

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.

Keywords: Wireless LAN; MAC; FER; IEEE 802.11a/g/n

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-

mentations do not exist. Similar to IEEE 802.3, basic IEEE 802.11 MAC operates according to a listen-before-talk scheme, and is known as the DCF (Distributed Coordination Function). It implements CSMA/CA rather than collision detection as in IEEE 802.3. Indeed, as collision cannot be detected in the radio environment, IEEE 802.11 waits for a backoff interval before each frame transmission rather than after collisions. In addition to DCF, the original IEEE 802.11 standard specifies an optional scheme that depends on a central coordination entity, the PCF (Point Coordination Function). This function uses the so called PC (Point Coordinator) that operates during the so-called contention-free period. The latter is a periodic interval during which only the PC initiates frame exchanges via polling. However, the PCF's poor robustness against hidden nodes resulted in negligible adoption by manufacturers. Having published its first IEEE 802.11 standard in 1997, the WG received feedback that many products did not provide the degree of compatibility customers expected. As an example, often the default encryption scheme, called WEP(Wired Equivalent Privacy), would not work between devices of different vendors. This need for a certification program led to the foundation of the WECA (Wireless Ethernet Compatibility Alliance) in 1999, renamed the WFA (Wi-Fi Alliance) in 2003. Wi-Fi certification has become a well-known certification program that has significant market impact. The tremendous success in the market and the perceived shortcomings of the base IEEE 802.11 standard provided a basis and impetus for a prolific program of improvements and extensions. This has led to revisions of the draft, driven by a complete alphabet of amendments. Wireless LAN standards are shown in **Table 1**.

Although not interoperable, the DSSS and FHSS PHY initially seemed to have equal chances in the market. The FHSS PHY even had a duplicate in the HomeRF group that aimed at integrated voice and data services. This used plain IEEE 802.11 with FHSS for data transfer, complemented with a protocol for voice that was very similar to the Digital Enhanced Cordless Telecommunications standard. Neither HomeRF nor IEEE 802.11 saw FHSS extensions, although plans for a second-generation

HomeRF existed that targeted at 10 Mb/s. In contrast, the high-rate project IEEE 802.11b was started in December 1997 and boosted the data rates of the DSSS PHY to 11 Mb/s. This caused IEEE 802.11b to ultimately supersede FHSS, including HomeRF, in the market. The first extension project, IEEE 802.11a, started in September 1997. It added an OFDM(Orthogonal Frequency Division Multiplexing) PHY that supports up to 54 Mb/s data rate. Since IEEE 802.11 a operates in the 5 GHz band, communication with plain IEEE 802.11 devices is impossible. This lack of interoperability led to the formation of IEEE 802.11 g, which introduced the benefits of OFDM to the 2.4 GHz band. As IEEE 802.11 g's extended rate PHY provides DSSS-compatible signaling, an easy migration from IEEE 802.11 to IEEE 802.11 g devices became possible. While IEEE 802.11b uses only DSSS technology, IEEE 802.11g uses DSSS, OFDM, or both at the 2.4 GHz ISM band to provide high data rates of up to 54 Mb/s. combined use of both DSSS and OFDM is achieved through the provision of four different physical layers. These layers coexist during a frame exchange, so the sender and receiver have the option to select and use one of the four layers as long as they both support it. The four different physical layers defined in the IEEE 82.11g standard are ERP-DSSS/CCK, ERP-OFDM, ERP-DSSS/PBCC and DSSS-OFDM. From the above four physical layers, the first two are mandatory and the other two are optional [1].

As the first project whose targeted data rate is measured on top of the MAC layer, IEEE 802.11n provides user experiences comparable to the well known Fast Ethernet (IEEE 802.3u). Far beyond the minimum requirements that were derived from its wired paragon's maximum data rate of 100 Mb/s, IEEE 802.11n delivers up to 600 Mb/s. Its most prominent feature is MIMO (Multiple-Input Multiple-Output) capability. A flexible MIMO concept allows for arrays of up to four antennas that enable spatial multiplexing or beam forming. Its most debated innovation is the usage of optional 40 MHz channels. Although this feature was already being used as a proprietary extension to IEEE 802.11a and IEEE 802.11g chipsets, it caused an extensive discussion on neighbor friendly behavior. Especially for the 2.4 GHz band, concerns were raised that 40 MHz operation would severely affect the performance of existing IEEE 802.11, Bluetooth (IEEE 802.15.1), ZigBee(IEEE 802.15.4), and other devices. The development of a compromise, which disallows 40 MHz canalizations for devices that cannot detect 20 MHz-only devices, prevented ratification of IEEE 802.11n until September 2009. As a consequence of 20/40 MHz operation and various antenna configurations, IEEE 802.11n defines a total of 76 different MCSs. **Figure 1** provides an overview of the IEEE 802.11 PHY amendments and their dependencies [2].

Table 1. Wireless LAN products on the market.

Standard	Spectrum	Maximum physical rate/Layer 2 Data rate	Tx	Compatible with
802.11n	2.4/5 GHz	600/100 Mbps	MIMO OFDM	802.11b/g/a
802.11b	2.4 GHz	11/6-7 Mbps	DSSS	802.11
802.11g	2.4 GHz	54/32 Mbps	OFDM	802.11/ 802.11b/ 802.11n
802.11a	5.0 GHz	54/32 Mbps	OFDM	None

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 is assumed to be Rayleigh fading channel. The probability of bit error is upper bound by

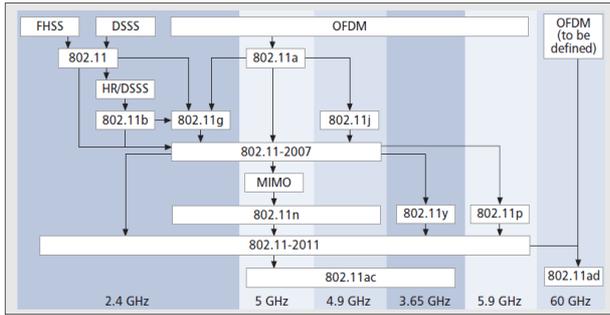


Figure 1. The IEEE 802.11 PHY layer amendments and their dependencies[2].

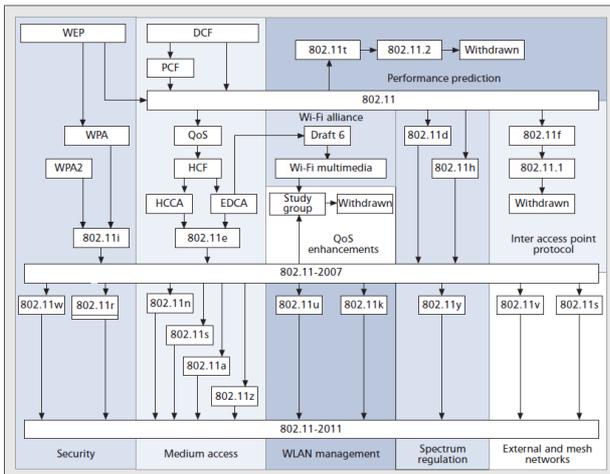


Figure 2. The IEEE 802.11 MAC layer amendments[2].

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

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

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

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

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

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

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

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 i^{th} sub-channel for MQAM with a square constellation as

$$P_i \approx \frac{4 \left(1 - \frac{1}{\sqrt{M}}\right) \cdot e^{-d \cdot \zeta_i \left[\frac{3qr\gamma_{bi}}{3qr\gamma_{bi} + 2(M-1)(\zeta_i + 1)} \right]}}{q\sqrt{2\pi c_2} \left[\frac{3qr\gamma_{bi} + 2(M-1)(\zeta_i + 1)}{2(M-1)(\zeta_i + 1)} \right]^d} \quad (5)$$

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

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 i^{th} sub-channel. ζ has 0 in a pure Rayleigh fading channel and ranges from 0 to 10 in a composite Rayleigh/Ricean fading channel. γ_{bi} is the ratio of received average energy per bit-to-noise power spectral density on the i^{th} sub-channel. The overall p is the average of the probability of bit error on each of the N OFDM sub-channels [5, 6].

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

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).

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

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).

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

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

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

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

$$+ \frac{1}{2k_c} \binom{d_{free}}{d_{free}/2} (q_b)^{d_{free}/2} (1 - q_b)^{d_{free}/2} \quad (d_{free} \text{ is even})$$

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].

$$q_b = \frac{Mq_s}{2(M-1)} \quad (10)$$

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

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

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 T_{pi} be the frame duration, then the frame error rate is given by (12).

$$FER = 1 - \frac{T_i}{T_i + T_f} P(t_i > T_{pi}) \quad (12)$$

where, t_i is inter-fading duration and t_f is fading duration. T_i is the mean value of the random variable t_i and T_f is the mean value of the random variable t_f . $P(t_i > T_{pi})$ is the probability that inter-fading duration lasts longer than T_{pi} . Since exponential distribution is assumed for t_i , $P(t_i > T_{pi}) = \exp(-\frac{T_{pi}}{T_i})$. For Rayleigh fading channel, the average fading duration is given by (13).

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

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

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

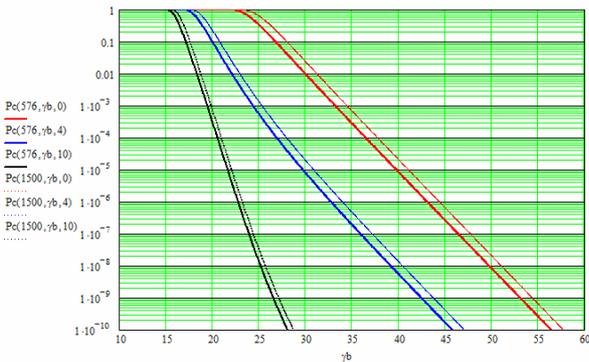
Equation (14) shows that frame error rate is determined by fading margin, maximum Doppler frequency and frame duration. Since fading margin and maximum Doppler frequency are hard to dynamically control, the only controllable parameter is frame duration to get required frame error rate. For the RTS/CTS access mode, the frame duration T_{pi} is $T_H + T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} \cdot T_H$ 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

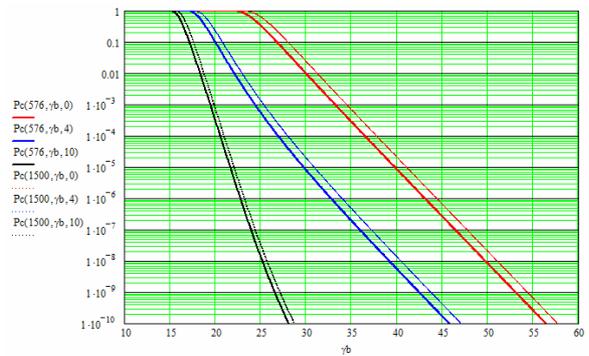
4.1. FER Results with Fixed Stations

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.

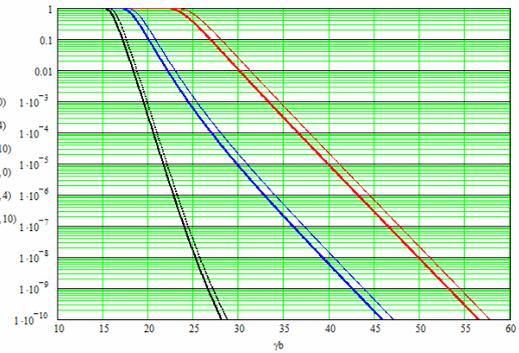
In the **Figure 4**, $q_s(\rho, K)$ shows SER(Symbol Error Rate) and $P_c(K, \rho, n_s, P)$ shows FER(Frame Error Rate) [6,7]. K means Rician factor and as expected, the FER performance improves with K and the smaller subframe' payload size is, the better performance is.



(a) IEEE 802.11a OFDM

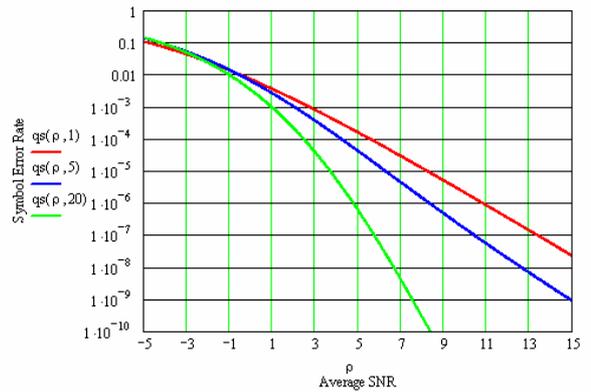


(b) IEEE 802.11g ERP-OFDM

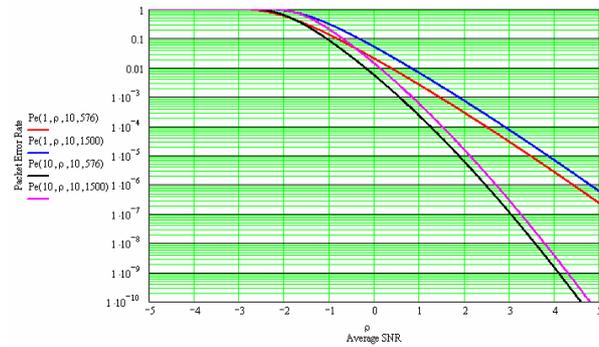


(c) 802.11g DSSS-OFDM

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



(a) SER



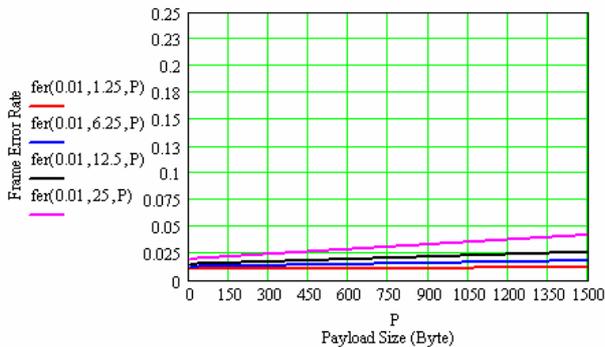
(b) FER

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

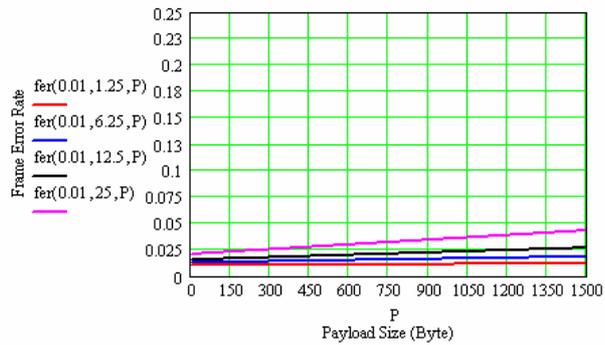
4.2. FER Results with Mobile Stations

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 (n_s, 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, n_s, 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

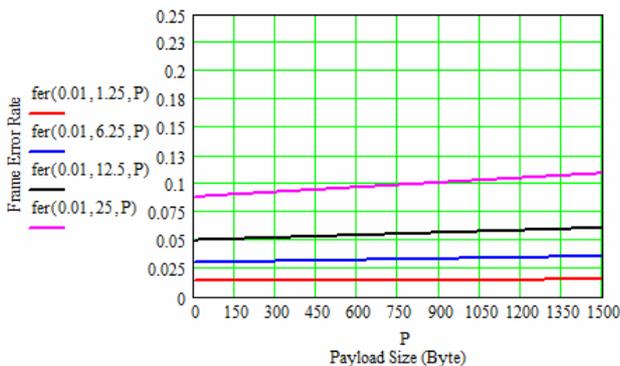
higher FER is. In case of payload size, the same result mentioned above is also acquired.



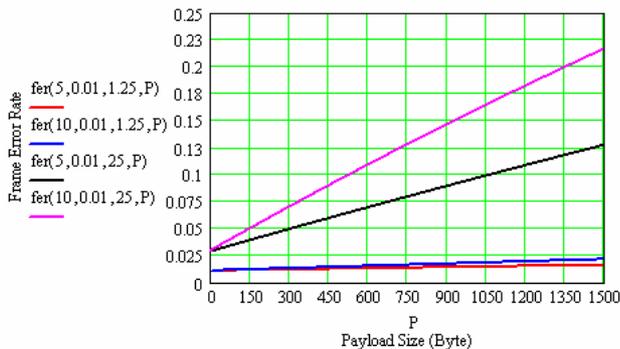
(a) IEEE 802.11a OFDM (54 Mbps)



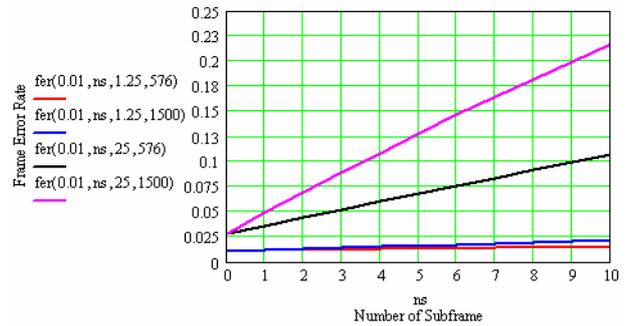
(b) IEEE 802.11g ERP-OFDM (54 Mbps)



(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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