wireless links. As a succession to a study of IEEE 802.11 links in an indoor environment, this paper presents observations and analysis from extensive measurements on IEEE 802.11 channels in an *outdoor* environment. The experiments are designed to investigate the channel dynamics through metrics such as successful frame delivery rate, loss rate, and Signal-to-Noise Ratio on IEEE 802.11 networks. The objective of this work is to reveal the interaction between these metrics and their variations in time and space. The following observations were obtained. Frame delivery rate for fixed stations fluctuates over time in most scenarios. Statistics over large time intervals get bursty and do not provide valuable information about channel conditions. Generally, Signal-to-Noise Ratio (SNR) varies widely over time even for fixed stations. However, the SNR remains stable for micro time scales. As a consequence, the frame delivery does not strongly correlate with SNR. If sent at a favorable time, a set of frames is likely to be delivered successfully continuously.**

I. INTRODUCTION

One distinguished feature of wireless links is that their channel conditions are highly time-varying due to multi-path fading, shadowing, mobility and transmission interferences or collisions. This dynamic channel nature incurs difficulties to the design of network architectures and protocols. Fore example, recent developments in wireless network interface cards use techniques based on current channel quality to select the most appropriate data rate. This is called *data rate adaptation* [1]–[3]. The fundamental challenge of data rate adaptation is the accurate assessment of the current quality of the channel. Another example is routing in multi-hop wireless networks that is challenging due to the dynamic nature of wireless channel quality. The selection of an optimal routing path is difficult because it is hard to assess the goodness of a path consisting of time-varying wireless links. A variety of routing metrics [4]–[7] aware of link quality/conditions have been proposed for multi-hop wireless networks. Whatever is the metric on a hop, it varies over time with the channel quality. To appreciate the difficulty of the routing problem, consider commuting from home to office in the situation where streets may experience flash flooding and moving riots spark here and there throughout the city.

Therefore, assessing channel quality is paramount to wireless networking problems in architectures and protocols. There are a variety of parameters to considered in assessment: Signal to Noise Ratio (SNR), frame loss rate, length of a streak of successful frame transmissions, and the number of consecutive frame losses. It is of interest to study how well these parameters characterize or reflect the quality of a channel.

This work investigates the transient behavior by analyzing a large amount of data collected with extensive measurements on a IEEE 802.11g channel at 2.4 GHz in an outdoor environments as an extension work to the indoor analysis [**?**]. Although IEEE 802.11g is not the latest standard version, the wireless frequency band it uses is still kept in IEEE 802.11n the latest version standard. Therefore, the channel dynamics reported in this paper are still valuable and valid. The observations of this work is important to the design of routing metrics, data rate adaptation as well other networking techniques used on IEEE 802.11 networks.

The rest of this paper is organized as following. Section II reviews related work in literature followed by Section III describing the experimental environment, test bed and methodology. The observations from collected measurements are presented in Section IV. Finally, Section V concludes this paper.

II. RELATED WORK

Some outdoor measurement based studies on IEEE 802.11 channels have been conducted. The following briefly reviews this literature and highlights our contribution in this paper.

Bianchi *et al.* [8] conducted measurement experiments outdoor on a campus to identify the network performance between IEEE 802.11b and IEEE 802.11g channels. They observed that these two standards behave noticeably differently even under the same environment because of the difference in the physical layer coding schemes. Long-range wireless link measurements conducted by Gupta [9] in an outdoor IEEE 802.11b WLAN shows that with possible interference around, SNR of a link is not closely related to modulation schemes that the link can support as in wireless communication principle. However, Chebrolu *et al*. [10] found that the loss rate changes as a function of received signal strength, but their experiments were conducted in a wild space with each link operates on non-overlapping IEEE 802.11 channels. As a result, interference or collision is almost avoided. Similar observations are obtained by Gokhale, *et al*. [11]. Another long-distance link measurement work is conducted by El-Sayed, Zeadally and Boulmalf [12]. Kotz *et al*. [13] attempt to verify the hypothesis about radio propagation that many network simulation models are based upon. The commonly accepted assumptions include: the wireless signal is propagated in the circular shape; all signals have equal transmission range; symmetric links; and signal strength is a simple function of communication distance. They conducted a set of IEEE 802.11b measurements in both indoor and outdoor environments. They observed that these assumptions do not adequately match real world channel behaviors. Cheng *et al*. [14] conducted experiments to study the impact of the antenna orientation to an unmanned aerial vehicle (UAV) with extensive outdoor measurements. They installed the UAV and the ground stations of IEEE 802.11a adapters. They concluded that the best throughput performance can be achieved when both antennas of the UAV and the ground station should be omnidirectional and placed horizontally with their null pointing to a direction perpendicular to the flying path. Finally, Giustiniano, *et al*. [15] revealed an engineering issue significantly impacting measurement experiments that the hardware/software diversity at a transmitter may induce weird behavior of wireless signal at a receiver in practice.

Our work is different from the above measurements in that: 1) this work is dedicated to the investigation of channel *dynamics* fundamentally impacting on IEEE 802.11 communications; the "mystery" revealed could benefit various fields in IEEE 802.11 network architectures and protocols, such as routing, MAC protocols, and rate adaptation; 2) the measurements are based on the IEEE 802.11g that is still widely being used in commercial products and still valuable to IEEE 802.11n since most of the modulation and coding schemes are kept in IEEE 802.11n, although most of the above measurements conducted on IEEE 802.11b that is obsolete. One weakness of this work is the absence of measurements with collisions and mobility. This will be covered in our future work.

III. EXPERIMENTAL METHODOLOGY

To obtain the trace in expected format to facilitate the analysis, we designed a measurement platform with a customized packet filter. The measurements were collected in a wild open space on a campus without any other IEEE 802.11 signal around. The experimental methodology and platform are presented as follows.

A. Environment and Platform

Figure 1 coarsely shows the outdoor environment where the experiments were conducted. The outdoor environment, shown in the figure, is free from obstacles like buildings or trees. In the figure, the triangle represents the location of the access point and the sniffer collecting the trace was placed side by side to the access point to obtain identical signals and information. The position of the endpoint laptop receiver is not important because this laptop is connected by wire to the access point and its wireless adapter is off. The circle spots represent the different locations where the sender laptop was placed. Locations are chosen such that the wireless nodes achieve specific maximal data rates. The data rates used are 6 Mpbs, 24 Mbps, and 54 Mbps. Four locations were selected: *L-1* and *L-2* for 54 Mbps; *L-3* for 24 Mbps and*L-4* for 6 Mbps. The wireless channel is set to channel 11 after a preliminary survey of wireless network traffic showed that no other surrounding wireless networks use that channel and hence channel contention would not be an issue.

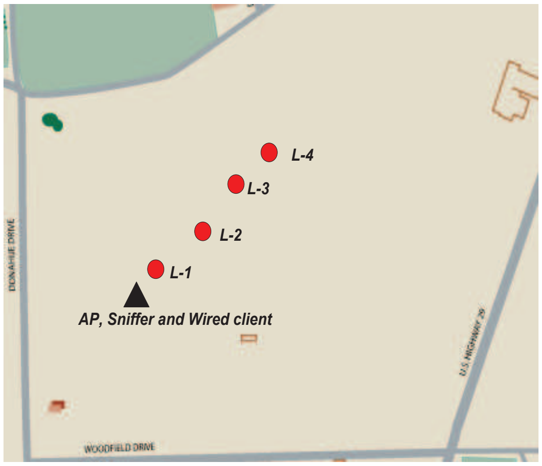

Fig. 1. Outdoor Measurement Environment

The hardware platform used in measurement is shown in Figure 2 and consists of three laptops and one access point. Each laptop was installed with an IEEE 802.11 adapter based on the Atheros chipset AR5212 supporting IEEE 802.11g. The adapters with this chipset are well supported by open source drivers from Madwifi-project [16] on Linux. The wired client is a system76 darter ultra notebook computer running Ubuntu 8.04 with a dual-core 2.2 GHz Intel processor, 2GB RAM and a Realtek RTL8111 Gigabit Ethernet adapter. The wireless client and the network sniffer are IBM T60 Thinkpad laptops running Fedora Core 9 with dual-core 1.66 GHz Intel processors, 2GB RAM. All three laptops ran Linux kernel 2.6.25. The access point is a Linksys WRT54GS [17]. During the measurements, the access point is static and placed at a height of two meters. One laptop, serving as a sniffer, is placed tightly close to the wireless access point to ensure (as much as possible) that its received wireless signal is similar to the signal received by the sniffer. The sniffer is passive and works in monitor mode in which the node does not associate with any access point and does not transmit any frame. The end-point traffic receiver is a laptop *wired* to the access point and its wireless adapter is turned off. The third laptop serves as the end-point traffic sender. All nodes were statically placed during experiments.

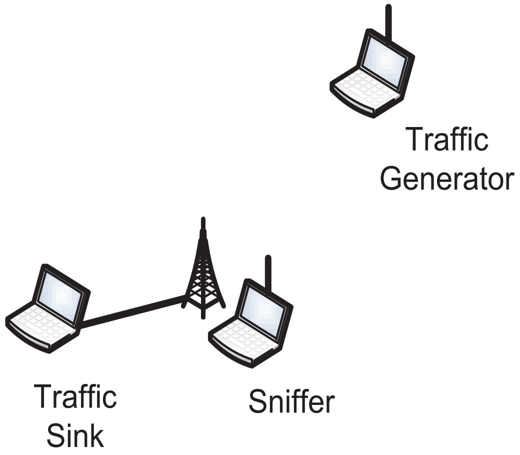

Fig. 2. The Measurement Hardware Platform

The driver software is slightly modified to allow the wireless adapter to report information we are interested in: data rate, channel used, and the received signal strength indication (RSSI). In MadWiFi, the reported RSSI for each frame actually refers to the Signal-to-Noise Ratio (SNR). The sniffer laptop records and reports the data rate, the channel number, the *SNR*, the *timestamp*, the *More Frag* flag, the *Retry* flag, the *sequence number*, the *fragment number*, and the *send/receive* flag of each received frame.The traffic consists of 1500-byte UDP packets. IEEE 802.11 RTS/CTS control frames are turned off. Each measurement took 60 seconds and was repeated six times for each scenario.

B. Customization of Measurement Tools

Open source tools *tcpdump* and *Iperf* are employed in the experiments: tcpdump [18] is slightly modified and customized to gather the wireless traffic trace and Iperf [19] is used to generate or receive UDP traffic.

1) tcpdump: tcpdump [18], developed at the Lawrence Berkeley National Laboratory, is an open source package widely used to capture frames. *tcpdump* uses the *libpcap* [20] library for capturing the frames. To customize *tcpdump* to our needs, we modified *tcpdump* to output only the information of interest to us. Particularly, we recorded the data rate, the channel used, the Signal-to-Noise Ratio (SNR), the timestamp, and the following flags: *More Frag*, *Retry*, *Sequence Control*, and *Send/Receive*. The *More Frag* flag indicates the latest fragment of a fragmented frame. We used it to ensure that fragmentation did not occur. The *Retry* flag indicates a retransmission. The *Send/Receive* indicates whether the frame is sent or received. We did not change the capturing functionality of *tcpdump*, but only the output format and content. *tcpdump* was configured to capture only data frames and ignore control/management for two reasons: 1) data frames are strictly sequential so losses are easy to identify, and 2) less storage space is required for the trace. Moreover, a MAC address filter was exploited to collect only frames transmitted from the MAC address of the wireless sender so that other traffic such as management frames are ignored: only data and acknowledge frames were recorded. All log files were generated in a customized plain text format.

2) Iperf: Iperf [19] is used as the traffic generator and sink of UDP packets in measurements. The wired endpoint receiver ran the Iperf sink to receive the UDP traffic and Iperf on the wireless sender generated the UDP traffic. The traffic lasted 60 seconds and that the sending rate is always 1/3 of the maximal achievable wireless data rate to avoid frame loss due to the overflow in transmission buffer. For example, if the highest achievable rate is 54 Mbps on the wireless link, Iperf generates 18 Mbps traffic.

IV. ANALYSIS AND OBSERVATIONS

With extensive measurements, we present the analysis on the collected trace and obtained observations in this section. Due to the problem that only a few frames are successfully received in the measurement at location 4, we have to omit the analysis for location 4 in the following

A. Spatial and Temporal Variations of Delivery Ratio

The first investigated case is the variation of the frame delivery ratio over time. The frame delivery ratio is defined as the ratio of the number of successfully delivered frames over the number of transmitted frames at each interval of 100 ms. The number of transmitted frames is determined from the "sequence control field" on the IEEE 802.11 frame header. The variation of delivery ratio is shown on Figure 3. The delivery ratio shown on Y-axis is averaged over six runs at each data rate. In the analysis, the very beginning and the end of the trace was trimmed to remove large variations due to startup and completion of an experiment. As we could observe from Figure 3, the delivery ratio for the basic rate (6 Mbps) or the highest rate (54 Mbps) stays relatively stable at locations where the wireless signal is strong, such as location 1 and 2. But, it largely varies at 24 Mbps. This might be because the modulation corresponding to 24 Mbps is the delivery "vulnerability" boundary at those locations: either lower rates leads to very strong delivery or higher rates incurs very weak delivery, but very stable. Another observation that follows wireless communication theory is that the delivery ratio decreases as the data rate increases at a certain location. It should be noted that the lower delivery ratio at higher bit rates does not lead to a lower throughput defined as the product of data rate and delivery ratio: the overall throughput at rate 54 Mbps is the best even though it has the lowest delivery ratio. Furthermore, delivery ratios get more irregular as transmission distance increases such as the scenarios for location 3. These observations lead to a conclusion that the delivery ratio *alone* can not effectively reveal channel conditions.

B. Delivery Ratio and Signal-to-Noise Ratio

We next attempt to identify the relation between delivery ratio and signal-to-noise ratio (SNR). The trace used in this investigation is from the measurement at 24 Mbps at location 1. The ratios are computed at intervals of 100 ms. Figure 4

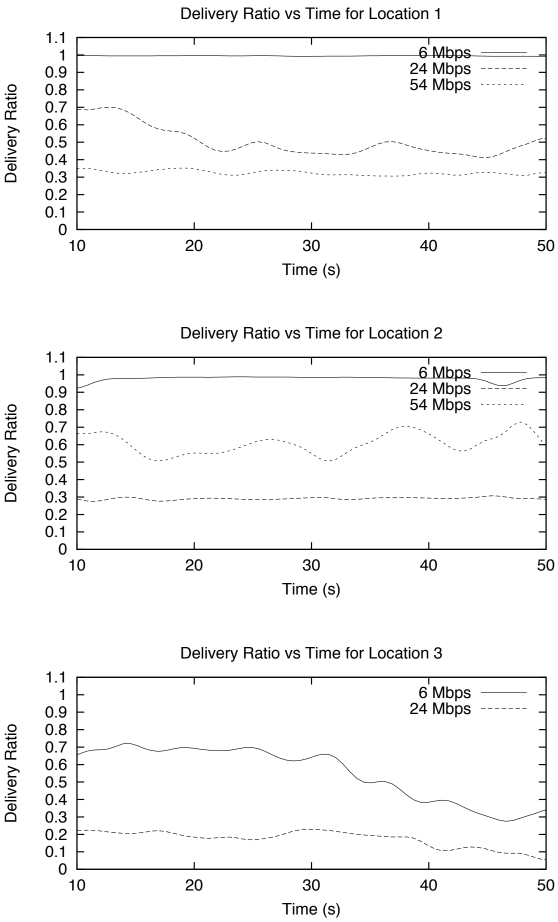

Fig. 3. Spatial and Temporal Variations of Delivery Ratios

depicts this investigation with delivery ratio represented by Y-axis and SNR by X-axis. From the figure, we observe that delivery ratio is not strongly correlated to SNR because 1) the delivery ratio at a certain SNR varies widely (vertically) and 2) different SNRs can lead to identical delivery ratio (horizontally). Therefore, we reach a conclusion that SNR *alone* is not reliable in predicting frame transmission consequence.

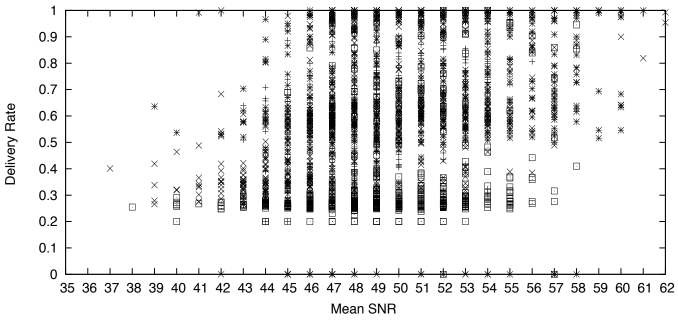

Fig. 4. Relation between Delivery Ratios and SNR

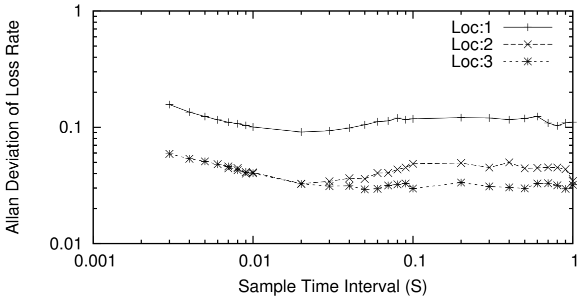

Fig. 5. Allan Deviations of Loss Rate

C. Allan Deviation of Loss Rate

In above investigations we calculated the delivery ratio and the average SNR at intervals of 100 ms. It is interesting and valuable to investigate whether the interval size would impact observations concluded. One approach to establish this analysis is to plot the Allan deviation [21] for concerned parameters. The Allan deviation could reveal the bursty nature of loss rate. Actually, delivery ratio can be easily translated to loss rate that we also measured. Therefore, we compute the Allan deviation of loss rate in this section. Allan deviation differs from standard deviation in that the former uses the difference between two consecutive samples while the latter utilizes the difference between a sample and the mean of all samples. The Allan deviation of a sequence of samples of l_i is calculated as:

$$AD = \sqrt{\frac{1}{2n}\sum_{i=2}^{n}(x_i - x_{i-1})^2} \tag{1}$$

In this study, the samples are the loss rates in consecutive intervals. We compute the Allan deviation of loss rate over different interval values on the same trace. According to the property of Allan deviation, when the time interval is close to the characteristic burst size of the loss rate, its Allan deviation is large. For very small or large intervals, the Allan deviation is small. Therefore, the Allan deviation is useful in identifying the time interval for which the loss rate varies most from sample to sample. Figure 5 plots the Allan deviation of the loss rate in our measurements. Each line corresponds to one location. The Allan deviation in the Y-axis is computed upon measurements at 24 Mbps. The X-axis shows the sizes of different intervals over which the loss rate is averaged. From Figure 5, the Allan deviation decreases when the computing intervals are less than 20 ms. When the sampling interval is greater than 100 ms, the deviation becomes too large. Therefore, statistics computed over internals greater than 100 ms is less informative or accurate in concluding observations.

D. Consecutive transmissions

At last, we strive to investigate the sustainability of consecutive transmissions at a given data rate. From the trace measured at 6 Mbps at location 1 or 2, we computed the cumulative

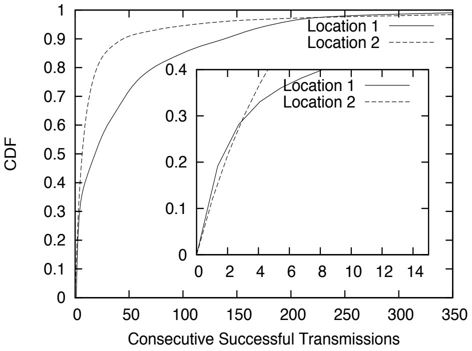

Fig. 6. CDF of Consecutive Transmissions

distribution function (CDF) of the number of consecutive successful transmissions between two transmission failures, which is plotted in Figure 6 with the Y-axis representing the CDF and the X-axis referring to the number of consecutive successful transmissions. The inner figure magnifies the fraction of streaks of the left bottom of the large figure. From these figures, we observe that it is very possible (greater than 60% in probability) that the channel can support transmission of more than 4 frames consecutively in the outdoor open space. It should be noted that these results are obtained in stable environments without interference or mobility.

V. CONCLUSION

This work presents observations from the analysis of extensive measurement trace on IEEE 802.11 channels in an outdoor environment with customized measurement tools and platform. In particular, delivery ratio alone can not reliably predict channel conditions and SNR can not reveal frame delivery consequence. The delivery ratio and SNR are not strongly correlated. Statistics obtained in intervals of longer than 100 ms are not informative. Mostly, multiple frames can be successfully transmitted consecutively. These observations are valuable in the design of wireless networking architectures and protocols.

VI. ACKNOWLEDGEMENT

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