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FER Performance in the IEEE 802.11 a/g/n Wireless LAN over Fading Channel

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ABSTRACT

This paper explores and compares FER (Frame Error Rate) of a MAC (Medium Access Control) layer in the IEEE 802.11 a/g/n wireless LAN. It is evaluated under the fading wireless channel, using theoretical analysis method. It 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. Especially, in the IEEE 802.11n, A-MSDU (MAC Service Data Unit Aggregation) scheme is considered and the number of subframe is used as the variable parameter. In the IEEE 802.11a/g wireless LAN, fixed wireless channel is assumed to be Rayleigh fading channel. 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.

1. Introduction

Over the past few years, wireless LAN has emerged as a promising applications. IEEE 802.11 a/g/n networks are currently the most popular wireless LAN products on the market. The conventional IEEE 802.11 g/a provides up to 54 Mbps data rate [1]. With the successful deployment of IEEE 802.11 a/g wireless LAN and the increasing demand for real-time applications over wireless, the IEEE 802.11n WG (Working Group) standardized a new MAC and PHY(Physical) layer specification to increase the bit rate to be up to 600 Mbps. In IEEE 802.11n wireless LAN, frame aggregation not only reduces the transmission time for preamble and frame headers, but also reduces the waiting time during CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) random backoff period for successive frame transmissions. Frame aggregation can be performed either by A-MPDU (MAC Protocol Data Unit Aggregation) or A-MSDU[2][3][4]. This paper analyzes the FER in the IEEE 802.11 a/g/n wireless LAN with fixed and mobile stations. In Section 2, wireless LAN history and standards are investigated. In Section 3, FER of wireless channel is derived with fixed station, and FER of mobile channel is also derived with mobile station by using theoretical analysis method. In Section 4, numerical results of FER are displayed in both fixed and mobile wireless channel. Finally, it is concluded with Section 5.

2. Wireless LAN History and Standards

Standards in the IEEE project 802 target the physical layer (PHY) and medium access control (MAC) layer [2]. When wireless LAN was first conceived, it seemed that it would be just another PHY of one of the available standards.

The first candidate considered for this was IEEE's most prominent standard IEEE 802.3(Ethernet). However, it soon became obvious that the radio medium is very different from the well-behaved wire. Due to tremendous attenuation even over short distances, collisions cannot be detected. Hence, IEEE 802.3's CSMA/CD (Carrier Sense Multiple Access with Collision Detection) could not be applied. The next candidate standard to be considered was IEEE 802.4. Its coordinated medium access, the token bus concept, was believed to be superior to IEEE 802.3's contention-based scheme. In the mean time, the standardization body realized that a wireless communication standard would need its own very unique MAC. Finally, on March 21, 1991, project IEEE 802.11 was approved. The first IEEE 802.11 standard was published in 1997. At the lowest PHY layer, it provides a FHSS (Frequency Hopping Spread Spectrum) and a DSSS (Direct Sequence Spread Spectrum) PHY in the unlicensed 2.4 GHz band, and an infrared PHY at 316–353 THz. Although all three provide a basic data rate of 1 Mb/s with an optional 2 Mb/s mode, commercial infrared imple-

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A key element to the IEEE 802.11 success is its simple MAC operation based on the DCF protocol. This scheme has proven to be robust and adaptive to varying conditions, able to cover most needs sufficiently well. Following the trends visible from the wired Ethernet, IEEE 802.11's success is mainly based on over provisioning of its capacity. The available data rate was sufficient to cover the original best effort applications, so complex resource scheduling and management algorithms were unnecessary. However, this may change in the future. Because of the growing popularity of IEEE 802.11, Wireless LANs are expected to reach their capacity limits. Moreover, applications like voice and video streaming pose different demands for quality of service. Therefore, traffic differentiation and network management might become inevitable. **Figure 2** shows IEEE 802.11 MAC layer amendments

3. FER Analysis

3.1. FER of Fixed Wireless Channel

In IEEE 802.11a/g wireless LAN, fixed wireless channel isassumed to be Rayleigh fading channel. The probability of bit error is upper bound by
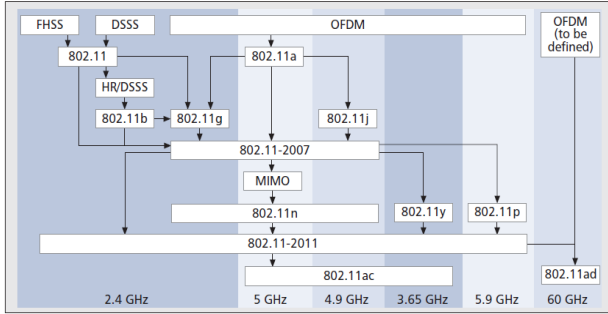
Figure 1. The IEEE 802.11 PHY layer amendments and their dependencies[2].
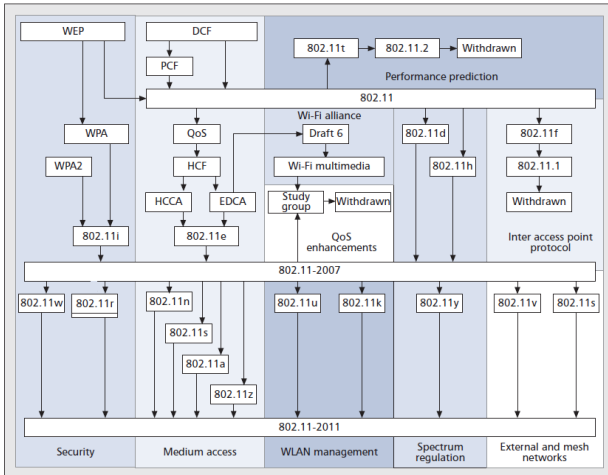
Figure 2. The IEEE 802.11 MAC layer amendments[2].

$$P_b < \frac{1}{k} \sum_{d=d_{free}}^{\infty} B_d P_d \qquad (1)$$

where d_{free} is the free distance of the convolutional code, B_d is the total number of information bit ones on all weight d paths, P_d is the probability of selecting a weight d output sequence as the transmitted code sequence, and k is the number of information bits per clock cycle. Because the weight structure is generally accepted that the first five terms in equation (1) dominate, equation (1) can be rewritten as

$$P_b < \frac{1}{k} \sum_{d=d_{free}}^{d_{free}+4} B_d P_d \qquad (2)$$

The probability of selecting the incorrect path when d is odd.

$$P_d = \sum_{i=\frac{d+1}{2}}^{d} \binom{d}{i} p^i (1-p)^{d-i} \qquad (3)$$

where p is the probability of channel bit error. The probability of selecting the incorrect path when d is even.

$$P_d = \sum_{i=\frac{d}{2}+1}^{d} \binom{d}{i} p^i (1-p)^{d-i} + \frac{1}{2} \binom{d}{d/2} p^{d/2} (1-p)^{d/2} \qquad (4)$$

To achieve data rates of 54 Mbps for wireless access, the IEEE 802.11 a standard utilizes MQAM ($q = 6$, $M = 64$) with convolutional coding at rate $r = 3/4$. We obtain the approximate channel bit error probability for the ith sub-channel for MQAM with a square constellation as

$$p_i \approx \frac{4\left(1-\frac{1}{\sqrt{M}}\right) \cdot e^{-d \cdot \zeta_i \left[\frac{3qr\overline{\gamma_{b_i}}}{3qr\overline{\gamma_{b_i}}+2(M-1)(\zeta_I+1)}\right]}}{q\sqrt{2\pi c_2}\left[\frac{3qr\overline{\gamma_{b_i}}+2(M-1)(\zeta_I+1)}{2(M-1)(\zeta_I+1)}\right]^d}$$

$$- \frac{2\left(1-\frac{1}{\sqrt{M}}\right)^2 \cdot e^{-d \cdot \zeta\left[\frac{3qr\overline{\gamma_{b_i}}}{3qr\overline{\gamma_{b_i}}+2(M-1)(\zeta_I+1)}\right]}}{\pi c_2 q\left[\frac{3qr\overline{\gamma_{b_i}}+(M-1)(\zeta_I+1)}{(M-1)(\zeta_I+1)}\right]} \qquad (5)$$

where $c_2 = 2.6 + 0.1\zeta$ is empirically obtained and d = 1 for HDD. ζ_i is the ratio of direct-to-diffuse signal power on the ith sub-channel. ζ has 0 in a pure Rayleigh fading channel and ranges from 0 to 10 in a composite Rayleigh/Ricean fading channel. $\overline{\gamma_{bi}}$ is the ratio of received average energy per bit-to-noise power spectral density on the ith sub-channel. The overall p is the average of the probability of bit error on each of the N OFDM sub-channels [5, 6].

$$p = \frac{1}{N}\sum_{i=1}^{N}p_i \qquad (6)$$

Note that for either no channel fading or for all sub-channels experiencing the same fading (that is, $\zeta_i = \zeta$ and $\gamma_{b_i} = \gamma_b$ for all i), then $p_i = p$. $\gamma_b = E_b/N_o$ is the ratio of received average energy per bit-to-noise power spectral density, ζ is the ratio of direct-to-diffuse signal power. Now, using equation (6) in equation (3) or (4) and taking the result into equation (2), we obtain the performance of 64 QAM with HDD over Ricean fading channels. For basic access mechanism, a data packet including the PHY header and the MAC header needs retransmission if any one bit of them is corrupted. We define a variable P_c which is the probability that a backoff occurs in a station due to bit errors in packets. We further assume that bit errors randomly appear in the packets. So frame error rate is represented by (7).

$$P_c = 1 - (1 - P_b)^{L_{preamble} + PHY_h + MAC_h + P + L_{ACK}} \qquad (7)$$

CSMA/CA is also used as the MAC scheme in IEEE 802.11n wireless LAN, and it has basic and RTS/CTS access scheme. Although there is a successful RTS/CTS transmission in the time slot, a frame has to be retransmitted when there is a bit error in a payload. For convenience, we define a variable P_e which is the probability that a backoff occurs in a station due to bit errors in packets. We further assume that bit errors randomly appear in the packets and A-MSDU scheme is used. So frame error rate is represented by (8).

$$P_e = 1 - (1 - q)^L \qquad (8)$$

where L is the aggregated MAC frame's size. For a convolutional code with a coding rate k_c/n_c, the bit error rate, denoted as q, can be approximated by

$$q = \frac{1}{k_c}\sum_{i = \frac{d_{free}+1}{2}}^{d_{free}}\binom{d_{free}}{i}(q_b)^i(1-q_b)^{d_{free}-i} \quad (d_{free} \text{ is odd}) \qquad (9)$$

$$q = \frac{1}{k_c}\sum_{i = \frac{d_{free}}{2}+1}^{d_{free}}\binom{d_{free}}{i}(q_b)^i(1-q_b)^{d_{free}-i}$$
$$+ \frac{1}{2k_c}\binom{d_{free}}{d_{free}/2}(q_b)^{d_{free}/2}(1-q_b)^{d_{free}/2}$$

$$(d_{free} \text{ is even})$$

where d_{free} is the maximum free distance of the convolutional code and q_b is the probability of a bit error for the M-QAM[5].

$$q_b = \frac{M q_s}{2(M-1)} \qquad (10)$$

q_s is the SER(Symbol Error Rate) under the Rician fading channel.

$$q_s = \left(\frac{1+K}{1+K+\frac{\rho(d_{min})^2}{8}}\right)^4 e^{-4\left(\frac{\frac{\rho(d_{min})^2}{8}(\|H\|)^2}{1+K+\frac{\rho(d_{min})^2}{8}}\right)} \qquad (11)$$

K is the Rician factor ρ may be interpreted as the average SNR at the receive antenna in a SISO fading link. d_{min} is the minimum distance of separation of the underlying scalar constellation. H is $M_R \times M_T$ channel transfer function and $\|H\|^2$ is the squared Frobenius norm of the channel [6, 7].

3.2. FER of Mobile Wireless Channel

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 $\rho < -10$dB. With the above assumptions, let Tpi be the frame duration, then the frame error rate is given by (12).

$$FER = 1 - \frac{Ti}{Ti + T_f}P(t_i > Tpi) \qquad (12)$$

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. $P(t_i > Tpi)$ 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 (13).

$$Ti = \frac{\exp(\rho)-1}{fd\sqrt{2\pi\rho}} \qquad (13)$$

$Ti + T_f$ is $\frac{1}{Nf}$, where Nf 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 $\frac{v}{\lambda}$. v is the mobile speed and λ is wavelength. Frame error rate can be expressed by (14).

$$FER = 1 - \exp(-\rho - f_d\sqrt{2\pi\rho}Tpi) \qquad (14)$$

Equation (14) 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[6,7].

4. Numerical Results of FER over the Fading Channel

4.1. FER Results with Fixed Stations

In the **Figure 3**, $P_c(P, \gamma_b, K)$ shows FER(Frame Error Rate) due to γ_b, the ratio of received average energy per bit- to-noise power spectral density[6,7]. K means Rician factor and P means payload size. And as expected, the FER performance improves with K and the smaller payload size is, the better performance is.
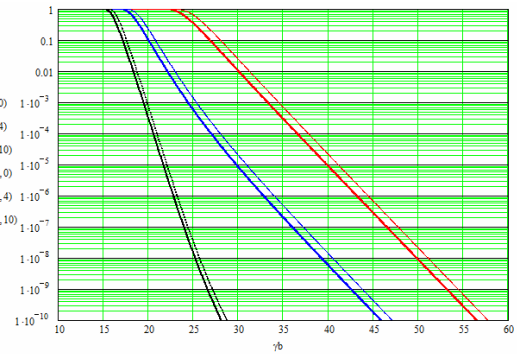
In the **Figure 4**, $q_s(\rho,K)$ shows SER(Symbol Error Rate) and $P_e(K,\rho,n_s,P)$ shows FER(Frame Error Rate) [6,7]. K means Rician factor and as expected, the FER performance improves with K and the smaller subframe' payload size is, the better performance is.
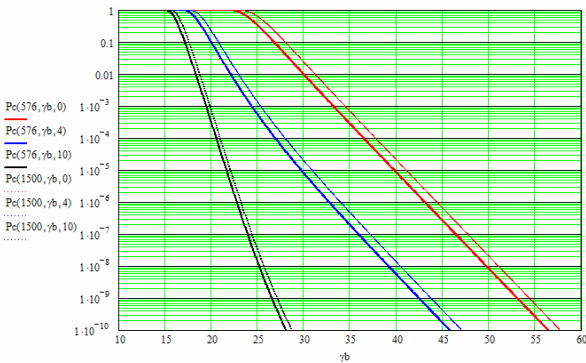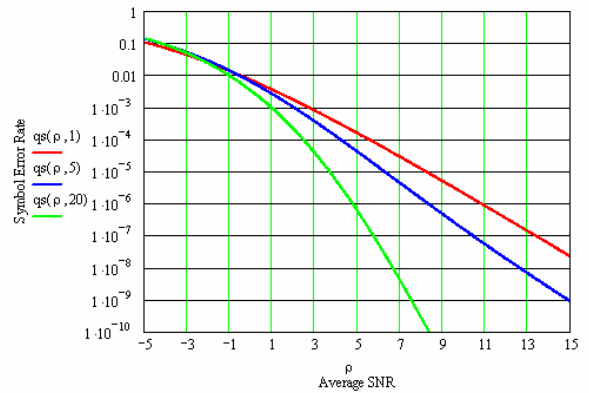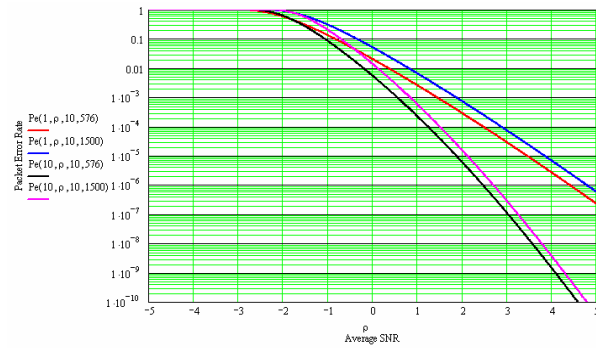

(a) IEEE 802.11a OFDM
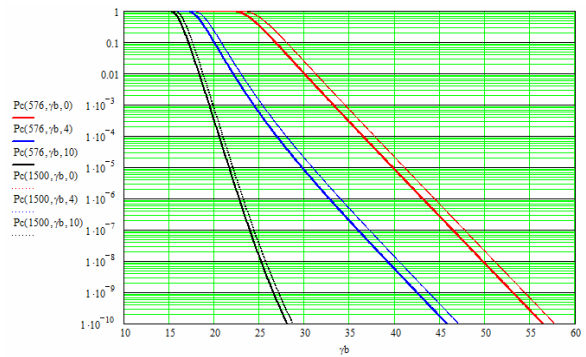
(b) IEEE 802.11g ERP-OFDM

(c) 802.11g DSSS-OFDM

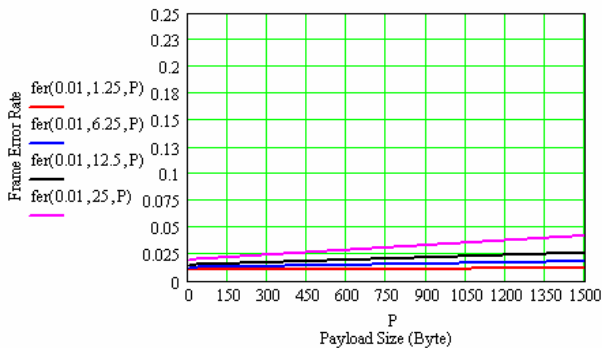**Figure 3. Frame error rate of IEEE 802.11a/g fixed LAN over Rayleigh fading channel.**

(a) SER

(b) FER

**Figure 4. SER and FER of IEEE 802.11n fixed LAN over Rician fading channel.**

4.2. FER Results with Mobile Stations

In the **Figures 5(a)-(c)**, the symbol fer (ρ, ν, P) shows frame error rate of IEEE 802.11a/g. In the **Figure 5(d)**, the symbol fer (ns, ρ, ν, P) shows frame error rate of IEEE 802.11n with the horizontal parameter of subframe' payload size. In the **Figure 5(e)**, the symbol fer (ρ, ns, ν, P) shows frame error rate of IEEE 802.11n using the number of subframes as the horizontal parameter. It is generally identified that the higher mobile speed is, the
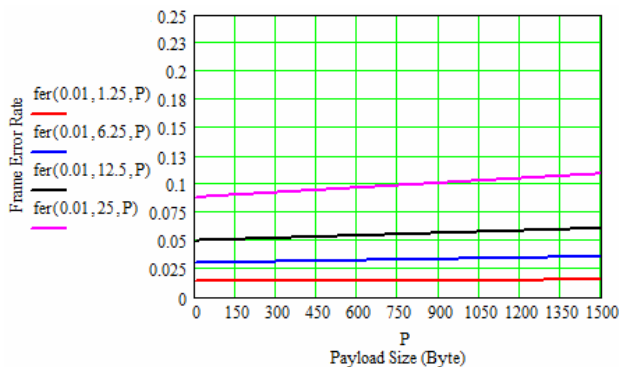
higher FER is. In case of payload size, the same result mentioned above is also acquired.
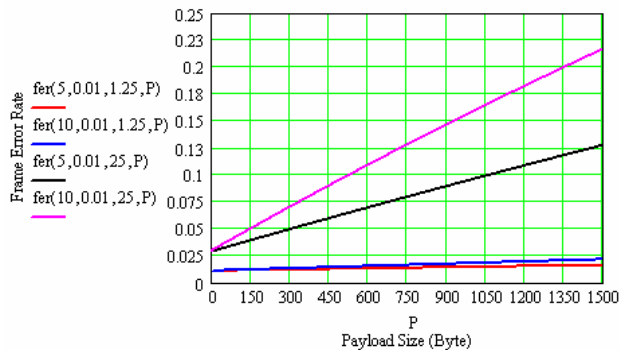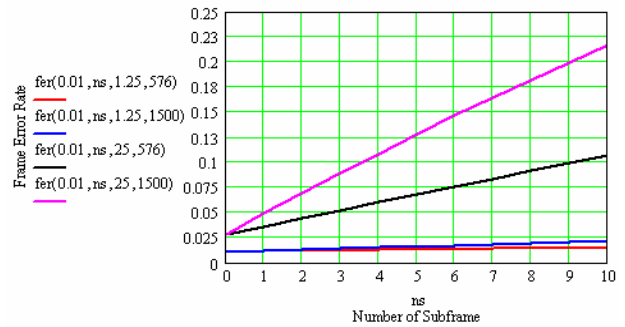

(a) IEEE 802.11a OFDM (54 Mbps)
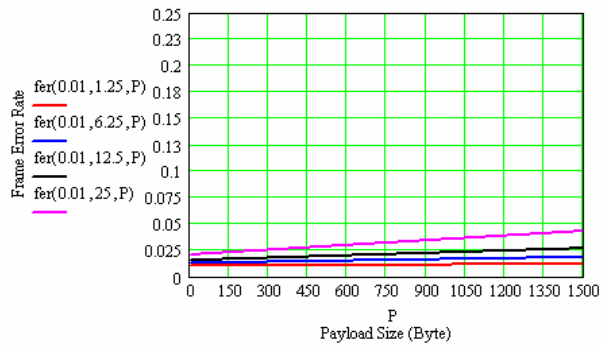
(b) IEEE 802.11g ERP-OFDM (54 Mbps)

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

(d) IEEE 802.11n OFDM (58.5 Mbps, Payload size)

(e) IEEE 802.11n OFDM (58.5 Mbps, number of subframe)

Figure 5. Frame error rate of IEEE 802.11a/g/n mobile LAN.

5. Remarks

This paper explored the FER performance of MAC layer in the IEEE 802.11a/g/n wireless LAN under the error-prone channel. The fixed wireless channel was assumed to be Rayleigh fading channel and the mobile wireless channel was assumed to be flat fading Rayleigh channel with Jake spectrum. The MAC protocol that they are based upon is the same and employs a CSMA/CA 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.

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