A MAC Throughput over Rayleigh Fading Channel in The 802.11a/g/n-based Mobile LAN

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***Abstract* – This paper explores a MAC (Medium Access Control) layer throughput with DCF (Distributed Coordination Function) protocol in the IEEE 802.11a/g/n-based mobile LAN. It is evaluated in Rayleigh fading wireless channel, using theoretical analysis method. The DCF throughput performance is analyzed by using the number of stations with both variable payload size and mobile speed on the condition that fading margin and transmission probability are fixed. In the IEEE 802.11n, A-MSDU (MAC Service Data Unit Aggregation) scheme is considered and number of subframe is used as the variable parameter. It is identified that MAC efficiency of IEEE 802.11n is the best out of four schemes.**

***Keywords* - Mobile LAN, MAC, Throughput, CSMA/CA, DCF, IEEE 802.11a/g/n.**

I. INTRODUCTION

Over the past few years, mobile networks have emerged as a promising approach for future mobile IP applications. With limited frequency resources, designing an effective MAC protocol is a hot challenge. IEEE 802.11b/g/a/n networks are currently the most popular wireless LAN products on the market [1]. The conventional IEEE 802.11b and 802.11g/a specification provide up to 11 and 54 Mbps data rates, respectively. However, the MAC protocol that they are based upon is the same and employs a CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) protocol with binary exponential back-off. IEEE 802.11 DCF is the de facto MAC protocol for wireless LAN because of its simplicity and robustness [2]. Therefore, considerable research efforts have been put on the investigation of the DCF performance over wireless LAN [2][3][4]. With the successful deployment of IEEE 802.11a/b/g wireless LAN and the increasing demand for real-time applications over wireless, the IEEE 802.11n Working Group standardized a new MAC and Physical Layer (PHY) specification to increase the bit rate to be up to 600 Mbps [5]. The throughput performance at the MAC layer can be improved by aggregating several frames before transmission [6]. Frame aggregation not only reduces the transmission time for preamble and frame headers, but also reduces the waiting time during CSMA/CA random backoff period for successive frame transmissions. The frame aggregation can be performed within different sub-layers. In 802.11n, frame aggregation can be performed either by MAC Protocol Data Unit Aggregation (A-MPDU) or MAC Service Data Unit Aggregation (A-MSDU). Although frame aggregation can increase the throughput at the MAC layer under ideal channel conditions, a larger aggregated frame will cause each station to wait longer before its next chance for channel access. Under error-prone channels, corrupting a large aggregated frame may waste a long period of channel time and lead to a lower MAC efficiency [6]. On the other hand, wireless LAN mobile stations that are defined as the stations that access the LAN while in motion are considered in this paper [4]. The previous paper analyzed the IEEE 802.11b/g/n MAC performance for wireless LAN with fixed stations, not for wireless LAN with mobile stations [2][3][7][8]. On the contrary, Xi Yong [4] and Ha Cheol Lee [9] analyzed the MAC performance for IEEE 802.11 wireless LAN with mobile stations, but considered only IEEE 802.11 and 802.11g/a wireless LAN specification. So, this paper extends the previous researches and analyzes the IEEE 802.11n MAC performance for wireless LAN with mobile stations. In other words, we will present the analytical evaluation of saturation throughput with bit errors appearing in the transmitting channel. IEEE 802.11g/a/n PHY and MAC layer focused in this paper are reviewed and frame error rate of mobile wireless channel is derived in Section 2. The DCF saturation throughput is theoretically derived in Section 3 and numerical results are analyzed in Section 4. Finally, it is concluded with Section 5.

II. WIRELESS ACCESS ARCHITECTURE

Fig. 1 shows ad hoc mode operation of wireless access architecture in the 802.11a/g/n-based mobile LAN. The protocols of the various layers are called the protocol stack. The TCP/IP protocol stack consists of five layers: the physical, data link, network, transport and application layers. 802.11 of Fig. 1 means physical layer and data link layer which consists of MAC and LLC (Logical Link Control) sub-layers. And this paper is focused on physical layer and MAC sublayer. An ad hoc network might be formed when people with laptops get together and want to exchange data in the absence of a centralized AP (Access Point).

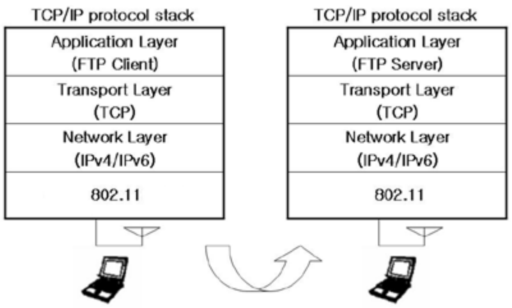
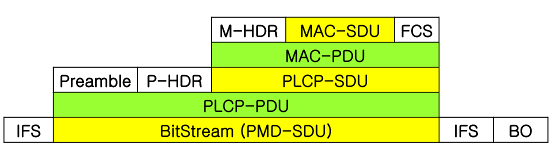


Figure 1. Ad hoc mode operation in the mobile LAN

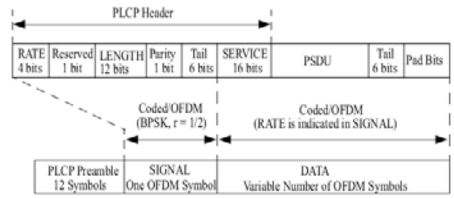
A. 802.11a/g PHY/MAC layer

Fig. 2 shows the 802.11a/g-based physical and MAC layer protocol stack and typical frame structure focused in this paper. When a higher layer pushes a user packet down to the MAC layer as a MAC-SDU (MSDU), the MAC layer header (M-HDR) and trailer (FCS) are added before and after the MSDU, respectively and form a MAC-PDU (MPDU). The PHY (Physical) layer is again divided into a PLCP (Physical Layer Convergence Protocol) sub-layer and a PMD (Physical Medium Dependent) sub-layer. Similarly the PLCP preamble and PLCP header (P-HDR) are attached to the MPDU at the PLCP sub-layer. Different IFS (Inter Frame Space)s are added depending on the type of MPDU.

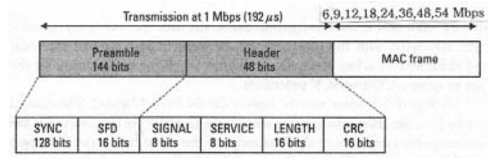
IEEE 802.11a operates in the 5 GHz band and uses OFDM (Multiple-Input Multiple-Output). The achievable data rates are 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. 802.11g uses DSSS, OFDM, or both at the 2.4 GHz ISM band to provide high data rates of up to 54 Mbps. 802.11g device can operate with an 802.11b device. Combined use of both DSSS and OFDM is achieved through the provision of four different physical layers. The four different physical layers defined in the 802.11g standards are ERP-DSSS/CCK, ERP-OFDM, ERP-DSSS/PBCC and DSSS-OFDM. The standards that support the highest data rate of 54 Mbps are ERP-OFDM and DSSS-OFDM. ERP-OFDM is a new physical layer in IEEE 802.11g and OFDM is used to provide IEEE 802.11a data rates at the 2.4 GHz band. DSSS-OFDM is a new physical layer that uses a hybrid combination of DSSS and OFDM. The packet physical header is transmitted using DSSS, while the packet payload is transmitted using OFDM. Fig. 3 shows basic access scheme of CSMA/CA mechanism. The SIFS (Short Inter-Frame Space) and the slot time are determined by the physical layer. DIFS (Distributed Inter-Frame Space) is defined based on the above two intervals.



(a) Protocol stack of physical and MAC layer



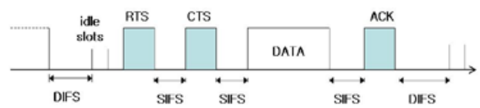
(b) 802.11a and 802.11g ERP-OFDM frame



(c) 802.11g DSSS-OFDM frame

Figure 2. Protocol stack and frame structure of IEEE 802.11a/g/n-based mobile LAN

(a) basic access scheme



(b) RTS/CTS scheme

Figure 3. IEEE 802.11g/a DCF channel access mechanism

B. 802.11n PHY/MAC layer

At the MAC layer, 802.11n use several new MAC, including the frame aggregation, block acknowledgement, and bi-directional data transmission. There are two ways to perform frame aggregation at the MAC layer as shown in Fig. 4. The first technique is by concatenating several MAC Service Data Units (MSDUs) to form the data payload of a large MAC Protocol Data Unit (MPDU). The PHY header and MAC header, along with the frame check sequence (FCS), are then appended to form the Physical Service Data Unit (PSDU). This technique is known as A-MSDU. The second technique is called A-MPDU. It begins with each MSDU appending with its own MAC header and FCS to form a sub-MPDU. An MPDU delimiter is then inserted before each sub-MPDU. Padding bits are also inserted so that each sub-MPDU is a multiple of 4 bytes in length, which can facilitate subframe delineation at the receiver. Then, all the sub-MPDUs are concatenated to form a large PSDU. Figure 4 also shows timing of the preamble fields in legacy, MF(Mixed Format) and GF (Green Field). At the PHY layer, 802.11n will use MIMO and OFDM (Orthogonal Frequency Division Multiplexing). It supports up to a transmission rate of 600 Mbps and is backward compatible with 802.11a/b/g. 802.11n provides support for both 2.4 GHz and 5 GHz frequency bands at the same time. 802.11n defines implicit and explicit transmit beamforming (TxBF) methods and space-time block coding (STBC),

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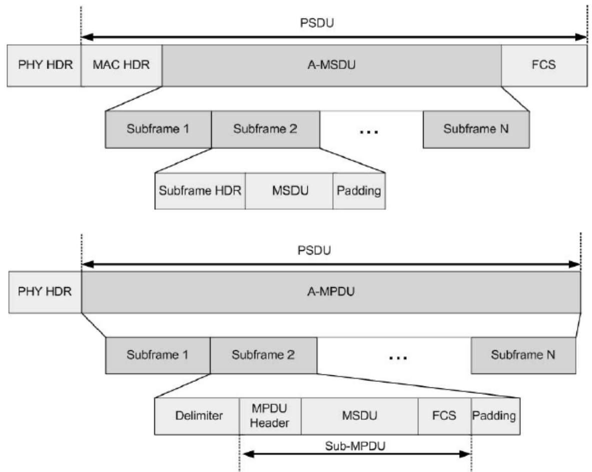
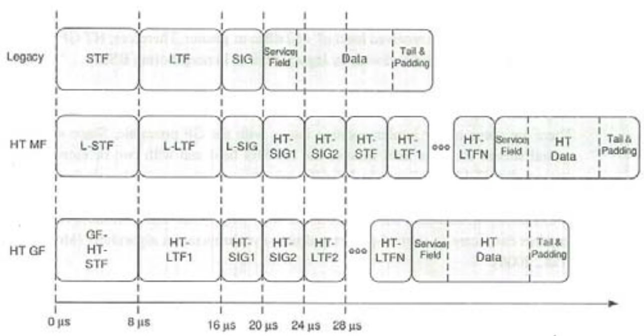


(a) 802.11n Frame Format for A-MSDU and A-MPDU



(b) Timing of the preamble fields in legacy, MF and GF

Figure 4. Frame structure of IEEE 802.11n-based mobile LAN

which improves link performance over MIMO with basic spatial-division multiplexing (SDM). It also defines a new optional low density parity check (LDPC) encoding scheme, which provides better coding performance over the basic convolutional code. The possible timing sequences for A-MPDU and A-MSDU in the uni-directional transfer case are shown in Figure 5. If RTS/CTS (Request To Send/Clear To Send) is used, the current transmission sequence of RTS–DATA (Data frame)–ACK (Acknowledgement) only allows the sender to transmit a single data frame. The DATA frame represents either an A-MPDU or an A-MSDU frame. The system time can be broken down into virtual time slots where each slot is the time interval between two consecutive countdown of backoff timers by non-transmitting stations. The 802.11n also specifies a bi-directional data transfer method. In the bi-directional data transfer method, the receiver may request a *reverse* data transmission in the CTS control frame. The sender can then grant a certain medium time for the receiver on the reverse link. The transmission sequence will then become RTS-CTS-DATAf-DATAr-ACK. This facilitates the transmission of some small feedback packets from the receiver and may also enhance the performance of TCP which requires the transmission of TCP ACK segments. Block Acknowledgement (BACK) can

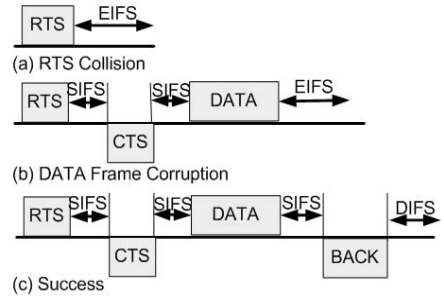


Figure 5. IEEE 802.11n Uni-directional RTS/CTS Access Scheme

be used to replace the previous ACK frame. The BACK can use a bit map to efficiently acknowledge each individual sub-frame within the aggregated frame.

C. Frame error rate

Mobile wireless channel is assumed to be flat fading Rayleigh channel with Jake spectrum. The channel is in fading states or inter-fading states by evaluating a certain threshold value of received signal power level. If and only if the whole frame is in inter-fading state, there is the successful frame transmission. If any part of frame is in fading duration, the frame is received in error. In the fading channel fading margin is considered and defined as $\rho = R_{req}/R_{rms}$, Where R_{req} is the required received power level and R_{rms} is the mean received power. Generally, the fading duration and inter-fading duration can be taken to be exponentially distributed for ρ<-10dB. With the above assumptions, let Tpi be the frame duration, then the frame error rate is given by (1) [4].

$$FER = 1 - \frac{Ti}{Ti + T_f} P(t_i > Tpi) \qquad (1)$$

Where, t_i is inter-fading duration and t_f is fading duration. Ti is the mean value of the random variable t_i and T_f is the mean value of the random variable t_f . $P(ti > Tpi)$ is the probability that inter-fading duration lasts longer than Tpi . Since exponential distribution is assumed for t_i , $P(t_i > Tpi) = \exp(-\frac{Tpi}{Ti})$. For Rayleigh fading channel, the average fading duration is given by (2).

$$Ti = \frac{\exp(\rho) - 1}{fd\sqrt{2\pi\rho}} \qquad (2)$$

$T_i + T_f$ is $\frac{1}{N_f}$, where N_f is the level crossing rate, which is given by $fd\sqrt{2\pi\rho}\exp(-\rho)$. f_d is the maximum Doppler frequency and evaluated as $\frac{\nu}{\lambda}$. ν is the mobile speed and λ is wavelength. Frame error rate can be expressed by (3).

$$FER = 1 - \exp(-\rho - f_d\sqrt{2\pi\rho}Tpi) \quad (3)$$

Equation (3) shows that frame error rate is determined by fading margin, maximum Doppler frequency and frame duration. Since fading margin and maximum Doppler frequency are hard to dynamically control, the only controllable parameter is frame duration to get required frame error rate. For the RTS/CTS access mode, the frame duration T_{pi} is $T_H + T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK}$. T_H is preamble transmission time + PLCP header transmission time + MAC header transmission time. T_{DATA} is MSDU transmission time and T_{ACK} is ACK frame transmission time. T_{RTS} is RTS frame transmission time and T_{CTS} is CTS frame transmission time.

III. DCF THROUGHPUT ANALYSIS

The back-off procedure of the DCF protocol is modeled as a discrete-time, two-dimensional Markov chain. Fig. 4 shows the Bianchi's Markov chain model for the back-off window size [7]. We define $W = CW_{\min}$. Let m, the maximum back-off stage, be such value that $CW_{\max} = 2^m W$. We also define $W_i = 2^i W$, where $i \in (0, m)$ is called the back-off stage. Let $s(t)$ be the stochastic process representing the back-off stage $(0,...,m)$ of the station at time t. p is the probability that a transmission is collided or unsuccessfully executed.

We will present the analytical evaluation of saturation throughput with bit errors appearing in the transmitting channel. The number of stations n is assumed to be fixed and each station always has packets for transmission. In other words, we operate in saturation conditions, the transmission queue of each station is assumed to be always nonempty.

Let S be the normalized system throughput, defined as the fraction of time in which the channel is used to successfully transmit payload bits. P_{tr} is the probability that there is at least one transmission in the considered slot time.

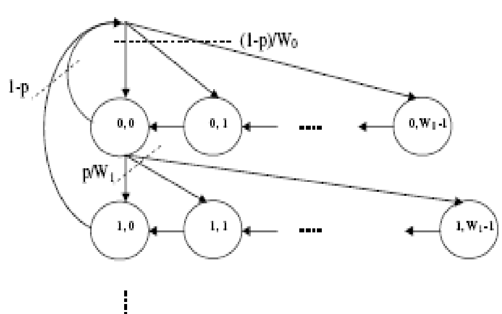


Figure 6. Markov chain model for the backoff window size

Since n stations contend on the channel and each transmits with probability τ, we get

$$P_{tr} = 1 - (1-\tau)^n \quad (4)$$

Table 1 shows physical and MAC layer parameters of IEEE 802.11a/g/n–based mobile LAN.

TABLE I
IEEE 802.11a/g PARAMETERS

Parameter	Explanation
FER	Frame error rate
τ	Packet transmission probability
N	Number of stations
P	Payload size
T_{RTS}	RTS frame transmission time
T_{CTS}	CTS frame transmission time
T_H	PLCP preamble transmission time + PLCP header transmission time + MAC header transmission time
T_{DATA}	Payload transmission time
T_{ACK}	ACK frame transmission time
T_{BACK}	Block ACK frame transmission time
σ	Slot time
T_{SIFS}	SIFS time
T_{DIFS}	DIFS time
T_{EIFS}	EIFS time
$CW_{\min}$	Minimum backoff window size
$CW_{\max}$	Maximum backoff window size

A. 802.11a/g DCF throughput

Saturation throughput is represented as shown in (5) [9].

$$S = \frac{P_s P_{tr} P}{(1-P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1-P_s)T_c} =$$

$$\frac{n\tau(1-\tau)^{n-1}(1-FER)P}{(1-\tau)^n\sigma + n\tau(1-\tau)^{n-1}(1-FER)T_s + [1-(1-\tau)^n]T_c - n\tau(1-\tau)^{n-1}(1-FER)T_c} \quad (5)$$

P_s is the probability that a transmission successfully occurs on the channel and is given by the probability that exactly one station transmits on the channel, conditioned on the fact that at least one station transmits.

$$P_s = \frac{n\tau(1-\tau)^{n-1}(1-FER)}{P_{tr}} \quad (6)$$

The average amount of payload information successfully transmitted in a slot time is $P_{tr}P_sP$, since a successful transmission occurs in a slot time with probability $P_{tr}P_s$. The average length of a slot time is readily obtained considering that, with probability $1-P_{tr}$, the channel is empty, with probability $P_{tr}P_s$ it contains a successful transmission, and with probability $P_{tr}(1-P_S)$ it contains a collision. Where T_S is the average time the channel is sensed busy because of a successful transmission, and T_C is the average time the channel is sensed busy by each station during a collision or error. σ is the duration of an empty slot time. In the RTS/CTS access scheme, we obtain,

$$T_S = T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} + T_{DIFS} + 3T_{SIFS} \tag{7}$$
$$T_C = T_{RTS} + T_{EIFS} = T_{RTS} + T_{SIFS} + T_{ACK} + T_{DIFS}$$

B. 802.11n DCF throughput

In the uni-directional case shown in Fig. 5, the saturation throughput can be calculated as follows [8].

$$S = \frac{E_p}{E_t} = \frac{L_p P_{tr} P_s (1-P_e)}{T_{idle}P_{idle} + T_c P_{tr}(1-P_s) + T_e P_{err} + T_{succ}P_{succ}}$$

$$\frac{L_p n\tau(1-\tau)^{n-1}(1-P_e)}{(1-\tau)^n\sigma + n\tau(1-\tau)^{n-1}(1-P_e)T_{succ} + [1-(1-\tau)^n - n\tau(1-\tau)^{n-1}]T_c + n\tau(1-\tau)^{n-1}P_eT_e} \tag{8}$$

where E_p is the number of payload information bits successfully transmitted in a virtual time slot, and E_t is the expected length of a virtual time slot. P_e is the error probability on condition that there is a successful RTS/CTS transmission in the time slot. P_{idle} is the probability of an idle slot. P_s is the probability for a non-collided transmission. P_{err} is the transmission failure probability due to error (no collisions but having transmission errors). P_{succ} is the probability for a successful transmission without collisions and transmission errors. T_{idle}, T_c and T_{succ} are the idle, collision and successful virtual time slot's length. T_e is the virtual time slot length for an error transmission sequence. L_p is the aggregated frame's payload length. In the RTS/CTS scheme, we obtain,

$$T_C = T_{RTS} + T_{EIFS} \tag{9}$$
$$T_{succ} = T_{RTS} + T_{CTS} + T_{DATA} + T_{BACK} + 3T_{SIFS} + T_{DIFS}$$
$$T_e = T_{RTS} + T_{CTS} + T_{DATA} + T_{EIFS} + 2T_{SIFS}$$

IV. NUMERICAL RESULTS

This section evaluated DCF throughput of the IEEE 802.11a/g-based mobile LAN. The maximum physical transmission rate of IEEE 802.11a/g is 54 Mbps and that of IEEE 802.11n-based mobile LAN is 600 Mbps. In this paper, bandwidth of 20 MHz, long guard interval and MCS (modulation and coding scheme) index of 15 for two spatial streams are used in Fig. 7. MCS index 15 uses 64-QAM modulation scheme and coding rate of 5/6. So, the physical transmission rate of 130 Mbps is assumed. Also, both ERP-OFDM and DSSS-OFDM standard are only used in this evaluation for the IEEE 802.11g standard because of considering their maximum transmission rate of 54 Mbps [14]. Generally, the three common packets passed down to the MAC layer are 60 bytes (TCP ACK), 576 bytes (typical size for web browsing) and 1,500 bytes (the maximum size for Ethernet) in length. In the IEEE 802.11n-based mobile LAN, the two common packets are only considered and the number of packets aggregated in one MAC frame varies from 1 to 80, which leads to an aggregated frame's payload length (L_p) from 576 and 1,500 bytes to 46.08 and 120 Kbytes. In the Fig. 7(a) ~ Fig. 7(c), the symbol S (P, ρ, ν, n, τ) shows the saturation throughput over error-prone channel according to the number of stations (n) for common packet sizes (P) on the condition that packet transmission probability (τ), mobile velocity (ν) and fading margin (ρ) are fixed. In the Fig. 8(a) and Fig. 8(b), the symbol S (n_s, P, ρ, ν, n, τ) and S (P, n_s, ρ, ν, n, τ) respectively shows the saturation throughput over error-prone channel according to the number of stations (n) and the typical number of packets aggregated in one MAC frame (n_s) for two subframe length on the condition that packet transmission probability (τ), mobile velocity (ν) and fading margin (ρ) are fixed. For example, in the Fig. 7(a), if the number of stations is 7, packet transmission probability is 0.05, packet length is 1,500 and fading margin is 0.01, mobile station with the speed of 1.25 m/s can get the throughput of 27.238 Mbps, whereas mobile station with the speed of 25 m/s can get the throughput of 26.968 Mbps. In the Fig. 8(a), if the number of subframe is 30 and the same conditions mentioned above are applied, mobile station with the speed of 1.25 m/s can get the throughput of 113.511 Mbps with six stations, whereas mobile station with the speed of 25 m/s can get the throughput of 84.607 Mbps. Also, Fig. 7(a~c) and Fig. 8(a) show that the longer frame (or subframe) length is, the higher throughput is. And, for the same frame (or subframe) length, the higher speed is, the lower throughput is. As the results of evaluation, we also know that there is optimum number of stations to maximize saturation throughput under the error-prone channel. Specially, in Fig. 8(b), the number of subframes is considered and it is identified that there is optimum number of subframes to maximize saturation throughput under the error-prone channel. In conclusion, we obtained the fact that there exist an optimal number of stations (or subframes) to maximize the saturation throughput under the error-prone channel. Also, we can identify that the larger payload (or subpayload) size be, the higher saturation throughput be. And if a mobile velocity of station is increased, the throughput is decreased a little. Out of the three different physical layers defined in this analysis with the maximum transmission rate of 54 Mbps, which are 802.11g ERP-OFDM, 802.11g DSSS-OFDM and 802.11a OFDM, the DCF saturation throughput of 802.11a OFDM is the highest.

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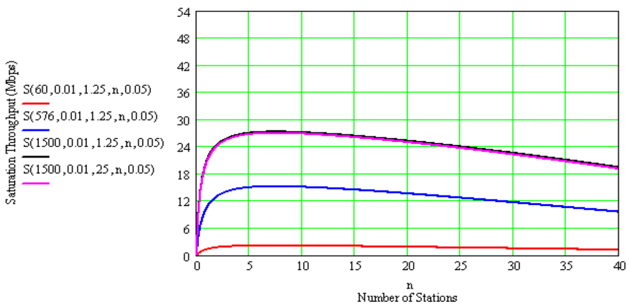
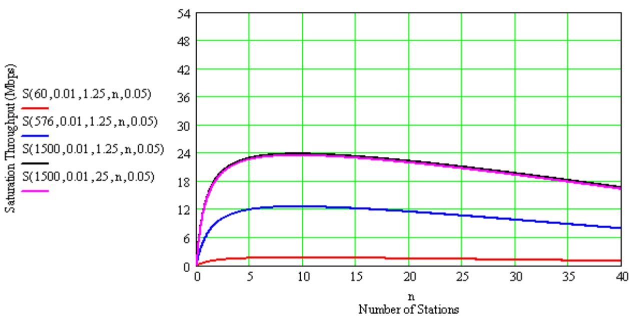
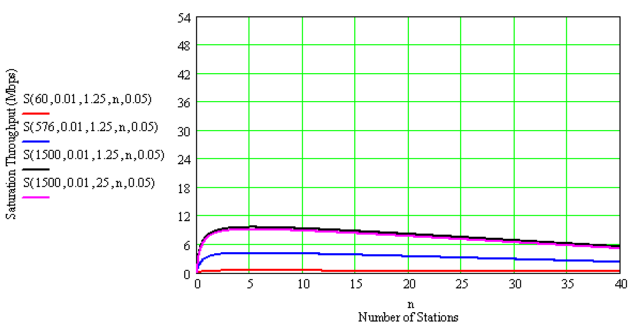
In the case of 802.11n, because A-MSDU (MAC Service Data Unit Aggregation) scheme is applied, it is identified that MAC efficiency of IEEE 802.11n is better than any other mobile LAN specifications.



(a) 802.11a OFDM (54 Mbps)

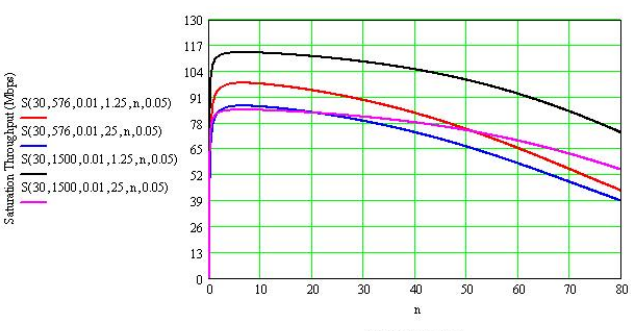


(b) 802.11g ERP-OFDM (54 Mbps)

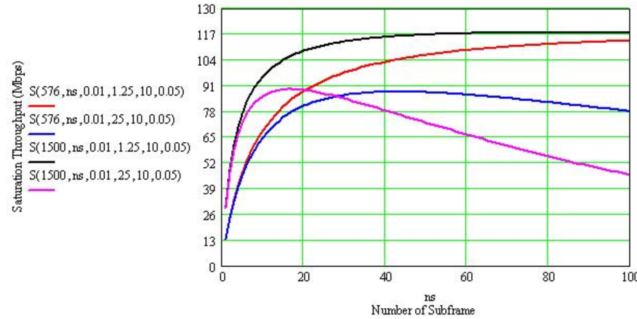


(c) 802.11g DSSS-OFDM (54 Mbps)

Figure 7. DCF throughput of IEEE 802.11a/g mobile LAN



(a) 802.11n OFDM (130 Mbps, number of stations)



(b) 802.11n OFDM (130 Mbps, number of subframe)

Figure 8. DCF throughput of IEEE 802.11n mobile LAN

V. CONCLUSIONS

This paper explored the saturation throughput performance of DCF protocol in the IEEE 802.11a/g/n-based mobile LAN under the error-prone channel. IEEE 802.11a and IEEE 802.11g have the same maximum transmission rate of 54 Mbps, but the DCF saturation throughput of 802.11a is higher than that of 802.11g. Of the two 802.11g standards, DCF saturation throughput of 802.11g ERP-OFDM is higher than that of 802.11g DSSS-OFDM. We are recognizing that a 802.11n-based device can operate with a 802.11 legacy devices, but 802.11a-based device does not operate with a 802.11b/g-based device. So either constructing 802.11a/n-based mobile LAN or constructing 802.11g/n-based mobile LAN have to be considered for interoperability.

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