# Throughput Analysis and Measurement on Real Terminal in Multi-rate Wireless LAN

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## ABSTRACT

IEEE802.11 wireless LAN system has several transmission rates (multi-rate).The appropriate rate should be chosen to obtain maximum Quality of Service (QoS) such as throughput. The throughput is determined by two factors; one is retransmission delay and the other is "carrier busy" waiting time. A previous research reveals that the appropriate rate should be changed in stepwise by the discrete distances between an access point (AP) and terminals with considering only the retransmission. Although it could be useful when no interferences cause carrier busy, the interferences from noise and other systems such as other wireless LANs must be considered in real situations. Therefore, this paper investigates how much the interferences affect the throughput by using real access points and terminals as well as the retransmission. Experimental results in various situations such as in indoors, in outdoors and in radio-shielded boxes are compared to show quantity evaluation of "carrier busy" waiting time. The results indicate that quite large portion of throughput degradation in outdoors is caused by "carrier busy" waiting time. For proposing and evaluating QoS control in wireless LAN, for example, AP assignment control, such large interferences should be taken account of to achieve more precise effects.

## Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

## General Terms

Experimentation

## Keywords

Multi-rate, Wireless LAN, Throughput analysis, Busy Carrier



## 1. INTRODUCTION

Wireless LAN is a rapidly spreading technology. The spread of mobile terminals on wireless LAN increases outdoor wireless LAN use; public wireless LAN services are thus widely developed. For such situations, Access Points (APs) and terminals adopt multiple transmission rates for efficient transmission. Each terminal can communicate using proper transmission rates to achieve appropriate throughput: high transmission rates for terminals in fine radio environments and low transmission rates in poor environments.

The transmission rate is generally lower with a longer distance between an AP and a terminal because the radio wave will be attenuated due to interruption of other radio waves. Computer simulations have already investigated the relationship between throughput and the distance from a terminal to an AP.

Using these results, several researchers have investigated optimizing multi-rate control for the wireless LAN. For example, there are AP selection problems [7, 8, 9, 15, 6, 13, 12] that decide which AP a new terminal should access when it joins a network. Selecting an AP depending on the proper transmission rate is important. Most multi-rate AP selection problems use theoretical or calculation values in computer simulations. For example, Miki et al. [12] mentions that fixed throughputs are given if MAC frame retransmissions do not occur, and provides the best rate model as a stepwise model for the distance. Computer simulations, however, could not consider interference such as other wireless LANs or noises. In real, there must have such interference. In CSMA/CA, the interference causes "carrier busy" waiting time. As effects of interference become larger according to the distance, the throughput decreases more due to increase of the "carrier busy" waiting time. Therefore, throughput is supposed not to decrease stepwise but to decrease monotonically and continuously even if there would be no retransmissions. Note that it is hard to directly measure the interference so that it is necessary to indirectly measure and calculate "carrier busy" waiting time.

In this paper, we investigate throughput behavior by using real terminals and APs. By analyzing the measured data, we show quantitative effects of interferences on throughput degradation. The throughputs were measured in various situations such as in indoors, in outdoors and in radio-shielded box [5], which cuts all radio signals out of the box. Then, in the box, we tried to measure retransmission delay by using artificial retransmissions without the interference. The measured data was compared to show quantity evaluation

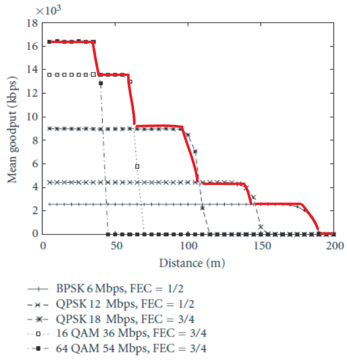


**Figure 1: Throughput in multi-rate by simulation**

of "carrier busy" waiting time. We believe that such interference should be taken account of in order to develop QoS control in wireless LAN, for example, AP assignment control.

The remainder of this paper is organized as follows: Section II describes the multi-rate model and problems in related works; Section III explains the dominant factor on throughput degradation; Section IV describes preliminary experiments; Section V discuses throughput evaluation in real machines; Section VI explains quantification of busy carriers and Section V states the concluding remarks.

# 2. RELATED WORKS AND PROBLEMS

A wireless LAN defines multiple transmission rates to keep the bit and/or frame error rates to proper values, and appropriate transmission rates are selected depending on the bit error state. Each vendor has defined this mechanism because it is not standardized. Kamerman et al. [11] shows one example as a standard for this mechanism. Their multi-rate control works as follows: a lower transmission rate is selected when a higher transmission rate cannot be kept due to a poor radio environment, and a higher transmission rate is selected in a fine radio environment. With such a mechanism, the multi-rate control can accommodate multiple terminals in different conditions. 11, 5.5, 2 and 1 Mbps are defined for IEEE802.11b and 54, 48, 36, 24, 18, 12, 9 and 6 Mbps are defined for IEEE802.11a/g as standard values in multi-rate control.

Miki et al. [12] shows the Performance Anomaly circumstances and causes in IEEE802.11a and how to select a proper transmission rate using the result. In addition, Miyata et al. [13] show which a new node an AP should connect to when it joins a network. These studies adopt the transmission rate determinant, as in [12], which is changed stepwise relative to the distance between an AP and a node.

A relation between throughput and distance in a different multi-rate set is also evaluated by simulation in [10] as shown in Fig.1. The best rate for the distance is the envelope as shown in red line in Fig.1.

Though these studies account for radio attenuation or fazing, they do not consider interference by other wireless LANs. Therefore, throughput must decrease as the distance from an AP increases, whereas throughput is fixed, as in [12], when a MAC frame retransmission does not occur. In real situations, however, throughput is supposed to decrease not in stepwise but to decrease monotonically and continuously

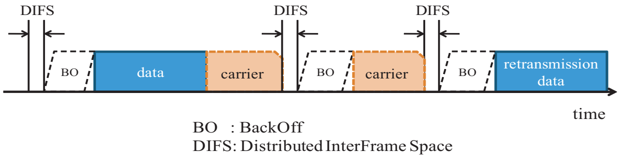


**Figure 2: Example behavior of CSMA/CA with carrier from other wireless LAN**

due to increasing packet retransmission times, caused by increasing bit error rates from radio interference and waiting times for carriers affected by other wireless LANs. Some measurement reports, for example, [2, 3] have shown such monotonically and continuously decreased throughput characteristics. However, these two factors of retransmission times and waiting times for carriers have not been identified in the reports. In addition, those two factors have not yet been investigated quantitatively. This paper clarifies the ratio of these two factors through experiments using real machines.

# 3. THE DOMINANT FACTOR ON THROUGHPUT DEGRADATION

Here, we discuss MAC factors that degrade throughput. Dominant throughput degradation factors include (1) retransmission and (2) busy carriers. Throughput degradation occurs if the inter-arrival time between two consecutive packets becomes large. These factors cause sending delays and result in throughput degradation.

Retransmission occurs when the MAC data frames fail, with the small probability that the MAC ACK frame fails. However, the ACK frame transmission rate is equal to or lower than the data frame because the length of the ACK frame is shorter than that of the data frame. Thus, ACK frames rarely fail when data frames are correctly received. Bit errors cause data frame failure; signal attenuation and noise rising, in turn, cause bit errors. Noise includes natural and artificial noises, including interference from other wireless LANs. Many wireless LAN simulations use only a signal attenuation model, such as the Rayleigh fading model; noise from other wireless LANs, however, cannot be ignored.

Busy carriers should attract more attention when considering a real situation. In CSMA/CA, a wait occurs when a carrier is detected and thus avoids collisions. When a sender understands an interference signal as a carrier, the sender must wait even if a receiver does not understand the signal as a carrier. Fig.2 illustrates such behavior and looks similar to well-known hidden terminal problems. Recognizing hidden terminal-like problems in real situations is important, as even the hidden terminals are in other wireless LANs.

# 4. PRELIMINARY EXPERIMENTS

## 4.1 Experimental settings

Here, we describe experimental settings and configurations, including experiment space, equipment, MAC technology, equipment configuration and terminal and AP location. Throughput from an IEEE802.11 wireless LAN depends on various factors, including places and obstacles. We investigated both indoor and outdoor cases in our experiments. Indoor factors are less effectively counted than outdoor factors. Many radio signals cause interference in the targeted outdoor wireless communication systems without obstacles

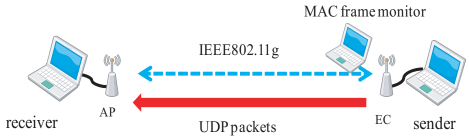


**Figure 3: Experimental terminal configuration**

such as walls, ceilings and doors. We therefore used the playground at our university. The ground measures approximately half of a soccer field and is surrounded by many residential and university buildings. As expected, many private APs were detected. Monitoring the APs' activities was difficult, but those APs were assumed to be active. The APs could thus be interference resources in our experiments. For example, at 5 m from our AP, the radio signal from our AP was almost the same as that from a private AP. Conversely, we obtained a nearly ideal field in the indoor athletic gymnasium in the university. The indoor field experiments did not suffer from any interference.

In these experiments, we used Planex MZK-MF300N[4] as our AP. The equipment enables users to manually set specific MAC frame transmission rates. We did not use automatic rate fallback (ARF) in the AP because ARF behavior has not been disclosed, and we could not know which transmission rates the AP uses. Few APs have such manual settings among those sold in consumer markets. Users can also control the radio emission power from 15 to 100 %. We should have similar evaluation results in the following sections if we use other APs. Terminals are laptop PCs with Windows XP. The wireless LAN terminal adapter is not a USB type but an Ethernet Converter (EC) type. EC is a kind of a MAC bridge that has Ethernet and wireless LAN interfaces. From the terminal to the EC, the Ethernet conveys packets encapsulated by the Ethernet frame. The packet is de-capsulated in the EC and sent to the AP through the IEEE802.11 protocol.

We measured throughput as follows. First, a terminal (receiver) connected to the AP was placed and fixed; second, a terminal (sender) connected to the EC was moved near the EC. We used Iperf and Windows XP to generate traffic and measured its throughput. Iperf sent UDP packets from the sender to the receiver. To monitor and capture the traffic, another PC was located on the side of the sender. This PC monitored all MAC frames [1] between the AP and the EC[1].

The terminal and the AP are located and moved as shown in Fig.3. We adopted IEEE802.11g and measured UDP throughput for each transmission rate. We referred the throughput results from [12], though it is based on IEE802.11a. The difference between IEEE802.11a and 802.11g is small and negligible in throughput characteristics.

The sending rate (200Mbps) was set large enough to saturate IEEE802.11g capacity, the measurement time was 40 seconds per trial, and the UDP packet length was 1470 Byte, the Iperf default. The throughput was calculated in 30 of 40 seconds, excluding the first and last five seconds to avoid counting unstable rate fluctuations. We adopted an average of 5 trials. For one trial, analyzing stable statistical results required 10,000 MAC frames or number of frames for 30 seconds. We used the following Iperf command:

The receiver: iperf -s -u

The sender: iperf -c (IP address of the receiver) -u -b 200M -t 40

## 4.2 Estimation for Contention Window values and retransmission time

Separating the measured inter-arrival time in retransmission and busy carrier times is difficult. Retransmission delays can be estimated if the Contention Window Minimum (CWmin) and Maximum (CWmax) are known. Contention Window (CW) defines back-off time. CW is a random integer in CWmin $\leq$ CW $\leq$ CWmax and is generated by the uniform distribution [0, CW]. CW increases exponentially with each retransmission.

For later throughput analysis, we estimated the times yielded by MAC frame retransmission and busy carriers. The measured inter-arrival time contains retransmission and busy carrier times, as shown in Fig.2. Calculating the exact time for MAC frame retransmission is difficult because the back-off time contains random variables. Formula (1) , however, enables us to calculate expectation time when retransmission occurs N times.

$$\begin{aligned} &\text{expectation time} \\ &= (\text{DIFS} + \text{data transimission time}) \times \text{N} \\ &+ (\text{sum of CW})/2 \times \text{slottime} \qquad (1) \end{aligned}$$

Since CW worked practically is not notified, the maximum retransmission is forced to occur artificially in a circumstance which contains little interference. CWmax can be determined using this result.

This experiment was executed in a building with various kinds of interference. AP, EC, MAC frame monitor and an antenna of MAC-frame Receiving-Opportunity Control (ROC) [14] board, a machine which makes MAC frames retransmissions artificially, are accommodated in a radio-shielded box, and we run ROC in it. As a result, we often observed 48 times retransmission, and the average time is 0.213 seconds. When CWmin = 15 and CWmax = 511, the expectation time required by 48 times retransmission is 0.242 seconds, thus CWmax in this case should be 511. Other parameters in IEEE802.11g are as follows: DIFS is 34 $\mu$sec, slottime is 20 $\mu$sec and CWmin is 15.

# 5. THROUGHPUT EVALUATION IN REAL TERMINALS

## 5.1 Throughput characteristics in real terminals

Fig.4 shows the experimental results and the relationship between distance and throughput. We measured the results outdoors using 100 % emission power; we also obtained similar but better results indoors.

In simulation models based on the Rayleigh fading model, throughput resembles a step function of the distance between a sender and receiver in all transmission rates; in real terminals, throughput does not have steps but continuously decreases over the distance because there is radio interference. The interference may affect MAC frame sendings through retransmission or busy carriers. Because the simulation model already considers retransmission, the interference differences between real terminals and simulations

[1]The monitor PC might fail to receive MAC frame ACKs that the receiver successfully receives, and vice versa. The failure happens because we cannot provide the same radio signals to both the receiver and the monitor. The probability was proven to be significantly small by analyzing captured MAC frames.

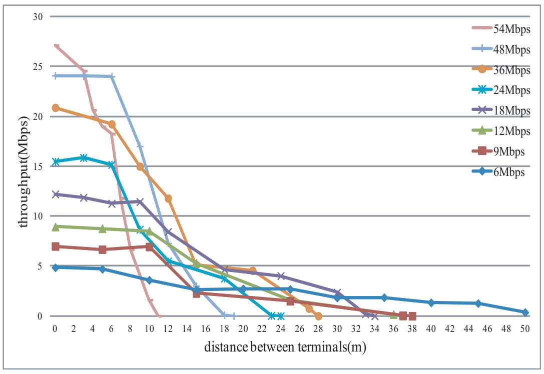


**Figure 4: Throughput for distance in multi-rates**

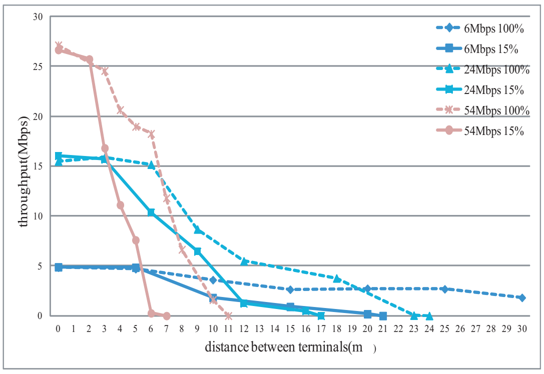


**Figure 5: Throughput with radio emission powers of 15 % and 100 %**

should come from busy carriers. The difference appears significant, implying that we should account for busy carriers in simulation models when we apply any performance evaluation considerations to a real situation. We analyze the reasons in Section 5.3.

## 5.2 Emission power and throughput characteristics

In this section, we state the relationship between the radio strength or emission power and throughput. We expect that a stronger radio signal yields larger throughput. Because strong radio signals may disturb other transmissions, weak radio signals are more desirable for mobile-type APs and terminals. Fig.5 shows the relationship between throughput and distance in 54, 24 and 6 Mbps, when the radio signal strength of AP, EC is 15 % and 100 %.

The figure shows that the distance shortens as the radio signal strength weakens at both 15 % and 100 %. Moreover, both curves in the same transmission rate are resemblances. Thus, we conclude that the throughput characteristics of any transmission rate are similar between different emission powers or radio signal strengths.

## 5.3 Analysis of throughput characteristics

### 5.3.1 *Factors affecting retransmission MAC frame content rate*

Here, we describe a relationship between the distance and MAC frame retransmission rate. MAC frame retransmission is a dominant factor in throughput degradation both in simulations and real terminals. Fig.6 explains a relationship

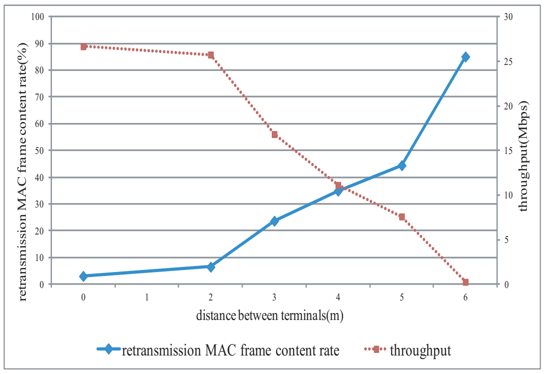


**Figure 6: Retransmission MAC frame content rate vs. throughput**

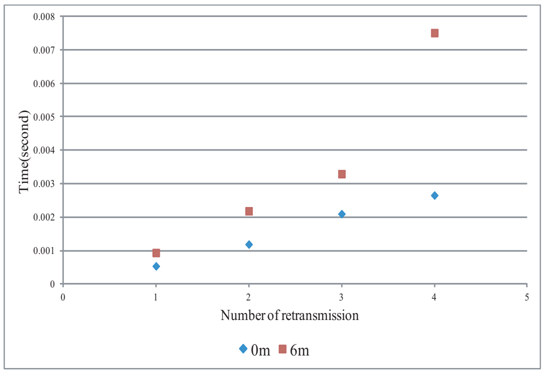


**Figure 7: Time of retransmission at 0m and 6m**

between the distance and MAC frame retransmission rate in real terminals. The curves show values measured at a 54 Mbps transmission rate at 15 % emission power in the outdoor experiment.

$$\text{retransmission MAC frame content rate} = \frac{\text{The number of MAC retransmission frames}}{\text{The number of MAC frames}} \times 100$$

### 5.3.2 *Factors affecting busy carrier*

Fig.7 shows the comparison of time required for retransmission at 0m and at 6m. The dots show values measured at a 54 Mbps transmission rate at 15 % emission power in the outdoor experiment. The time at 6m is much bigger that of 0m, this is because busy carrier exists.

# 6. QUANTIFICATION OF BUSY CARRIER

Here, we evaluate busy carrier quantitatively. The time of busy carrier is difficult to be measured in real terminals. Therefore, the time is calculated by subtraction.

And we quantitate carrier busy in three circumstances, the first one is in the ground which is considered to contain a lot of busy carriers (outdoor), the second one is in a gymnasium which is considered to contain less busy carrier, and the third one is that there is another wireless LAN in the same channel which continues transmission(background).

The result outdoors is shown in Fig.8 The horizontal axis represents number of retransmission[2] the solid line represents the expectation time, and the dots represent measured

[2]In this experiment, the maximum number of retransmissions was set at 48 in the equipment, and the settings could not be modified. Though the setting is unusual, compared

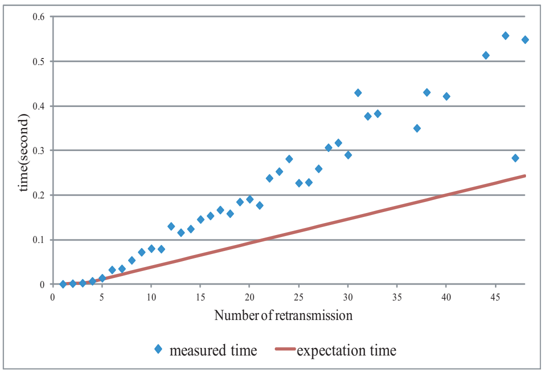


**Figure 8: Measured inter-arrival and expectation retransmission times**

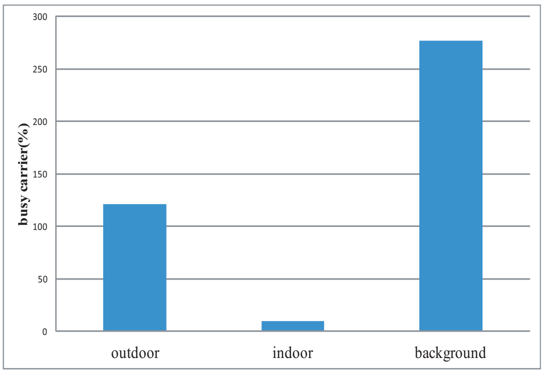


**Figure 9: busycarrier in some circumstances**

time. The difference between the solid line and dots is due to the busy carriers. The average difference between the expectation time and the measured time is 121%. Similarly, we experimented in other circumstances, indoors and in background. The averages are 10% in indoor and 277% in background. Fig.9 shows this result. Busy carrier can be quantitated in this way.

In simulation, throughput reduction affected by busy carrier is ignored. In real situation, however, interference must be a factor of throughput degradation, and therefore an experiment which quotes a result of simulation experiment without interference may mislead wrong result. Therefore, an effect of interference must be taken into consideration also in simulation model.

# 7. CONCLUSION

This paper investigated multi-rate throughput characteristics of IEEE802.11g wireless LANs using real terminals. Measured throughputs in every transmission rates, 54, 48, 36, 24, 18, 12, 9 and 6 Mbps, decreased when the distance between an access point and a terminal increased, as shown in many simulation models. However, the decrease observed in the real terminals differed from those of the simulations because the latter only considered radio signal attenuation models, such as the Rayleigh fading model; the real terminals suffered from busy carrier effects due to radio interferences from other systems and fading. Even in indoor there is 10% busy carrier, in outdoor which is suffered from other interference, there is 121% busy carrier. Busy carrier must be a factor of throughput degradation For that reason, simulation experiment has to consider the effect of interference.

with the IEEE802.11 MAC default of 7, we can easily monitor busy carriers.

# 8. ACKNOWLEDGMENTS

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