Journal of the Korean Institute of Industrial Engineers
Vol. 33, No. 3, pp. 381-392, September 2007.

802.11 Ad Hoc LANs with Realistic Channels : Study of Packet Fragmentation

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In this paper, we present an analytical method for estimating the saturation throughput of an 802.11 ad hoc LAN in the presence of noise distorting transmitted frames. This is the first method that allows studying analytically the 802.11 network performance with consideration of correlated channel failures usually inherent to realistic wireless channels. With the study, we consider the possible packet fragmentation that can be adopted to reduce the performance degradation caused by noise-induced distortions. In addition to the throughput, our method allows estimating the probability of a packet rejection occurring when the number of packet transmission retries attains its limit. The obtained numerical results of investigating 802.11 LANs by the developed method are validated by simulation and show high estimation accuracy as well as the method efficiency in determining the optimal fragmentation threshold.

Keywords: Packet Fragmentation, 802.11 Ad Hoc Network, Correlated Channel Failures

1. Introduction

IEEE 802.11 is one of the most popular technologies for wireless ad hoc and mobile networking. The fundamental access mechanism in the IEEE 802.11 protocol is the Distributed Coordination Function (DCF), which implements the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method.

Under the DCF, data packets are transferred in general via two methods. With the Basic Access mechanism, a station confirms the successful reception of a DATA frame by a positive acknowledgment ACK after a Short InterFrame Space (SIFS). The optional Request-To-Send/Clear-To-Send (RTS/CTS) mechanism, where an inquiring RTS frame and a granting CTS frame anticipate the DATA transmission, is not considered in the paper, since previous studies Anastasi and Lenzini (2000), Lyakhov and Vishnevsky (2005), and Vishnevsky and Lyakhov (2002) have shown that it is efficient only in rare cases, when the number of active stations is very large (>20). After a packet transfer attempt, the station passes to the backoff state after a DCF Inter-Frame Space (DIFS) if the attempt was successful or after an Extended InterFrame Space (EIFS) if the attempt failed. Further, we use the notation δ, δ_d and δ_e for SIFS, DIFS, and EIFS intervals.

After a station has passed to the backoff state, its backoff counter is reset to the initial value b, which is called the backoff time, measured in units of backoff slots of duration σ, and chosen uniformly from a set $\{0, \cdots, w, -1\}$. The value w, called the contention window, depends on the number n_r of attempts performed for transmitting the current packet:

$$w = W(n_r) = \begin{cases} W_o 2^{n_r} & \text{for } n_r \le N_r \\ W_{\max} & \text{for } n_r > N_r. \end{cases} \quad (1)$$

This work was supported by grant No. R01-2006-000-10668-0 from the Basic Research Program of the Korea Science & Engineering Foundation
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Received May 2007; revision received July 2007; accepted July 2007.

Backoff counting stops when the channel becomes busy. When the channel becomes free, the station resumes counting the backoff after δ_d or δ_e. When the backoff counter attains its zero value, the station starts transmission. Collisions happen when two or more stations starts their transmissions simultaneously.

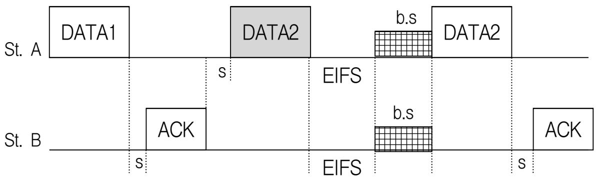

Figure 1. Fragmented Packet Transmission: DATA 1 and DATA 2 frames contains successive fragments (s-SIFS, b.s-backoff slots)

For reducing the influence of noise, the 802.11 standard (Xi *et al*. (2006)) recommends subdividing a packet longer than a fragmentation threshold L_f into fragments of size L_f (except for the last fragment). Thus, a packet is transferred as a continuous chain of DATA frames, which contain sequential fragments and are interspaced with ACK frames and SIFS intervals (see <Figure 1>). In the course of transmission of a current fragment, the transmitting station counts the number n_s of retries that is limited by N_s, and the related packet is rejected when n_s attains the limit. After the rejection or success of a packet transmission, the next packet is chosen with the values of n_r and n_s equal to 0. Notice that, in contrary to the n_r-counter referring to a whole packet, the n_s-counter refers to a fragment and is zeroed after the fragment transmission success.

If a fragment (DATA 2 in <Figure 1>) or an ACK frame is distorted, the station passes to the backoff state, advancing the retry counters n_r and n_s by one, and thereafter the packet transmission is resumed precisely with this distorted fragment. Thus, the transmission of a packet can be considered as a transfer of one or several continuous chains of frames (there are two chains in <Figure 1>), and these chains are separated by backoff intervals. Only the DATA frame being the first in a chain can be involved into collisions, while subsequent DATA frames as well as all ACK frames are not affected by collisions, because all other stations hear the transmission of previous DATA and ACK frames and defer from their attempts.

In early studies, the DCF performance was evaluated either by simulation (e.g., Anastasi and Lenzini, 2000) or by approximate analytical models (Chhaya and Gupta, 1997; Ho and Chen, 1996) based on assumptions simplifying considerably the DCF access rules. The DCF was studied in depth in Bianchi (2000), Bruno *et al*. (2001), Cali *et al*. (2000), Tay and Chua (2001) and Velkov and Spasenovski (2003), where analytical methods were developed for evaluating the performance of 802.11 wireless LANs in the saturation conditions, when there are always queues for transmitting at every wireless LAN station. This performance index called the saturation throughput was evaluated in Bianchi (2000) with the assumption of ideal channel conditions, i.e., in the absence of noise, causing the throughput overestimation. There may be different noise sources in realistic channels: other devices located in the LAN neighborhood and operating on the same license-free frequency band, multi-path fading, co-/adjacent channel interference, etc. (Detail arguing of noise sources can be found in Willig *et al*. (2002), for example.) Recently, IEEE 802.11 DCF performances under error-prone channel are studied in Chatzimisios and Vitsas (2004), Chien and Lettieri (1999), Fethi (2005), He *et al*. (2002), Kim *et al*. (2005), Lyakhov and Vishnevsky (2003, 2004 and 2005), Nadeem and Agrawala (2004), Ni *et al*. (2005), Tourrihes (2001), Velkov and Spasenovski (2003), Vishnevsky and Lyakhov (2002), Wang and Moayeri (1995), Willig *et al*. (2002), Xi *et al*.(2006), Yeo and Agrawala (2003), and Yin *et al*. (2004). These studies show that the channel noise degrades the network throughput. To improve the transmission reliability in hostile wireless channel, IEEE 802.11 standard recommends fragmenting a long Medium Access Control (MAC) service data unit (MSDU) into smaller MAC protocol data units (MPDUs) since the probability of successful transmission increases as the size of MPDU decreases. This process is called fragmentation. However, there is no explicit specification to choose an optimal fragment size in the current standard. There are only a few works on performance evaluation of IEEE 802.11 DCF fragmentation and a few efforts about optimal fragment size or adaptive fragmentation: see Fethi (2005), Kim *et al*. (2005), Lyakhov and Vishnevsky (2003, 2004 and 2005), Nadeem and Agrawala (2004), and Tourrihes (2001). Moreover, a few of them consider both collision and channel error.

Previous analytical methods developed in Chatzimisios and Vitsas (2004), Fethi (2005), He *et al*. (2002), Kim *et al*. (2005), Lyakhov and Vishnevsky (2003, 2005), Nadeem and Agrawala (2004), Ni *et al*. (2005), Tourrihes (2001), Velkov and Spasenovski (2003), Vishnevsky and Lyakhov (2002), and Yin *et al*. (2004) to study the influence of noise on the 802.11 LAN performance assume channel failures (that is, noise-induced distortions) uncorrelated, for instance, in case of a channel adding white Gaussian noise. However, it is known (e.g., see Wang and Moayeri, 1995; Zorzi and Rao, 1997) that a wireless link behavior is better characterized by the Gilbert (1960) representing a two-state Markov chain. There are Good and Bad states, which differ in the Bit Error Rate (BER) being constant in each state. Obviously, according to the model, channel failures caused by noise influence are correlated, and this correlation makes hard the 802.11 network performance analysis, forcing previous investigators of the problem to adopt simulation (see Bruno *et al*.(2001), Chien and Lettieri (1999) and Yeo and Agrawala (2003), for instance). Nevertheless, in Lyakhov and Vishnevsky (2004), we have first succeeded in studying analytically the performance of the 802.11 network with correlated channel failures, assuming that stochastic sojourn times in Bad and Good states are exponentially distributed. In Lyakhov and Vishnevsky (2004), only homogeneous case is considered, when all wireless links in the LAN stations experience the same BER. However, the farther a packet receiver is located from a noise source, the less the BER is. This paper extends the analysis in Lyakhov and Vishnevsky (2004), considering a heterogeneous case, when wireless links are characterized with different BERs and different packet length distribution.

Further, in Sections 2-4, we study a fragmented packet transmission process in an 802.11 ad hoc LAN with correlated channel failures and develop a novel analytical method of estimating the saturation throughput and the probability of a packet rejection occurring when the number of packet transmission retries attains its limit. In Section 5, we give some numerical research results of 802.11 LAN performance evaluation. These results obtained by both our analytical method and simulation allow us to validate the developed method and to show how the correlation of channel failures affects the LAN performance and packet fragmentation efficiency. Finally, the obtained results are summarized in Section 6.

2. Throughput Evaluation

Let us consider a small-size 802.11 ad hoc LAN of N stations working in saturation. In fact, we mean by N not a number of all stations of the LAN, but a number of active stations, whose queues are not empty for a quite long observation interval. Since the distance between ad hoc LAN stations is usually small, we neglect the propagation delay and assume that there are no hidden stations and noise occurs concurrently at all stations. The assumption implies that all stations "sense" the common wireless channel identically.

In our study, we consider two cases. In the simplest Homogeneous case (Hom-case): (i) the lengths of packets (in bytes) chosen by every station from the queue have an identical probability distribution $\{d_l, l=1,\cdots,L\}$; (ii) all stations use the same fragmentation threshold L_f. In the most generic Heterogeneous case (Het-case): (i) a packet chosen by station x from its queue is destined for station y with probability K_{xy}; (ii) for a wireless link (x, y) where x is a packet transmitter and y is a receiver, packet length probability distribution is $\{d_l^{xy}, l=1,\cdots, L\}$; (iii) stations use different fragmentation thresholds L_{fx}.

We assume there is a strong interference source common for all stations of the LAN. So to describe the channel state change, we adopt the Gilbert model (1960) modified as follows: the channel stays in state $i\,(i=0,1)$ during an exponentially distributed time interval with parameter λ_i. The channel states differ in BER values. In the Het- case, a distance from the interference source to the LAN stations is comparable with distances between the stations, so BERs are different for different wireless links. In the Hom-case, the source is quite far from all the stations, and we can assume the same BER for all wireless links.

More precisely, in state i, for wireless link (x, y), BER is equal to $\mu_{ih}^{xy}/8$ and $\mu_i^{xy}/8$ (that is, μ_{ih}^{xy} and μ_i^{xy} are Byte Error Rates) with transmitting a PHY h-byte header and the other frame part, respectively, and an $h+f$-byte frame transmitted entirely with the channel state i is distorted with probability $1-\exp\{-\mu_{ih}^{xy}h-\mu_i^{xy}f\}$. (Further, we will omit indices x and y with considering the Hom-case.) We have to adopt different BERs, since PHY headers are usually transmitted with a lower channel rate, but more reliable coding and modulation scheme. The channel state change rates λ_0 and λ_1 are assumed to be not too high, so that no more than one state change can happen during a frame transmission or an interframe space.

As in Bianchi (2000) and Lyakhov and Vishnevsky (2005), let us subdivide the time of the LAN operation into non-uniform virtual slots such that every station changes its backoff counter at the start of a virtual slot and can begin transmission if the value of the counter becomes zero. Such a virtual slot is either (a) an "empty" slot in which no station transmits, or (b) a "successful" slot in which one and only one station transmits, or (c) a "collisional" slot in which two or more stations transmit. As in Bianchi (2000) and Lyakhov and Vishnevsky (2005), we assume that the probability that a station x starts transmitting a packet in a given slot does not depend neither on the previous history, nor on the behavior of other stations, and is equal to τ_i^x, which depends only on the current channel state i. Hence the probabilities that an arbitrarily chosen virtual slot starting, when the channel is in state i, is "empty" (p_e^i), "successful" (p_s^i), or "collisional" (p_c^i) are

$$p_e^i=\prod_{x=1}^{N}(1-\tau_i^x),\ p_s^i=\sum_{x=1}^{N}p_s^{ix},$$
$$p_s^{ix}=\tau_i^x\prod_{z\neq x}(1-\tau_i^z), \tag{2}$$

for the Het-case (where p_s^{ix} is the probability of station x's success in the slot), and

$$p_e^i=(1-\tau_i)^N,\ p_s^i=N\tau_i(1-\tau_i)^{N-1}, \tag{3}$$

for the Hom-case, while

$$p_c^i=1-p_e^i-p_s^i. \tag{4}$$

With every packet transmission attempt, a chain of data frames is tried to be transferred, the first frame of the chain containing the first fragment which has not been transferred correctly yet. So let us associate every packet transmission attempt starting, when the channel is in state i, with a pair (l,k), where l is the length (in bytes) of the packet which the chain is related to and k is the number of the packet fragments remaining to be transferred, and call it as (i,l,k)-attempt. Let d_{lk}^{ixy} be the probability that an arbitrarily chosen packet transmission attempt carried out by station x when the channel is in state i is an (i,l,k)-attempt destined for station y.

The throughput S is defined as the average number of successfully transferred payload bits per second. Obviously,

$$S=\sum_{i=0}^{1}\Psi_i S_i \tag{5}$$

where S_i is the throughput observed when the channel is in state i and $\Psi_i=\lambda_{i^*}/(\lambda_0+\lambda_1)$ is the time fraction that the channel spends in state i. (Here and in what follows, $i^*=1$ with $i=0$ and $i^*=0$ with $i=1$).

Note that we should count the transferred payload bits only after a successful completion of transmitting a whole packet, but not after each fragment transmission, because a packet transmission process can end with the packet rejection in spite of the fact that some fragments of the packet can be transferred successfully. Thus, similarly to Lyakhov and Vishnevsky(2003, 2004, 2005), the throughput S_i is determined by the formula

$$S_i=\frac{1}{T_{sl}^i}\sum_{x=1}^{N}\sum_{y\neq x}\sum_{l=1}^{L}\sum_{k=1}^{K_x(l)}8p_s^{ix}\,l\,Q_{i0}^{xy}(l,k)\,d_{lk}^{ixy} \tag{6}$$

where $T_{sl}^i=p_e^i\sigma+p_s^iT_s^i+p_c^iT_c^i$, T_s^i and T_c^i are the mean durations of a virtual slot, the "successful" and "collisional" slots, respectively, starting when the channel is in state i. $K_x(l)$ is the number of fragments, which the packet of length l is subdivided to, and equal to the minimal integer not less than l/L_{fx}. $Q_{i0}^{xy}(l,k)$ is the probability that an (i,l,k)-attempt carried out in a "successful" slot completes successfully the whole packet transmission from x to y.

3. Slot Durations

The duration of the "collisional" slot is the sum of the transmission time of the longest frame involved in the collision and the EIFS. Let $t_d(r) = H + H_{MAC} + 8r/V$ be the transmission time of a DATA frame including a fragment of length r and PHY and MAC headers transmitted in time H and H_{MAC}, respectively, where V is the channel rate (in bits per a second) adopted for all frame parts except of the PHY header transmitted with rate V_h. Then the duration of a collision, where exactly *m* stations are involved in, is equal to $t_d(r) + \delta_e$ if (and only if): (i) each of these stations tries transmitting a fragment of length $r_0 \in \{1, \cdots, r\}$, and (ii) at least one of these stations transmits a fragment of length r. In the Hom-case, the mean duration T_c^{im} of such collisions starting, when the channel is in state i, is:

$$T_c^{im} = \sum_{r=1}^{L_f} [t_d(r) + \delta_e][D(r, i)^m - D(r-1, i)^m], \quad (7)$$

where $D(r, i)$ is the probability that a chain with the first fragment of length $r_o \le r$ is transferred in the current attempt, i.e., $D(L_f, i) = 1$ and

$$D(r, i) = \sum_{h=1}^{r} \sum_{k=0}^{k_{\max}(r)} d^i_{kL_f + r, 1}$$

with $r < L_f$. [Here $k_{\max}(r)$ is the integer part of the ratio $(L-r)/L_f$.]

Since

$$\pi_{im}^N = \binom{N}{m} (\tau_i)^m (1-\tau_i)^{N-m}$$

is the probability that exactly m of N stations transmit in a slot starting when the channel is in state i, we obtain the following formula for the mean duration of a "collisional" slot:

$$T_c^i = \delta_e + (p_e^i)^{-1} \sum_{r=1}^{L_f} t_d(r) \{\alpha_i^N(r) - \alpha_i^N(r-1) - p_s^i [D(r, i) - D(r-1, i)]\} \quad (8)$$

where $\alpha_i^N(r) = \{1 - \tau_i[1 - D(r, i)]\}^N$.

In the Het-case, we neglect probabilities of collisions which three or more stations are involved in. We have:

$$T_c^i = \delta_e + \frac{\sum_{x, z, z \neq x} \tau_x^i \tau_z^i T_c^{ixz}}{\sum_{x, z, z \neq x} \tau_x^i \tau_z^i},$$

where $T_c^{ixz} + \delta_e$ is the mean duration of a collision of stations x and z. Let $L_{fx} \ge L_{fz}$, then

$$T_c^{ixz} = \sum_{r = L_{fz}+1}^{L_{fz}} \hat{d}^i_{rx} t_d(r) + \sum_{r=1}^{L_{fz}} t_d(r) \times \left[\hat{d}^i_{rx} \hat{d}^i_{rz} + \hat{d}^i_{rx} \sum_{r'=1}^{r-1} \hat{d}^i_{r'z} + \hat{d}^i_{rz} \sum_{r'=1}^{r-1} \hat{d}^i_{r'x}\right]$$

where $\hat{d}^i_{rx}$ is the probability that the length of the first fragment transmitted by station *x* with channel state *i* is equal to r:

$$\hat{d}_{rx} = \sum_{y \neq x} \sum_{k=0}^{k_{\max}(x, r)} d^{xy}_{kL_{fx}+r, 1}, \qquad r \le L_{fx},$$

$$\hat{d}_{L_{fx}x} = 1 - \sum_{r=1}^{L_{fx}-1} \hat{d}_{rx}$$

where $k_{\max}(x, r)$ is the integer part of the ratio $(L-r)/L_{fx}$.

Now we study a "successful" slot starting when the channel is in state i. At the beginning of this slot, only one station *x* makes an attempt of transmission to a station y, which is an (i, l, k)-attempt with probability d_{lk}^{ixy}. This attempt is concluded successfully, i.e., with successful transfer of a whole packet of length l, with probability $Q_{i0}(l, k)$ if none of the frames exchanged between the sender and receiver in this process is distorted by noise, that is,

$$T_s^i = \sum_{y \neq x} \sum_{l=1}^{L} \sum_{k=1}^{k_x(l)} d_{lk}^{ixy} T_x(l, k) Q_{i0}^{xy}(l, k) + \sum_{y \neq x} \sum_{l=1}^{L} \sum_{k=1}^{k_x(l)} d_{lk}^{ixy} \sum_{m=1}^{k} T_{ixy}^e(l, k, m) [Q_{ii}^{mxy}(l, k) + Q_{ii^*}^{mxy}(l, k)], \quad (9)$$

where

$$T_x(l,\, k) = (k-1)[t_d(L_{fx}) + \delta] + kt_{ACK} + t_d(r_l^0) + \delta_d$$

is the average duration of successful $(i,\, l,\, k)$-attempt of station x, t_{ACK} is the ACK transmission time, and r_l^0 is the length of the last fragment.

$$T_{ixy}^e(l,\, k,\, m) = (m-1)[t_d(L_{fx}) + t_{ACK}\,\delta] + t_d(r_{lk}^m) \\ + (t_{ACK} + \delta)\Theta_{ixy}^a(l,\, k,\, m) + \delta_e$$

is the “successful” slot average duration taken under the condition that the first $m-1\,(m < k)$ fragments of the packet remainder were transmitted successfully, while the m-th fragment which length is r_{lk}^m fails. $Q_{ii^*}^{mxy}(l,\, k)$ and $Q_{ii}^{mxy}(l,\, k)$ are the probabilities that the condition holds and the channel state changes or does not after the slot completion. [Here and further, we determine the probabilities separately for cases of changing (subscript “ii^*”) and not changing (subscript “ii”) the channel state.] At last, $\Theta_{ixy}^a(l,\, k,\, m)$ is the probability that the failure happens just because of the last ACK frame distortion. Let us find these probabilities.

A transmission of a frame of length f bytes (including the h_{MAC}-byte MAC header), which starts when the channel is in state i, is completed successfully with probabilities

$$v_{ii}^{0xy}(f) = \exp\{-\lambda_i(H + f/V) - \mu_{ih}^{xy}h - \mu_i^{xy}f\}$$
and

$$v_{ii^*}^{0xy}(f) = e^{-\mu_{i^*}^{xy}f}\, I_i^h + e^{-\mu_{ih}^{xy}h - \lambda_i H}\, I_i(f),$$

where

$$I_i^h = \int_0^H \lambda_i\, e^{-\lambda_i t} \exp\{-V_h[\mu_{ih}^{xy}\, t + \mu_{i^*h}^{xy}(H-t)]\}\, dt,$$

that is,

$$I_i^h = e^{-\mu_{i^*h}^{xy}h}\, \frac{\lambda_i H}{\lambda_i H + h(\mu_{ih}^{xy} - \mu_{i^*h}^{xy})} \times \\ [1 - e^{-\lambda_i H - h(\mu_{ih}^{xy} - \mu_{i^*h}^{xy})}]$$

with $\lambda_i H \neq h(\mu_{i^*h}^{xy} - \mu_{ih}^{xy})$ and $I_i^h = \lambda_i H e^{-\mu_{i^*h}^{xy}h}$ otherwise. $I_i(f)$ is similarly defined with the substitution of f for h, f/V for H, and μ_i^{xy} and $\mu_{i^*}^{xy}$ for μ_{ih}^{xy} and $\mu_{i^*h}^{xy}$, respectively. The transmission fails with probabilities

$$v_{ii}^{1xy}(f) = \exp\{-\lambda_i(H + f/V)\} \times \\ [1 - \exp\{-\mu_{ih}^{xy}h - \mu_i^{xy}f\}]$$

and

$$v_{ii^*}^{1xy}(f) = 1 - v_{ii}^{0xy}(f) - v_{ii^*}^{0xy}(f) - v_{ii}^{1xy}(f)$$

Now let us consider the process of transmitting a fragment of length *r*, including the possible ACK frame reception in response. Let the process start when the channel is in state *i*. Then it succeeds with probabilities

$$\eta_{ii}^{0xy}(r) = v_{ii}^{0xy}(f_r)[\gamma_i v_{ii}^{0yx}(l_{ACK}) + \overline{\gamma}_i v_{i^*i}^{0yx}(l_{ACK})] \\ + v_{ii^*}^{0xy}(f_r)[\gamma_{i^*} v_{i^*i}^{0yx}(l_{ACK}) + \overline{\gamma}_{i^*} v_{ii}^{0yx}(l_{ACK})]$$

and

$$\eta_{ii^*}^{0xy}(r) = v_{ii^*}^{0xy}(f_r)[\gamma_{i^*} v_{i^*i^*}^{0yx}(l_{ACK}) + \overline{\gamma_{i^*}}\, v_{ii^*}^{0yx}(l_{ACK})] \\ + v_{ii}^{0}(f_r)[\gamma_i\, v_{ii^*}^{0xy}(l_{ACK}) + \overline{\gamma}_i\, v_{i^*i^*}^{0xy}(l_{ACK})]$$

where $f_r = r + h_{MAC}$, $\gamma_i = 1 - \overline{\gamma_i} = \exp\{-\lambda_i\delta\}$, and l_{ACK} is the ACK length. The process fails with probabilities

$$\eta_{ii}^{1xy}(r) = v_{ii}^{1xy}(f_r) + v_{ii}^{0xy}(f_r)[\gamma_i v_{ii}^{1yx}(l_{ACK}) \\ + \overline{\gamma}_i v_{i^*i}^{1yx}(l_{ACK})]$$
and

$$\eta_{ii^*}^{1xy}(r) = 1 - \eta_{ii}^{0xy}(r) - \eta_{ii^*}^{0xy}(r) - \eta_{ii}^{1xy}(r).$$

Note that the process fails because of DATA distortion with probabilities $v_{ii}^{1xy}(f_r)$, if the channel state does not change, and $v_{ii^*}^{1xy}(f_r)$, if the channel passes from state i to i^*.

Now we can find the sought probabilities $Q_{ii^*}^{mxy}$, Q_{ii}^{mxy} and Θ_{ixy}^a:

$$Q_{ii}^{mxy}(l,\, k) = \beta_{ii}^{(m-1)xy}[\eta_{ii}^{1xy}(r_{lk}^m)\gamma_i^e + \eta_{ii^*}^{1xy}(r_{lk}^m)\overline{\gamma}_{i^*}^e] \\ + \beta_{ii^*}^{(m-1)xy}[\eta_{i^*i^*}^{1xy}(r_{lk}^m)\overline{\gamma}_{i^*}^e + \eta_{i^*i}^{1xy}(r_{lk}^m)\gamma_i^e],$$

$$Q_{ii^*}^{mxy}(l,\, k) = \beta_{ii}^{(m-1)xy}[\eta_{ii}^{1xy}(r_{lk}^m)\overline{\gamma}_i^e + \eta_{ii^*}^{1xy}(r_{lk}^m)\gamma_{i^*}^e] \\ + \beta_{ii^*}^{(m-1)xy}[\eta_{i^*i^*}^{1xy}(r_{lk}^m)\gamma_{i^*}^e + \eta_{i^*i}^{1xy}(r_{lk}^m)\overline{\gamma}_i^e],$$

$$\Theta_{ixy}^a(l,\, k,\, m) = 1 - \frac{\Theta_{ii}^{mxy}(l,\, k) + \Theta_{ii^*}^{mxy}(l,\, k)}{Q_{ii}^{mxy}(l,\, k) + Q_{ii^*}^{mxy}(l,\, k)},$$

where $\gamma_i^e = 1 - \overline{\gamma}_i^e = \exp\{-\gamma_i\,\delta_e\}$, $\|\beta_{iij}^{(m)xy}\| = \|\beta_{ij}^{xy}\|$, $i, j = 0, 1$, $\beta_{ii}^{xy} = \eta_{ii}^{0xy}(L_f)\,\gamma_i + \eta_{ii^*}^{0xy}(L_f)\,\overline{\gamma_{i^*}}$ and $\beta_{ii^*}^{xy} = \eta_{ii^*}^{0xy}(L_f)\,\gamma_{i^*} + \eta_{ii}^{0xy}(L_f)\,\overline{\gamma}_{i^*}$. Θ_{ii}^{mxy} and $\Theta_{ii^*}^{mxy}$ are determined similarly to Q_{ii}^{mxy} and $Q_{ii^*}^{mxy}$, substituting the appropriate functions v^{1xy} with argument $r_{lk}^m + h_{MAC}$ for all functions η^{1xy}.

At last, the probability of a successful (i, l, k) -attempt completing the whole packet transmission is obviously equal to

$$Q_{i0}^{xy}(l, k) = 1 - \sum_{m=1}^{k}\left[Q_{ii}^{mxy}(l, k) + Q_{ii^*}^{mxy}(l, k)\right],$$

and the channel appears in state i or i^* upon this attempt completion with probabilities

$$Q_{i0}^{ixy}(l, k) = \beta_{ii}^{(k-1)xy}\left[\eta_{ii}^{0xy}(r_l^0)\gamma_i^d + \eta_{ii^*}^{0xy}(r_l^0)\overline{\gamma}_{i^*}^d\right] + \beta_{ii^*}^{(k-1)xy}\left[\eta_{i^*i^*}^{0xy}(r_l^0)\,\overline{\gamma}_{i^*}^d + \eta_{i^*i}^{0xy}(r_l^0)\gamma_i^d\right]$$

and

$$Q_{i0}^{i^*xy}(l, k) = Q_{i0}^{xy}(l, k) - Q_{i0}^{ix}(l, k)$$

respectively, where $r_i^d = 1 - \overline{\gamma}_i^d = \exp\{-\gamma_i\,\delta_d\}$.

Thus, we have found all components of (10), and the throughput S can be found by (6) - (9) if the transmission beginning probabilities τ_0^x and τ_1^x and the probability distributions $\{d_{lk}^{ixy}\}$ are known.

4. Transmission Probabilities

Let f_l^{ixy} and w_l^{ixy} be the mean numbers of the packet transmission attempts and virtual slots in which the considered station defers from transmission during the process of transmitting a packet of length l by station x to station y. These attempts and slots are taken into account only if the channel is in state i at their beginnings. Then

$$\tau_i^x = \sum_{y \neq x} k_{xy} \sum_{l=1}^{L} d_l^{xy} f_l^{ixy} \Big/ \sum_{y \neq x} k_{xy} \sum_{l=1}^{L} d_l^{xy}\left(f_l^{ixy} + w_l^{ixy}\right). \tag{10}$$

To find the distribution $\{d_{lk}^{ixy}, y \neq x, l = 1 \cdots L, k = 1 \cdots K_x(l)\}$, we can use the following formula:

$$d_{lk}^{ixy} = k_{xy}\, d_l^{xy} f_{lk}^{ixy} \Big/ \sum_{z \neq x} k_{xz} \sum_{u=1}^{L} \sum_{v=1}^{K_x(u)} d_u^{xz}\, f_{uv}^{ixy} \tag{11}$$

where f_{lk}^{ixy} is the mean number of (i, l, k)-attempts carried out within the considered process.

Moreover, we can also find the averaged probability $\overline{p}_{rej}^x$ of rejecting a packet transmitted by station x, because the n_s-counter attains its limiting value N_s. This probability can be found from the following sum:

$$\overline{p}_{rej}^x = \sum_{y \neq x} k_{xy} \sum_{l=1}^{L} d_l^{xy}\, p_{rej}^{xy}(l), \tag{12}$$

where $p_{rej}^{xy}(l)$ is the probability of rejecting a packet of length l during its transmission from x to y.

Further in this section, we study the process of transmitting a packet of length l by station x to station y. This process starts when the packet is chosen from the queue and ends with either the successful transmission of the packet or its rejection. Since (x, y) couple is fixed for the considered transmission process, we omit the related indices, where it is possible.

Let us start with looking for f_l^i. We can write it in the following form:

$$f_l^i = \sum_{i_s=0}^{1} \Psi_{i_s}^p\, F_l^i[i_s, K(l), 0, 0] \tag{13}$$

where $\Psi_{i_s}^p$ is the probability that the packet transmission process starts when the channel is in the initial state i_s, and it is easy to show that

$$\Psi_i^p = (1 - \Phi^{i^*})/(2 - \Phi_0 - \Phi_1) \tag{14}$$

where Φ_i is the probability that, at the end of a packet transmission process, the channel appears in the same state i as at the process beginning.

Function $F_l^i(i_s, k, n_r, n_s)$ represents the mean number of the packet transmission attempts that remain to be performed under the following conditions:

(i) k fragments remain to be transferred;
(ii) the station has just passed to the backoff state with the contention window equal to $W(n_r)$;
(iii) at the moment, the channel is in state i_s; and
(iv) the value of n_s-counter is n_s.

Obviously, the function is calculated recursively:

$$F_l^i(l_s,\, k,\, n_r,\, n_s) = \sum_{j=0}^{1} q_j\,[n_r,\, i_s] \times \Big\{ f_0^{ij} + 1(n_s < N_s) \sum_{u=0}^{1} [p_j^{cc}\, Q_{ju}^{c}\,(t_{lk}^{cj}) + \overline{p}_j^{cc}\, Q_{ju}^{1}\,(l,\,k)]\, F_l^i(u,\,k,\,n_r^*,\,n_s+1) + 1(k>1) \times \sum_{m=2}^{k} \overline{p}_j^{cc}\, Q_{ju}^{m}\,(l,\,k)\, F_l^i(u,\,k-m+1,\,n_r^*,\,1] \Big\} \quad (15)$$

where $n_r^* = n_r + 1$ with $n_r < N_r$ and $n_r^* = N_r$ otherwise. Here and in what follows, we use the Boolean function 1(condition) which takes the value 1 if the condition within brackets holds.

Moreover, in (15), $f_0^{ij} = 1(i=j)$, $p_j^{cc} = 1 - \overline{p}_j^{cc}$, is the probability of the current attempt failure due to a collision, during which the channel passes from state j to state u with probability $Q_{ju}^c\,(t_{lk}^{cj}) = 1 - Q_{jj}^c(t_{lk}^{cj})$, where

$$Q_{jj}^c(t) = \overline{\gamma}_u^e + (1 - \overline{\gamma}_u^e / \gamma_j^e)\exp\{-\lambda_j\, t\}$$

and t_{lk}^{cj} is the mean duration of this collision. For the Hom-case, $p_j^{cc} = 1 - \overline{p}_j^{cc} = 1 - (1-\tau_j)^{N-1}$ and t_{lk}^{cj} is determined similarly to (5)-(7):

$$t_{lk}^{cj} = \delta_e + (p_j^{cc})^{-1} \sum_{m=1}^{N-1} \pi_{jm}^{N-1}\, \hat{t}_{lk}^{\,cjm},$$

where

$$\hat{t}_{lk}^{\,cjm} = t_d(r_{lk}^1)[D(r_{lk}^1,\, j)]^m + \sum_{r=r_{lk}^1+1}^{L_f} t_d(r) \times \{[D(r,\,j)]^m - [D(r-1,\,j)]^m\}$$

is the mean duration of such collision, where exactly m of other $N-1$ stations collide with the considered stations. After transformations, we have

$$t_{lk}^{cj} = \delta_e + \frac{t_d(r_{lk}^1)}{p_j^{cc}}\,[\alpha_j^{N-1}(r_{lk}^1) - \overline{p_j^{cc}}] + (p_j^{cc})^{-1} \times \sum_{r=r_{lk}^1+1}^{L_f} t_d(r)[\alpha_j^{N-1}(r) - \alpha_j^{N-1}(r-1)].$$

In the Het-case,

$$p_j^{cc} = 1 - \prod_{z \neq x} (1 - \tau_j^z)$$

and

$$t_{lk}^{cj} = \delta_e + \frac{\sum_{z \neq x} \tau_j^z\, T_c^{jxz}}{\sum_{z \neq x} \tau_j^z}.$$

At last, $q_j[n_r,\, i_s]$ is the probability that the channel appears in state j upon completion the backoff time of the considered station, which current contention window is $W(n_r)$, and this probability is taken under the condition that the channel was in state i_s at the beginning of the backoff. It is easy to show that

$$q_j[n_r,\, i_s] = \frac{1}{W(n_r)} \sum_{b=0}^{W(n_r)-1} p_{i_s j}^{(b)},$$

where $\|p_{ij}^{(b)}\| = \|p_{ij}\|^b$, $i,\, j = 0,\, 1$, and p_{ij} is the probability that the channel passes from state i to j for a virtual slot, during which the given station *x* does not transmit. Obviously,

$$p_{ii} = 1 - p_{ij} = \hat{p}_e^{\,i}\, e^{-\lambda_i \sigma} + \hat{p}_c^{\,i}\, Q_{ii}^c\,(\hat{T}_c^i) + \hat{p}_s^{\,i}\, Q_s^{ii},$$

where $\hat{p}_e^{\,i}$, $\hat{p}_s^{\,i}$, $\hat{p}_c^{\,i}$, and $\hat{T}_c^i$ are defined similarly to p_e^i, p_s^i, p_c^i, and T_c^i. In particular, in the Hom-case, we just substitute $N-1$ for N. Moreover,

$$Q_s^{ii} = \sum_{l=1}^{L} \sum_{k=1}^{K(l)} d_{lk}^i \left[Q_{i0}^i\ (l,\,k) + \sum_{m=1}^{k} Q_{ii}^m\,(l,\,k) \right]$$

is the probability that the channel does not change its state during a “successful” slot.

In the Het-case,

$$\hat{p}_e^{\,i} = \prod_{x' \neq x}^{N} (1 - \tau_i^{x'}),\ p_s^i = \sum_{x' \neq x}^{N} p_s^{ix'},$$

$$p_s^{ix'} = \tau_i^{x'} \prod_{z \neq x',x} (1 - \tau_i^z),$$

$$\hat{T}_c^{\,i} = \delta_e + \frac{\sum_{x' \neq x,\, z \neq x,\, x'} \tau_{x'}^i\, \tau_z^i\, T_c^{ix'z}}{\sum_{x' \neq x,\, z \neq x,\, x'} \tau_{x'}^i\, \tau_z^i}$$

and

$$Q_s^{ii} = \sum_{x' \neq x} \frac{\hat{p}_s^{\,ix'}}{\hat{p}_s^{\,i}} \sum_{y' \neq x,x'} \sum_{l=1}^{L} \sum_{k=1}^{K_{x'}(l)} d_{lk}^{ix'y'} \times \left[Q_{i0}^{ix'y'}(l,\,k) + \sum_{m=1}^{k} Q_i^{mx'y'}(l,\,k) \right].$$

To find w_l^i, f_{lv}^i, and $p_{rej}(l)$, we can also adopt formula (13), using functions $\overline{W}_l^i[i_s, K(l), 0, 0]$, $\overline{F}_{lv}^i[i_s, K(l), 0, 0]$ and $R_l[i_s, K(l), 0, 0]$, respectively, instead of $F_l^i(\cdot)$, while

$$\Phi_i = \sum_{l=1}^{L} d_l\, \phi_l^i\, [i, K(l), 0, 0]. \quad (16)$$

Functions $\overline{W}_l^i(\cdot)$, $\overline{F}_{lv}^i(\cdot)$, $R_l(\cdot)$, and $\phi_l^i(\cdot)$ with arguments i_s, k, n_r, and n_s are defined, in turn, by (15) modified as follows :

1) For $\overline{W}_l^i(\cdot)$, f_o^{ij} is excluded and the item $w_{i_s}^i(n_r) = \sum_{b=1}^{W(n_r)-1} \frac{W(n_r)-b}{W(n_r)}\, p_{i_s i}^{(b-1)}$ starts the right part of (15).
2) For $\overline{F}_{lv}^i(\cdot)$, we substitute $f_1^{ij}(k, v) = 1(i=j)1(k=v)$ for f_0^{ij} and the operator $1(k>v)$ for $1(k>1)$.
3) For $R_l(\cdot)$, we replace f_0^{ij} by $r_0^j(l, k, n_s) = 1(n_s = N_s - 1)\{p_j^{cc} + \overline{p}_j^{cc}[\eta_{jj}^1(r_{lk}^1) + \eta_{jj*}^1(r_{lk}^1)]\}$
4) For $\phi_l^i(\cdot)$, f_0^{ij} is replaced by $\phi_0^{ij}(l, k, n_s) = \overline{p}_j^{cc} Q_{j0}^i(l, k) + 1(n_s = N_s - 1)\{p_j^{cc} Q_{ji}^c(t_{lk}^{cj}) + \overline{p}_j^{cc} Q_{ji}^1(l, k)\}$.

Thus, we can calculate the throughput S and the averaged packet rejection probability $\overline{p}_{rej}$. In particular, in the Hom-case, we use the following iterative procedure. Firstly, we calculate $Q_{ij}^m(l, k)$ and $Q_{i0}^i(l, k)$ for all possible $i, j, l, k = 1, \cdots, K(l)$, and $m = 1, \cdots, k$. Then we define initial values for $\tau_i, \Psi_i^p, S, \overline{p}_{rej}$ and d_{lk}^i with all possible i, l, k and calculate their modified values by (5)~(13). If not both relative differences of initial and modified values of S and $\overline{p}_{rej}$ are less than a small pre-defined limit, then we set new initial values of $\tau_i, \Psi_i^p, S, \overline{p}_{rej}$ and d_{lk}^i equal to half-sums of their modified and old initial values and repeat the calculation. We do not prove exactly the convergence of this iterative technique due to its complexity. In practice, numerous examples of adopting the technique with various values of 802.11 ad hoc LAN parameters have shown that it provides very fast convergence to the solution and high speed of calculating the values of estimated performance indices. It takes few seconds to calculate S and $\overline{p}_{rej}$ when executing its program implementation on Intel Pentium IV 3.0 GHz.

5. Numerical Results

The object of our numerical investigations was a saturated 802.11 ad hoc LAN consisting of N stations. The values of protocol parameters used to obtain numerical results for the analytical model and simulation were the IEEE 802.11b default values for the Long Preamble mode and summarized in Table 1. Moreover, the payload size l (in bytes) was sampled uniformly from the set $\{1, \cdots, L=2000\}$. To make the numerical analysis easier and its results more tractable, we considered the Hom-case only.

To validate our model, we have compared its results with that obtained by GPSS (General Purpose Simulation System) simulation in Schriber(1974). In our simulation model, we took into account of all real features of the 802.11 MAC protocol and did not adopt the assumptions used in analytical modeling and described in Section 2. In each run (it took about an hour on the average) of the simulation model, we observed values of the measured performance indices and stopped the simulation when their fluctuations became quite small (within 0.5%).

In <Figure 2> and <Figure 3>, we present some results of studying the throughput and the averaged rejection probability with varying the BER and fixed $N = 20$. <Figure. 2b> and <Figure 3b> correspond to the case of uncorrelated channel failures, while the curves in <Figure 2a> and <Figure 3a> have been obtained for the case of correlated failures with the following channel model parameters:

Table 1. Values of Protocol Parameters

Slot time, σ	20 μs	PHY header transfer time, H	192 μs
PHY header, h	24 bytes	MAC header transfer time, H_{MAC}	25 μs
MAC header, h_{MAC}	34 bytes	Length of ACK, l_{ACK}	14 bytes
SIFS	10 μs	ACK transfer time, t_{ACK}	202 μs
DIFS	50 μs	Channel rate, V	11 Mbps
EIFS	364 μs	Minimal contention window, W_0	32
Retry limit, N_s	7	Maximal contention window, $W_{\max}$	1024

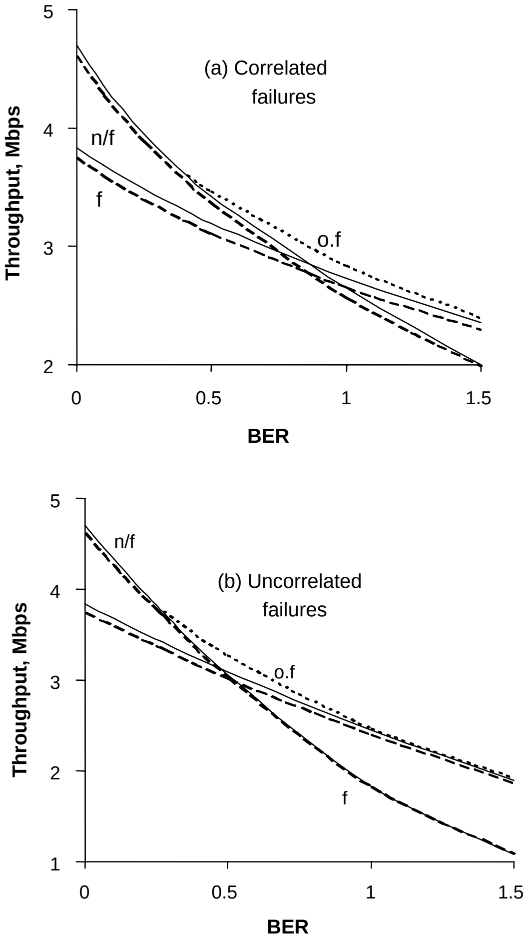

Figure 2. Throughput versus BER · 10^4

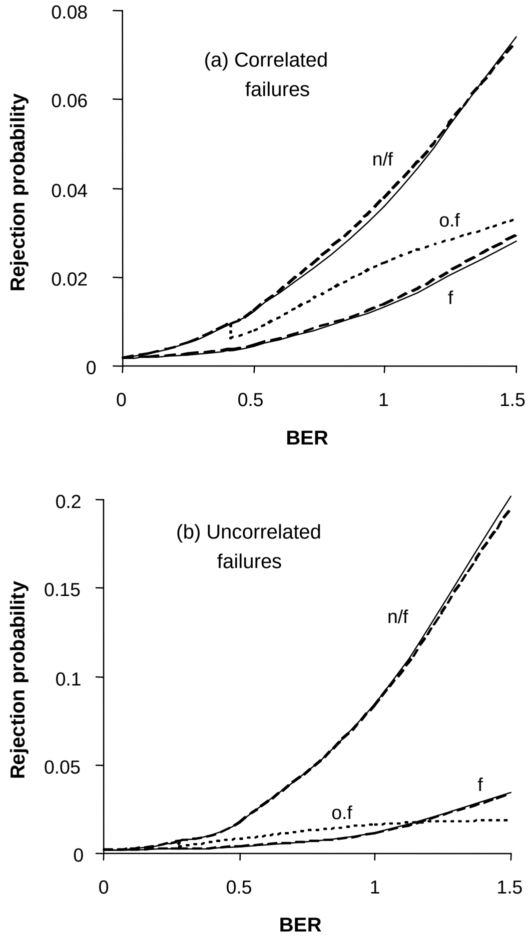

Figure 3. Rejection Probability versus BER · 10^4

$\lambda_0 = 10^{-5}$, $\lambda_1 = 5\lambda_0$, $\mu_0 = 4$ · BER, $\mu_1 = 28$ · BER. (State 0 is assumed to be the Good one.)

Here and further in the section, we study packet transmission without fragmentation (curves "n/f"), with fixed fragmentation (curves "f") when the fixed fragmentation threshold $L_f = 560$ bytes is adopted, and with optimal fragmentation (dotted curves "o.f") when the threshold is chosen optimally, using our method and depending on values of channel parameters. (The optimization criterion is the maximal throughput.) Moreover, we assume that $\mu_i^h = 0.1\mu_i$, $i = 0, 1$.

Further, we see that both throughput and rejection probability are much more sensitive to the BER growth with uncorrelated failures than with correlated ones, especially in the case of non-fragmented transmission: with very high BER = 1.5 × 10^{-4}, we have $S = 1.1$ Mbps and $\overline{p}_{rej} = 0.19$ for uncorrelated failures, and $S = 2.0$ Mbps and $\overline{p}_{rej} = 0.07$ for correlated ones. Packet fragmentation allows relaxing the noise influence and makes the performance measures shown with correlated and uncorrelated failures closer to each other: for the same high BER and the fixed fragmentation, we have $S = 1.9$ Mbps and $\overline{p}_{rej} = 0.033$ with uncorrelated failures, and $S = 2.3$ Mbps and $\overline{p}_{rej} = 0.029$ with correlated ones. The optimal fragmentation provides only slightly improving the throughput (no more than by 10% in the shown cases) with respect to the maximum of throughput values obtained with the fixed fragmentation and non-fragmented transmission.

Now let us investigate in detail how the correlation parameters affect the throughput and fragmentation efficiency.

<Figure 4> shows the throughput versus the Byte Error Rate μ_0 observed in the Good state with fixed BER = 10^{-4}, $\lambda_0 = 10^{-5}$ and $N = 5$. Families (a) and (b) of curves correspond to (a) $\lambda_1 = \lambda_0$ and (b) $\lambda_1 = 5\lambda_0$, and in each of these families, solid, dashed and dotted curves are related to non-fragmented transmission, the fixed fragmentation, and the optimal fragmentation, respectively. Comparing the con

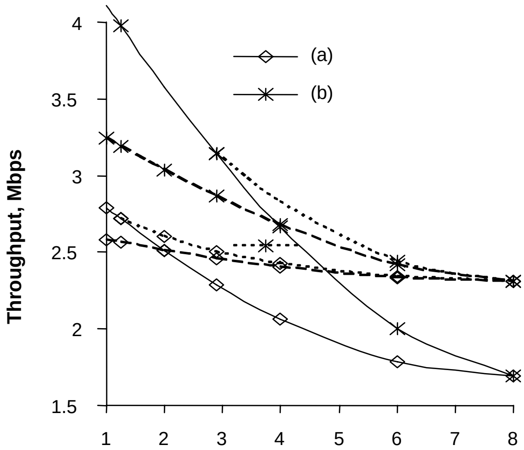

Figure 4. Throughput versus Byte Error Rate $\mu_0 \cdot 10^4$ in the Good state

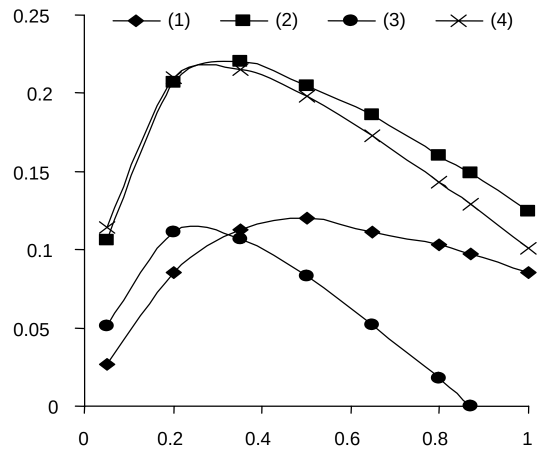

Figure 5. Fragmentation Efficiency Areas (μ_0/μ_1 versus λ_0/λ_1)

sidered cases, we see that the less Good state BER and the Bad state mean duration, the higher throughput is and fragmentation is less effective. <Figure 5> concluding this investigation shows fragmentation efficiency areas in the following cases :

(1) BER = 10^{-4}, $N = 5$, $\lambda_0 = 10^{-5}$;
(2) BER = 5×10^{-4}, $N = 5$, $\lambda_0 = 10^{-5}$;
(3) BER = 5×10^{-4}, $N = 20$, $\lambda_0 = 10^{-5}$;
(4) BER = 5×10^{-4}, $N = 5$, $\lambda_0 = 2 \times 10^{-5}$.

For each of these cases, points located upper the related curve form the fragmentation efficiency area, where fragmentation with optimally chosen threshold provides higher throughput than non-fragmented transmission. First of all, let us note that the bounding curves are not monotonic: fragmentation efficiency increases when the mean Bad state duration becomes both closer to and much less than the mean Good state duration. As we could expect, the fragmentation efficiency area widens with the BER growth [curves (1) and (2)]. Further, we see [curves (2) and (3)] that the area widens also with increasing the number *N* of active stations. At last, we should mention that a joint growth of the Good and Bad durations [curves (2) and (4)] does not much affect the fragmentation efficiency area.

6. Conclusions

In this paper, an extension of Lyakhov and Vishnevsky (2004), we have developed a novel analytical method for estimating the throughput of an 802.11 ad hoc LAN operating under saturation and in the presence of noise. This method is useful in estimating the 802.11 LAN performance indices under packet fragmentation recommended in the standard ANSI/IEEE Std 802.11 (1999) for reducing the influence of noise. Besides the throughput, our method allows evaluating the probability of a packet rejection due to attaining the retry number threshold.

Moreover, it is the first analytical method for 802.11 network performance evaluation in case of correlated failures inherent to realistic wireless channels. The failures correlation has been described with the modified two-state Gilbert model (1960), where sojourn times in each of channel states are assumed to be exponentially distributed.

According to numerical results obtained by both the developed method and simulation, our method is quite accurate: the errors never exceed 3% with throughput estimation and 6% with rejection probability estimation. This method provides a high speed of calculating the values of performance indices, which has allowed us to perform the exhaustive search of optimal fragmentation threshold and to show how the fragmentation efficiency depends on failures correlation.

As a future research activity, we propose extensions of this method to take into account a possible presence of hidden stations as well as to consider and to optimize a channel rate switching mechanism which promises to be effective in the case of correlated failures.

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