Performance of IEEE 802.11b Wireless Links: An Experimental Study

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Abstract— **This paper reports the experimental results of IEEE 802.11b wireless link performance in ad hoc mode. The throughput and packet loss rate are measured for User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) traffic in both indoor and outdoor environments. Various factors that affect the performance of the wireless link, such as the packet size, the transmission rate, the distance between stations, the retry limit and the network topology are considered. Experimental measurements are also compared against theoretical calculations.**

I. INTRODUCTION

Wireless Local Area Networks (WLANs) are now used commonly in the communication infrastructure due to their convenience in setup, usage and maintenance. The most popular WLAN standard is IEEE 802.11 [1], which covers the Medium Access Control (MAC) sublayer of the Data Link Control (DLC) layer and the Physical (PHY) layer. The performance of 802.11 MAC has been investigated through various analytical studies [2], [3] and simulation studies [4], [5]. The 802.11b [6] is an enhanced version of the original 802.11 standard and can offer transmission rates of 1, 2, 5.5 and 11 Megabits per second (Mb/s).

Nevertheless, a detailed understanding of 802.11b WLAN performance, and quantification of the characteristics of 802.11b links are still needed. In this paper, the throughput and packet loss rate of 802.11b links in ad hoc mode are measured on a real testbed.

The paper provides the theoretical calculations, followed by an extensive set of experiments on a real testbed. The conclusions gained from the theoretical calculations and experiment results are also presented.

II. PERFORMANCE OF AN IEEE 802.11B LINK

An IEEE 802.11 WLAN can operate in two modes: ad hoc or infrastructure. In the infrastructure mode, stations must communicate with each other through an Access Point (AP). In the ad hoc mode, stations can directly communicate with each other establishing point-to-point links.

A. Experiment Description

A network topology similar to the one described in [7] was used. The test network was built with laptop computers running Linux version 2.4.20-8 and 802.11b WLAN cards. The computers were kept stationary during the experiments. Three performance categories of the IEEE 802.11b were investigated:

1) The effects of UDP packet size to throughput between two stations at different transmission rates.
2) The effects of distance to packet loss and throughput between two stations at different transmission rates and retry limits.
3) The throughput of multiple simultaneous sessions in a network of four stations. (Fig. 6)

TABLE I
LENGTH OF THE PROTOCOL HEADERS AND 802.11B PARAMETERS

Parameter	Symbol	Value
UDP header (bits)	L_{UDP}	64
TCP header (bits)	L_{TCP}	256
UDP or TCP header	L_4	
IP header (bits)	L_{IP}	160
LLC/SNAP header (bits)	L_{2u}	40
MAC header + FCS (bits)	L_{MAC}	272
Transmission time of PLCP preamble and PLCP header (μs)	T_{PHY}	192
Timeslot (μs)	T_{slot}	20
SIFS duration (μs)	T_{SIFS}	10
DIFS duration (μs)	T_{DIFS}	50
Minimum CW (Timeslots)	CW_{min}	31
RTS frame (bits)	L_{RTS}	160
CTS frame (bits)	L_{CTS}	112
MAC ACK frame (bits)	L_{ACK}	112
Transmission rate of control frames (Mb/s)	R_{control}	1

B. Effects of Packet Size to Throughput

The purpose of this section is to show that the throughput between two stations, which is only a fraction of the transmission rate of the WLAN cards, varies with the packet size. The theoretical throughput is calculated and then compared with the measured throughput.

1) Theoretical throughput: Table I shows the various parameters and the length of the protocol headers used. Each packet of size m bytes at the application layer is encapsulated either in the User Datagram Protocol (UDP) or Transmission Control Protocol (TCP) protocol, which adds an UDP header or a TCP header respectively. The length of the UDP or TCP header is referred to as L_4. If the resultant packet is larger than 1480 bytes, it is fragmented at the Internet Protocol (IP) layer into multiple IP datagrams, each with 1480 bytes of IP payload (except for the last fragment) and 20 bytes of IP header. This is because the Maximum Transfer Unit (MTU) or the maximum size of an IP datagram that the DLC layer can transmit was set in the WLAN cards to the default value of 1500 bytes.

The DLC layer adds a Logical Link Control/Sub Network Attachment Point (LLC/SNAP) header, its length is defined as L_{2u}. The resultant unit of data is referred to as an MAC payload. The MAC sublayer adds a MAC header and Frame Check Sequence (FCS), together referred to as MAC_{hdr} with length L_{MAC} . Finally, the Physical layer adds a Physical Layer Conversion Protocol (PLCP) preamble and a PLCP header, together referred to as PHY_{hdr}.

Each transmitted TCP packet requires an ACK packet, referred to as TCP-ACK to distinguish it with the ACK frame at the MAC layer. The TCP-ACK packet consists of zero bytes at application layer ($m = 0$) and only the headers of the lower layers. The control frames, including RTS, CTS and ACK frames, and PHY_{hdr} are transmitted at 1 Mb/s, while the MAC payload and MAC_{hdr} are transmitted at one of the transmission rates of 1, 2, 5.5 or 11 Mb/s. The average backoff is $T_{\text{bo}} = CW_{\text{min}} \times T_{\text{slot}}/2$.

For the basic access method without the RTS/CTS mechanism, without IP fragmentation, the transmission time T_{bas} of an UDP, TCP-data or TCP-ACK packet is

$$T_{\text{bas}} = T_{\text{DIFS}} + T_{\text{bo}} + T_{\text{SIFS}} + \left(T_{\text{PHY}} + \frac{L_{\text{ACK}}}{R_{\text{control}}}\right) + \left(T_{\text{PHY}} + \frac{8 \times m + L_4 + L_{\text{IP}} + L_{\text{2u}} + L_{\text{MAC}}}{R_{\text{data}}}\right). \quad (1)$$

If the UDP packet is fragmented at the IP layer into n IP datagrams, the first $(n-1)$ IP datagrams are 1500 bytes long (1480 bytes of IP payload and 20 bytes of IP header), the last IP datagram is $l = m + L_{\text{UDP}} - 1480(n-1)$ bytes of payload and 20 bytes of IP header. For the basic access method without RTS/CTS, the transmission time of an UDP packet that is fragmented into n IP datagrams is

$$\begin{aligned} T_{\text{bas}} = n \left[T_{\text{DIFS}} + T_{\text{bo}} + T_{\text{SIFS}} + \left(T_{\text{PHY}} + \frac{L_{\text{ACK}}}{R_{\text{control}}}\right)\right] + \\ (n-1)\left[T_{\text{PHY}} + \frac{8 \times 1500 + L_{\text{2u}} + L_{\text{MAC}}}{R_{\text{data}}}\right] + \\ \left[T_{\text{PHY}} + \frac{8 \times l + L_{\text{IP}} + L_{\text{2u}} + L_{\text{MAC}}}{R_{\text{data}}}\right]. \quad (2) \end{aligned}$$

With the RTS/CTS mechanism, transmission of each UDP, TCP-data or TCP-ACK packet requires extra time as compared with the basic access method and is given by

$$\begin{aligned} T_{\text{rts}} = T_{\text{bas}} + T_{\text{SIFS}} + \left(T_{\text{PHY}} + \frac{L_{\text{RTS}}}{R_{\text{control}}}\right) + \\ T_{\text{SIFS}} + \left(T_{\text{PHY}} + \frac{L_{\text{CTS}}}{R_{\text{control}}}\right). \quad (3) \end{aligned}$$

2) Comparison of theoretical and measured throughput: Table II shows the settings of the WLAN cards used in the throughput versus packet size experiment.

Fig. 1 shows the comparison between theoretical and measured UDP throughput versus packet size, at transmission rates of 2 and 11 Mb/s and with/without RTS/CTS.

The comparison between theoretical and measured TCP throughput with packet sizes of 1448 bytes, at transmission rates of 1, 2, 5.5 and 11 Mb/s and with/without RTS/CTS is shown in Fig. 2.

TABLE II

SETTINGS OF THE WLAN CARDS FOR THE THROUGHPUT VERSUS PACKET SIZE EXPERIMENT

Parameter	Value
Environment	Indoor
Distance (m)	0.1
Transport layer protocol	UDP, TCP
Application layer packet size (bytes)	500, 512, 1000, 1024, 1472, 2000, 2048, 3000, 4096 (UDP); 1448 (TCP)
MTU (bytes)	1500
Experiment duration (s)	10
Transmission rate (Mb/s)	1, 2, 5.5, 11
RTS/CTS	OFF, ON

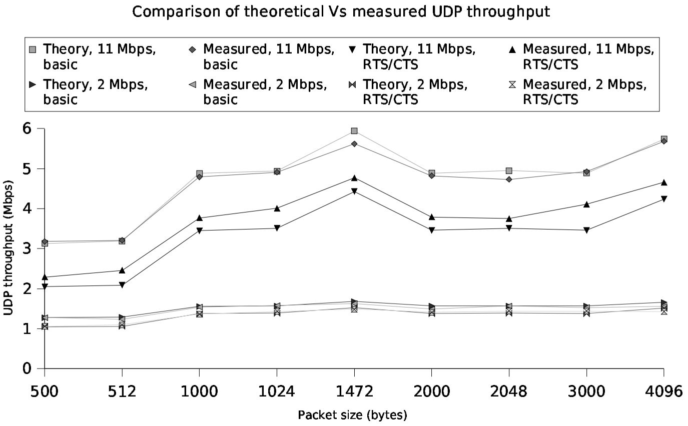

Fig. 1. Comparison of theoretical and measured UDP throughput

As can be seen from Fig. 1 and Fig. 2, the throughput between two stations is only a fraction of the transmission rate of the WLAN cards. For example, at transmission rate of 11 Mb/s, the maximum UDP throughput is 5.68 Mb/s while maximum TCP throughput is only 4.44 Mb/s. This is due to the headers of the protocol layers, the idle medium during carrier sensing and backoff and the transmission of ACK frames. For TCP traffic, the throughput is less than UDP traffic because of the extra transmission of TCP-ACK packet for each TCP data packet. With RTS/CTS mechanism, due to the extra transmission of RTS and CTS frames, the throughput is further reduced.

The measurement of throughput between two stations agrees well with theoretical calculation, with the exception of RTS/CTS mechanism at higher transmission rates (5.5 and 11 Mb/s). This may be due to the RTS/CTS frames are transmitted at 2 Mb/s, while in the theoretical calculation, they are assumed to be transmitted at 1 Mb/s. Both theoretical calculation and measurement show that there is an optimal value of packet size that maximizes the throughput between two stations.

C. The Effects of Distance to Packet Loss and Throughput

The purpose of this section is to present the form of increase in packet loss rate and reduction in throughput with distance

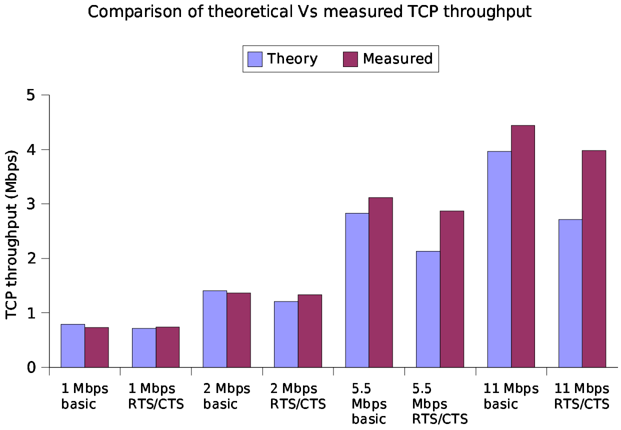

Fig. 2. Comparison of theoretical and measured TCP throughput, packet size 1448 bytes

TABLE III
SETTINGS OF THE WLAN CARDS FOR THE PACKET LOSS RATE AND THROUGHPUT VERSUS DISTANCE EXPERIMENT

Parameter	Value
Environment	Outdoor
Height above ground (m)	0.45
Distance between stations (m)	10, 20, 30,...
Transport layer protocol	UDP
Application layer packet size (bytes)	512
MTU (bytes)	1500
Experiment duration (s)	10
Frequency (GHz)	2.412
Transmission rate (Mb/s)	1, 2, 5.5, 11
Transmitted power (dBm)	20
Antenna gain (dBi)	2.2
Retry limit of WLAN card	1, 2, 16
RTS/CTS	OFF

between two stations. We also show that the setting of the retry limit can affect the throughput as well as the packet loss rate.

Table III shows the settings of the WLAN cards used in the packet loss rate and throughput versus distance experiment.

The experiment was conducted outdoors on a grass field and the two communicating laptops are always kept in line of sight (LOS). Therefore, there was a direct signal path and a single ground reflected signal path between the sending station and the receiving station. Assume that the ground reflection ratio is -1, the received signal power P_r is related to the transmitted power P_t by [8]

$$P_r = P_t G_t G_r \left(\frac{\lambda}{2\pi d} \right)^2 \sin^2 \left(\frac{2\pi H_t H_r}{\lambda d} \right), \tag{4}$$

where G_t and G_r are the gains of the transmitting and receiving antennas, λ is the wavelength, d is the distance between two stations, H_t and H_r are the heights of the transmitting and receiving antennas above the ground.

Assume an additive white Gaussian noise (AWGN) channel with noise power spectral density N_0, the bit error rate (BER) at transmission rate R_b is given by [9].

BER at a transmission rate of 1 Mb/s is

$$\mathrm{BER}_{\mathrm{1Mb/s}} = \frac{1}{2} e^{-\frac{E_b}{N_0}}, \tag{5}$$

BER at a transmission rate of 2 Mb/s is

$$\mathrm{BER}_{\mathrm{2Mb/s}} = Q_1(a,b) - \frac{1}{2} I_0(ab) e^{(-(a^2+b^2))}, \quad \text{and} \tag{6}$$

BER at a transmission rate of 5.5 and 11 Mb/s is

$$\mathrm{BER}_{\mathrm{5.5,\ 11Mb/s}} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-X}^{\infty} \left(\frac{1}{\sqrt{2\pi}} \int_{-(\nu+X)}^{\nu+X} e^{-\frac{y^2}{2}} dy \right)^{\frac{N}{2}-1} e^{-\frac{\nu^2}{2}}, \tag{7}$$

where $E_b = P_r / R_b$ is the average energy per bit, $Q_1(a,b)$ is the Marcum function and $I_0(ab)$ is the modified Bessel function of order zero, whose parameters are given by $a = \sqrt{2E_b/(N_0(1-\sqrt{1/2}))}$ and $b = \sqrt{2E_b/(N_0(1+\sqrt{1/2}))}$, $X = \sqrt{2E_b/N_0}$ and N is equal to 4 and 8 for 5.5 and 11 Mb/s, respectively.

Assume that the PLCP header of the data frame and the ACK frame are always successfully received, with the packet total length of L bits (excluding PLCP header), the packet error rate (PER) is given by

$$\mathrm{PER} = 1 - (1 - \mathrm{BER})^L. \tag{8}$$

The packet loss rate (PLR) is the probability that a packet is dropped when the retry limit is reached and is given by

$$\mathrm{PLR} = \mathrm{PER}^{m+1}, \tag{9}$$

where m is the maximum retransmission limit. Due to the space limitations, a more exact formulation of PLR is not included here but will be presented in a later publication. However, it is expected that the PLR increases and the throughput decreases as the distance between two stations increases, following the curves as displayed in the measurements.

Fig. 3 shows the measured UDP packet loss rate versus the distance between two stations, at transmission rates of 1, 2, 5.5 and 11 Mb/s and with a retry limit of 1.

The expected PLR curve and the measured UDP packet loss rate versus the distance between two stations at transmission rate of 1 Mb/s and retry limit of 1, 2 and 16 are shown in Fig. 4.

Fig. 5 shows the expected throughput curve and the measured UDP throughput versus the distance between two stations at transmission rate of 1 Mb/s and retry limit of 1, 2 and 16.

As can be seen from Fig. 3, at a fixed distance, the packet loss rate is higher at higher transmission rate. This is because with the same transmitted power and distance, therefore same received power P_r, the higher transmission rate R_b has lower average energy per bit $E_b = P_r / R_b$. From Fig. 4 and Fig. 5, with a fixed transmission rate, the PLR increases and the throughput decreases as the distance between two stations increases. This is also due to the decrease in average energy per bit E_b when the distance increases, according to (4). With the

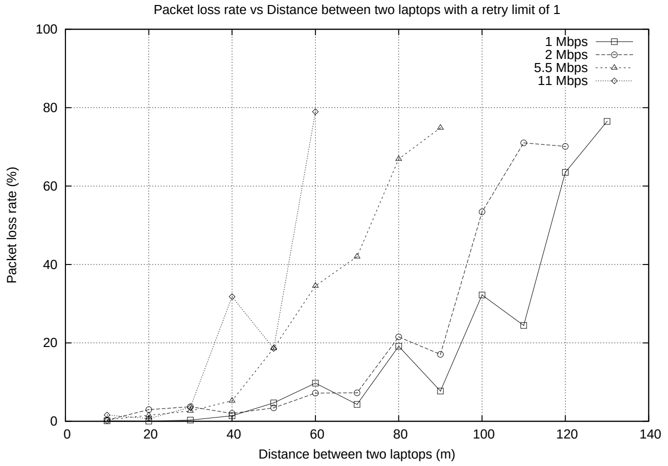

Fig. 3. Measured UDP packet loss rate versus distance between two stations at transmission rates of 1, 2, 5.5 and 11 Mb/s and with a retry limit of 1

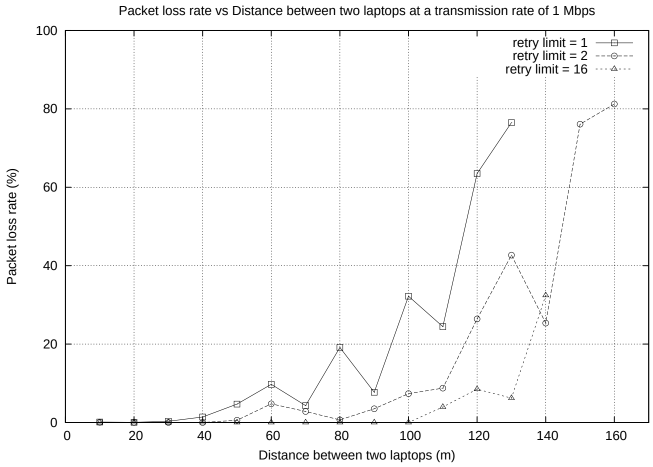

Fig. 4. Measured UDP packet loss rate versus distance between two stations at a transmission rate of 1 Mb/s and retry limit of 1, 2 and 16

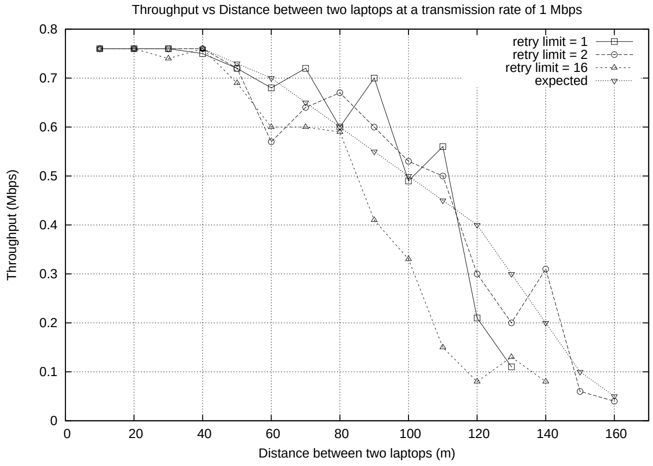

Fig. 5. Measured UDP throughput versus distance between two stations at a transmission rate of 1 Mb/s and retry limit of 1, 2 and 16

TABLE IV

PARAMETERS FOR THE THROUGHPUT OF MULTIPLE SESSIONS CALCULATION

Parameter	Symbol	Value
Number of stations	n	4
Max. retransmission number	m	5
P(a station transmits in a slot)	τ	0.0507
P(a transmitted packet collides)	p	0.1444
P($\geq$ one transmission in a slot)	P_{tr}	0.1879
P(a successful transmission)	P_s	0.9233
Average number of idle slots between two transmissions	$E[\Psi]$	4.3220
Data transmission rate (Mb/s)	R_{data}	2
Application layer packet size (bytes)	P	512, 1024, 1448

average energy per bit decreases, the BER increases and PLR also increases, resulting in a decrease in throughput. However, when the distance between two stations is relatively small (for example, 40m at the transmission rate of 1 Mb/s), the packet loss rate and throughput remain steady. Furthermore, there is a trade-off between packet loss rate and throughput with the setting of the retry limit. Lower retry limit gives higher packet loss rate but also higher throughput and vice versa.

D. Throughput of Multiple Simultaneous Sessions

The purpose of this section is to illustrate the behavior of WLAN consisting of a number of simultaneous sessions between stations.

1) Theoretical throughput: Table I and Table IV show the values of the parameters used in the calculation.

The theoretical normalized system throughput, using the analytical model described in [2], is given by

$$S = \frac{P_s E[P]}{E[\Psi] + P_s T_s + (1 - P_s) T_c}, \tag{10}$$

where $E[P]$ is the average packet size. T_s is the average time of busy channel due to a successful transmission and T_c is the average time of busy channel due to a collision.

For the basic access method without the RTS/CTS mechanism,

$$\begin{aligned} T_s^{\text{bas}} = &\left(T_{\text{PHY}} + \frac{L_{\text{data}}}{R_{\text{data}}}\right) + T_{\text{SIFS}} + \\ &\left(T_{\text{PHY}} + \frac{L_{\text{ACK}}}{R_{\text{control}}}\right) + T_{\text{DIFS}}, \end{aligned} \tag{11}$$

$$T_c^{\text{bas}} = \left(T_{\text{PHY}} + \frac{L_{\text{data*}}}{R_{\text{data}}}\right) + T_{\text{DIFS}}. \tag{12}$$

With the RTS/CTS mechanism,

$$\begin{aligned} T_s^{\text{rts}} = &\left(T_{\text{PHY}} + \frac{L_{\text{RTS}}}{R_{\text{control}}}\right) + T_{\text{SIFS}} + \\ &\left(T_{\text{PHY}} + \frac{L_{\text{CTS}}}{R_{\text{control}}}\right) + T_{\text{SIFS}} + \\ &\left(T_{\text{PHY}} + \frac{L_{\text{data}}}{R_{\text{data}}}\right) + T_{\text{SIFS}} + \\ &\left(T_{\text{PHY}} + \frac{L_{\text{ACK}}}{R_{\text{control}}}\right) + T_{\text{DIFS}}, \end{aligned} \tag{13}$$

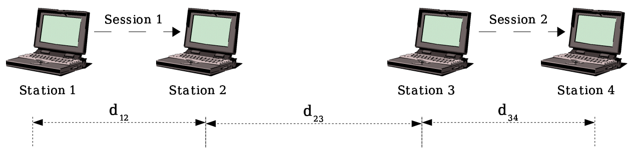

Fig. 6. Network topology for the throughput of multiple sessions experiment

TABLE V
SETTINGS OF THE WLAN CARDS FOR THE THROUGHPUT OF MULTIPLE SESSION EXPERIMENT

Parameter	Value
Environment	Outdoor
Height above ground (m)	0.45
Distance d_{12} (m)	10
Distance d_{23} (m)	20
Distance d_{34} (m)	10
Transport layer protocol	UDP, TCP
Application layer packet size (bytes)	512, 1024 (UDP), 1448 (TCP)
MTU (bytes)	1500
Experiment duration (s)	10
Transmission rate (Mb/s)	2
Retry limit of WLAN cards	16
RTS/CTS	OFF, ON

$$T_c^{\text{rts}} = \left(T_{\text{PHY}} + \frac{L_{\text{RTS}}}{R_{\text{control}}} \right) + T_{\text{DIFS}}. \tag{14}$$

In both cases, L_{data} and L_{data^*} are given by

$$\begin{aligned} L_{\text{data}} &= E[P] + L_4 + L_{\text{IP}} + L_{\text{2u}} + L_{\text{MAC}}, & (15)\\ L_{\text{data}^*} &= E[P^*] + L_4 + L_{\text{IP}} + L_{\text{2u}} + L_{\text{MAC}}, & (16) \end{aligned}$$

where $E[P^*]$ is the average size of the longest packet in a collision. For UDP traffic, $E[P] = P$, while with TCP traffic, since every TCP-data packet requires a TCP-ACK packet with zero bytes of payload, $E[P] = P/2$. With both UDP and TCP traffic, $E[P^*] = P$.

2) Comparison of theoretical and measured throughput: Fig. 6 shows the network settings used in the throughput of multiple sessions experiment. Two simultaneous sessions run for 10 seconds. In session 1, station 1 transmits data to station 2 and in session 2, station 3 transmits data to station 4. The distance between station i and j is d_{ij}.

The settings of the WLAN cards used in the multiple session experiment are shown in Table V.

Fig. 7 shows the measured throughput of sessions 1 and 2 with UDP and TCP traffic at transmission rate of 2 Mb/s.As can be seen from Fig. 7, with two simultaneous sessions between four stations, there is one session (session 1) that gets much higher throughput than the other session (session 2). This can be explained as the station that has one successful transmission resets its contention window to minimum value CW_{min}. Future packets from the "winning" station has more chance to be transmitted before the packets from other stations. Therefore, the session with the "winning" station as a sender will have higher throughput.

Fig. 8 shows the comparison between the theoretical and measured total throughput of UDP and TCP traffic at transmission rate of 2 Mb/s. As can be seen from Fig. 8, the measured total throughput matches the theoretical calculation. Both theoretical calculation and measurement show that with only two simultaneous sessions between four stations, the basic access method has higher throughput than the RTS/CTS mechanism.

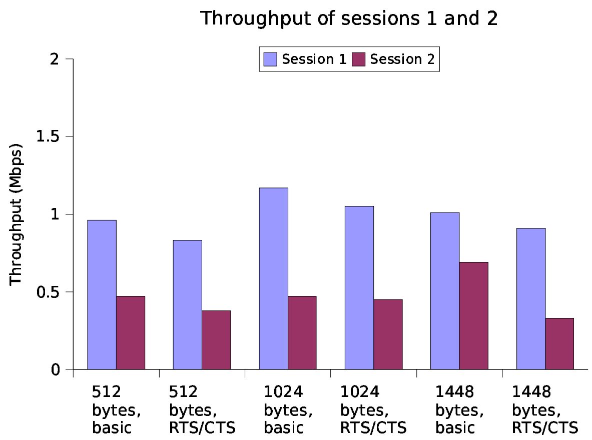

Fig. 7. Measured throughput of sessions 1 and 2 at transmission rate of 2 Mb/s

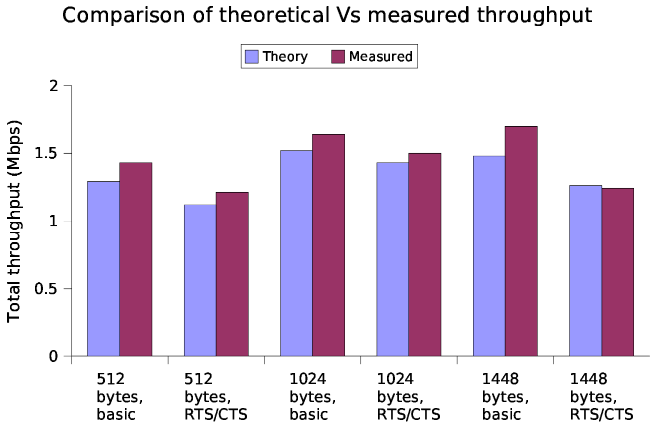

Fig. 8. Comparison between theoretical and measured total throughput at transmission rate of 2 Mb/s

III. CONCLUSIONS

This paper presents theoretical calculations and measurements for the throughput and packet loss rate versus the packet size and the distance between two stations. The effects of different transmission rates and retry limits are illustrated. The network topology with two simultaneous sessions between four stations are also considered. The measurements agree well with the theoretical calculations.

From the theoretical calculations and experiment results, a number of conclusions and suggestions for improving the transmission rate in a WLAN link can be made as follows:

1) The throughput between two stations is only a fraction of the transmission rate of the WLAN cards. This throughput increases with the packet size. Both theoretical calculation and measurement show that there is an optimal value of packet size that maximizes the

throughput between two stations. Multimedia services have small packet, therefore, it may be useful if they are combined at the MAC layer to reduce MAC overhead, as well as to form a packet with optimal size.

2) At a given transmission rate, the packet loss rate and the throughput remain stable up to a certain distance. Beyond this threshold, the packet loss rate increases and the throughput decreases rapidly with distance. By choosing the appropriate range in which the stations operate, the packet loss and throughput is not degraded significantly and QoS can be guaranteed.
3) There is a trade-off between packet loss rate and throughput with the setting of the retry limit. Lower retry limit gives higher packet loss rate but also higher throughput, and is best suitable for multimedia services with some tolerance on packet loss but requires high throughput. On the other hand, higher retry limit is more suitable for best-effort services.
4) The 802.11 MAC mechanism does not provide fair access to the medium for all stations, with the measurement shows that a session obtains most of the throughput of the medium. The measurement also demonstrates that the RTS/CTS mechanism is only efficient if there are a large number of stations and/or there are hidden stations.

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