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Performance analysis of IEEE 802.11 DCF networks

Krzysztof SZCZYPIORSKI[†], Józef LUBACZ
(*Institute of Telecommunications, Warsaw University of Technology, Nowowiejska 15/19, Warsaw 00-665, Poland*)
[†]E-mail: ksz@tele.pw.edu.pl

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Abstract: This paper presents an analytical saturation throughput model of IEEE 802.11 DCF (distributed coordination function) with basic access in ad hoc mode. The model takes into account freezing of the backoff timer when a station senses busy channel. It is shown that taking into account this feature of DCF is important in modeling saturation throughput by yielding more accurate and realistic results than models known from literature. The proposed analytical model also takes into account the effect of transmission errors. All essential features of the proposed analytical approach are illustrated with numerical results. The presentation of the model is proceeded by an overview of approaches to IEEE 802.11 network performance evaluation presented in the literature.

Key words: IEEE 802.11, Distributed coordination function (DCF), CSMA/CA, Modeling
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INTRODUCTION

This paper presents an analytical saturation throughput model of IEEE 802.11 DCF (distributed coordination function), also referred to as CSMA/CA (carrier sense multiple access with collision avoidance), with basic access in ad hoc mode (IEEE 802.11, 1999). Saturation throughput is an efficiency measure of the maximum load in saturated conditions, i.e., when all stations involved in transmission have no empty queues. The 802.11 standard makes it mandatory that all stations implement the DCF. If a station wanting to send a frame senses busy channel above a specific threshold, the station wanting access will wait until the medium is idle before transmitting the frame. The collision avoidance aspect of the DCF pertains to the use of acknowledgements (ACKs) that a receiving station sends to the sending station to verify error-free reception. According to the DCF protocol, when a station senses busy channel, the backoff is suspended in effect of freezing of the station backoff timer. It is shown that taking into account this feature of DCF is important in modeling saturation throughput by yielding more accurate results than models known from literature. The proposed analytical model, based on a Markov chain, also takes into account the effect of transmission errors.

According to the authors' knowledge the first analytical model of DCF was proposed by Bianchi (2000). Bianchi proposed a Markov chain based model to evaluate saturation throughput, assuming a finite number of stations and ideal channel conditions (no errors). The model provides closed-form expressions for the saturation throughput and is based on a simple and elegant discrete-time Markov chain that describes the dynamics of the contention window of 802.11 MAC (medium access control) layer. It analyzes ad hoc and infrastructure modes, and works fine whether RTS/CTS (request to send/clear to send) is enabled or not.

Wu *et al.*(2002) modified Bianchi's model through introducing a limit on the number of retransmissions (maximum number of backoff stages) and a maximum size of the contention window according to 802.11 standard. They also proposed a new scheme named DCF+, which is compatible with DCF, to enhance the performance of reliable transport protocols (especially TCP) over 802.11. Their study includes performance of TCP over 802.11 expressed with three metrics: goodput, fairness index, and delay.

Ziouva and Antonakopoulos (2002), and probably independently Ergen and Varaiya (2005), extended Bianchi's model through taking into account freezing of the backoff timer during busy channel occurrences. In these models it is assumed that after successful transmission a station can access the medium without backoff; this assumption does not comply with the IEEE 802.11 standard. In (Ergen and Varaiya, 2005) the present analytical solution of the introduced Markov chain is erroneous (probability of state (0, 0) is calculated erroneously).

The abovementioned models assume ideal channel conditions, i.e., no transmission errors. Chatzimisios *et al.*(2003) and Ni *et al.*(2005) extended Wu's model to take account of transmission failures. In (Ni *et al.*, 2005)'s model ACK frames loss due to errors is taken into account; while in (Chatzimisios *et al.*, 2003) ACK frames loss is not considered.

In (Bianchi, 2000; Wu *et al.*, 2002; Ergen and Varaiya, 2005), RTS/CTS is considered, but without taking into account the two independent retransmission counters: SSRC (station short transmission retry counter) and SLRC (station long transmission retry counter). The SSRC is associated with the RTS frame and the SLRC is associated with the data frame. The SSRC is incremented whenever an RTS frame is unsuccessfully transmitted and is reset to 0 whenever a CTS frame is received in response to an RTS frame. The SLRC is incremented whenever a data frame is unsuccessfully transmitted and is reset to 0 whenever an ACK frame is received in response to a data frame. Therefore, even the SLRC may be reset after a successful RTS frame transmission, the subsequent data frame transmission may be unsuccessful, leading to an increment of the SLRC. In effect the models proposed by (Bianchi, 2000; Wu *et al.*, 2002; Ergen and Varaiya, 2005) cannot be extended to take account of transmission errors. In (Chatzimisios *et al.*, 2003; Ni *et al.*, 2005) transmission errors are considered, however, only for the case of basic access, i.e., only with the account of the SLRC counter. To consider these two counters the Markov chain has to be modified and extended.

It should be noted that in (Bianchi, 2000; Wu *et al.*, 2002; Chatzimisios *et al.*, 2003) the authors have mistakenly taken DIFS (DCF interframe space) for EIFS (extended interframe space). This mistake does not, however, have a very important impact on the evaluation of saturation throughput.

All the aforementioned analyses are based on Markov chains. Also other approaches were presented, e.g., elementary conditional probability arguments in (Bianchi and Tinnirello, 2005), *p*-persistent models in (Cali *et al.*, 2000), and average values of variables in (Tay and Chua, 2001). These approaches make several simplifying assumptions and thus do not take into account important features of DCF.

Some Markov models consider non-saturated conditions (Ergen and Varaiya, 2005). Some also deal with enhanced DCF (EDCF), known from IEEE 802.11e (Xiao, 2003; 2004; Engelstad and Østerbø, 2006).

The model presented in this paper is, generally speaking, in line with the extensions of the basic Bianchi's model (Bianchi, 2000), which were proposed in (Wu *et al.*, 2002; Ni *et al.*, 2005). The essential difference of the present model with respect to the latter two is in that it takes into account the effect of freezing of a station's backoff timer together with the limitation of the number of retransmissions, the maximum size of the contention window, and the impact of transmission errors.

MODEL

Assumptions

(1) Saturated conditions are considered; stations have no empty queues—there is always a frame to be sent.

(2) n stations compete for medium access (for n=1 only one station sends frames to other stations which can only reply with ACK).

(3) Errors in the transmission medium are randomly distributed; this is the worst case for the frame error rate (FER). All stations have the same bit error rate (BER).

(4) All stations are in transmission range and there are no hidden terminals.

(5) Stations communicate in ad hoc mode (BSS, basic service set) with basic access method.

(6) All stations use the same physical layer (PHY).

(7) The transmission data rate R is the same and constant for all stations.

(8) All frames are of constant length L.

(9) Only data frames and ACK frames are exchanged.

(10) Collided frames are discarded—the capture effect (Kochut *et al*., 2004) is not considered.

Saturation throughput expressed through characteristics of the physical channel

The saturation throughput S is defined as (Bianchi, 2000)

$$S = \frac{E[DATA]}{E[T]}, \tag{1}$$

where $E[DATA]$ is the mean value of the successfully transmitted payload, and $E[T]$ is the mean value of the duration of the following channel states: T_I–idle slot, T_S–successful transmission, T_C–transmission with collision, $T_\mathrm{E\_DATA}$–unsuccessful transmission with data frame error, $T_\mathrm{E\_ACK}$–unsuccessful transmission with ACK error.

Fig.1 illustrates the dependence of the above channel states on the following durations: T_PHYhdr–duration of a PLCP (PHY layer convergence procedure) preamble and a PLCP header, T_DATA–duration to transmit a data frame, T_ACK–duration to transmit an ACK frame, T_SIFS–duration of SIFS (short interframe space), T_DIFS–duration of DIFS, T_EIFS–duration of EIFS.

The relation of the saturation throughput to physical channel characteristics is calculated similarly as in (Ni *et al*., 2005):

$$\begin{cases} T_\mathrm{I} = \sigma, \\ T_\mathrm{S} = 2T_\mathrm{PHYhdr} + T_\mathrm{DATA} + 2\delta + T_\mathrm{SIFS} + T_\mathrm{ACK} + T_\mathrm{DIFS}, \\ T_\mathrm{C} = T_\mathrm{PHYhdr} + T_\mathrm{DATA} + \delta + T_\mathrm{EIFS}, \\ T_\mathrm{E\_DATA} = T_\mathrm{PHYhdr} + \delta + T_\mathrm{DATA} + T_\mathrm{EIFS}, \\ T_\mathrm{E\_ACK} = T_\mathrm{S}, \end{cases} \tag{2}$$

where σ is the duration of idle slot [*aSlotTime* in (IEEE 802.11, 1999)] and δ is the propagation delay.

For OFDM (orthogonal frequency division multiplexing) PHY (IEEE 802.11a, 1999; IEEE 802.11g, 2003),

$$T_\mathrm{DATA} = T_\mathrm{symbol} \left\lceil \frac{L_\mathrm{SER} + L_\mathrm{TAIL} + L_\mathrm{DATA}}{N_\mathrm{BpS}} \right\rceil, \tag{3}$$

$$T_\mathrm{ACK} = T_\mathrm{symbol} \left\lceil \frac{L_\mathrm{SER} + L_\mathrm{TAIL} + L_\mathrm{ACK}}{N_\mathrm{BpS}} \right\rceil, \tag{4}$$

where T_symbol is the duration of a transmission symbol, L_SER the OFDM PHY layer SERVICE field size, L_TAIL the OFDM PHY layer TAIL field size, N_BpS the number of encoded bits per symbol, L_ACK the size of ACK frame, and L_DATA the size of data frame.

For DSSS (direct sequence spread spectrum) PHY (i.e., IEEE 802.11, 1999 with 1 and 2 Mbps, IEEE 802.11b, 1999 with a long preamble), Eqs.(3) and (4) may be applied with $L_\mathrm{SER}=L_\mathrm{TAIL}=0$ (there are no such fields). Values of σ, T_PHYhdr, T_SIFS, T_DIFS, T_EIFS, T_symbol, N_BpS, L_SER and L_TAIL are defined in accordance with 802.11 standard.

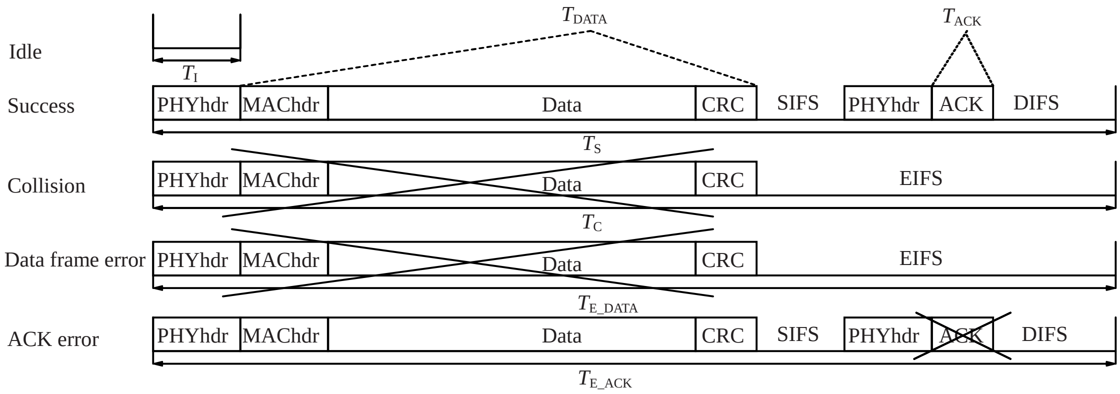

Fig.1 Dependence of five states of the channel on frame duration

Probabilities corresponding to states of the channel are denoted as follows: P_I–probability of idle slot, P_S–probability of successful transmission, P_C–probability of collision, $P_\text{E\_DATA}$–probability of unsuccessful transmission due to data frame error, $P_\text{E\_ACK}$–probability of unsuccessful transmission due to ACK error.

Let τ be the probability of frame transmission, $p_\text{e\_data}$ the probability of data frame error, and $p_\text{e\_ACK}$ the probability of ACK error. These are related to channel state probabilities as follows:

$$\begin{cases} P_\text{I} = (1-\tau)^n, \\ P_\text{S} = n\tau(1-\tau)^{n-1}(1-p_\text{e\_data})(1-p_\text{e\_ACK}), \\ P_\text{C} = 1-(1-\tau)^n - n\tau(1-\tau)^{n-1}, \\ P_\text{E\_DATA} = n\tau(1-\tau)^{n-1} p_\text{e\_data}, \\ P_\text{E\_ACK} = n\tau(1-\tau)^{n-1}(1-p_\text{e\_data}) p_\text{e\_ACK}. \end{cases} \quad (5)$$

The saturation throughput

$$S = \frac{P_\text{S} L_\text{pld}}{T_\text{I}P_\text{I} + T_\text{S}P_\text{S} + T_\text{C}P_\text{C} + T_\text{E\_DATA}P_\text{E\_DATA} + T_\text{E\_ACK}P_\text{E\_ACK}}, \quad (6)$$

where L_pld is MAC payload size and $L_\text{pld}=L-L_\text{MAChdr}$, where L_MAChdr is the size of the MAC header plus the size of FCS (frame checksum sequence).

S can be normalized to data rate R:

$$\overline{S} = S/R, \quad (7)$$

where

$$R = N_\text{BpS}/T_\text{symbol}. \quad (8)$$

As a result, saturation throughput S is expressed as a function of τ, $p_\text{e\_data}$ and $p_\text{e\_ACK}$. In the following subsections these probabilities are evaluated.

Probability of frame transmission τ

Let $s(t)$ be a random variable describing the DCF backoff stage at time t, with values from $\{0, 1, 2, \ldots, m\}$. Let $b(t)$ be a random variable describing the value of the backoff timer at time t, with values from $\{0, 1, 2, \ldots, W_i-1\}$. These random variables are dependent because the maximum value of the backoff timer depends on the backoff stage:

$$W_i = \begin{cases} 2^i W_0, & i \le m', \\ 2^{m'} W_0 = W_m, & i > m', \end{cases} \quad (9)$$

where W_0 is an initial size of the contention window and m' is a maximum number by which the contention window can be doubled; m' can be greater than, smaller than, or equal to m. W_0 and $W_{m'}$ depend on CW_min and CW_max, respectively:

$$W_0 = CW_\text{min} + 1, \quad (10)$$

$$W_{m'} = CW_\text{max} + 1 = 2^{m'} W_0. \quad (11)$$

The 2D process $(s(t), b(t))$ will be analyzed with an embedded Markov chain (in steady state) at time instants at which the channel state changes. Let (i, k) denote the state of this process. The one-step conditional state transition probabilities will be denoted by $P=(\cdot, \cdot|\cdot, \cdot)$.

Let p_f be the probability of transmission failure and p_coll the probability of collision. The non-null transition probabilities are determined as follows (Fig.2):

$$P(i, k|i, k+1)=1-p_\text{coll}, \quad 0\le i\le m,\ 0\le k\le W_i-2, \quad (12a)$$
$$P(i, k|i, k)=p_\text{coll}, \quad 0\le i\le m,\ 1\le k\le W_i-1, \quad (12b)$$
$$P(0, k|i, 0)=(1-p_\text{f})/W_0, \quad 1\le i\le m-1,\ 0\le k\le W_0-1, \quad (12c)$$
$$P(i, k|i-1, 0)=p_\text{f}/W_i, \quad 1\le i\le m,\ 0\le k\le W_i-1, \quad (12d)$$
$$P(0, k|m, 0)=1/W_0, \quad 0\le k\le W_0-1. \quad (12e)$$

(12a): The station's backoff timer is decremented from $k+1$ to k at a fixed ith backoff stage, i.e., the station has detected an idle slot, so the channel is idle. The probability of this event is Pr\{channel is idle\}=1−Pr\{one or more station is transmitting\}. Considering the saturated conditions, Pr\{one or more station is transmitting\}=p_coll.

(12b): The station's backoff timer is frozen at a fixed ith backoff stage, i.e., the channel is busy. Pr\{channel is busy\}=Pr\{one or more station is transmitting\}=p_coll.

(12c): The station's backoff timer is changed from 0 to k and the backoff stage is changed from i to 0. The probability of this event is Pr\{transmission is successful and number k was randomly chosen to initiate the backoff timer at stage 0\}=Pr\{transmission is successful\}·Pr\{number k was randomly chosen to initiate the backoff timer at stage 0\}. The probability of successful transmission is equal to $1-p_{\mathrm{f}}$ and the probability that number k was randomly chosen to initiate the backoff timer at stage 0 equals $1/W_0$.

(12d): The station's backoff timer is changed from 0 to k and the backoff stage is changed from $i-1$ to i. The probability of this event is $Pr\{$transmission is unsuccessful and number k was randomly chosen to initiate the backoff timer at stage $i\}=Pr\{$transmission is unsuccessful$\}\cdot Pr\{$number k was randomly chosen to initiate the backoff timer at stage $i\}$. The probability of unsuccessful transmission equals p_{f} and the probability that number k was randomly chosen to initiate the backoff timer at stage i equals $1/W_i$.

(12e): The station's backoff timer is changed from 0 to k and the backoff stage is changed from m to 0, i.e., the station has reached maximum retransmission count. The probability of this event equals the probability that number k was randomly chosen to initiate the backoff timer at stage 0, i.e., $1/W_0$.

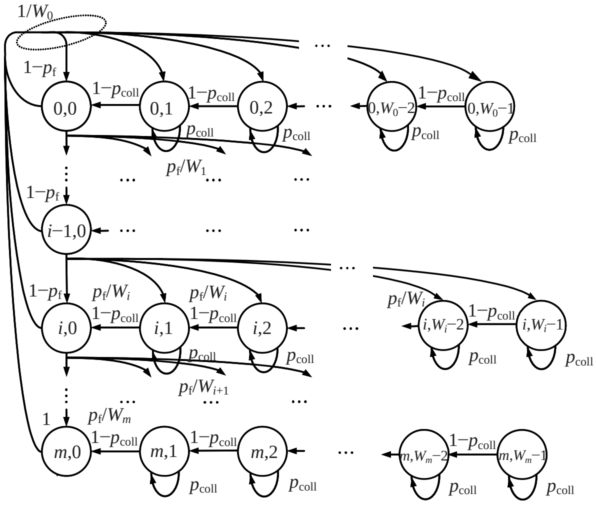

Fig.2 Graphical presentation of Markov chain transitions

Let $b_{i,k}$ be the probability of state (i, k). It can be shown that

$$b_{i,0}=p_{\mathrm{f}}b_{i-1,0}, \tag{13}$$

$$b_{i,0}=p_{\mathrm{f}}^{i}b_{0,0}, \tag{14}$$

and

$$b_{i,k}=\begin{cases}\dfrac{W_i-k}{W_i(1-p_{\mathrm{coll}})}p_{\mathrm{f}}^{i}b_{0,0}, & 0<k\le W_i-1,\\ p_{\mathrm{f}}^{i}b_{0,0}, & k=0,\end{cases} \tag{15}$$

From

$$\sum_{i=0}^{m}\sum_{k=0}^{W_i-1}b_{i,k}=1 \tag{16}$$

and

$$\sum_{i=0}^{m}b_{i,0}=b_{0,0}\frac{1-p_{\mathrm{f}}^{m+1}}{1-p_{\mathrm{f}}}, \tag{17}$$

we have

$$b_{0,0}^{-1}=\begin{cases}\dfrac{(1-p_{\mathrm{f}})W_0(1-(2p_{\mathrm{f}})^{m+1})-(1-2p_{\mathrm{f}})(1-p_{\mathrm{f}}^{m+1})}{2(1-2p_{\mathrm{f}})(1-p_{\mathrm{f}})(1-p_{\mathrm{coll}})}\\ \quad+\dfrac{1-p_{\mathrm{f}}^{m+1}}{1-p_{\mathrm{f}}}, & m\le m',\\ \dfrac{\Psi}{2(1-2p_{\mathrm{f}})(1-p_{\mathrm{f}})(1-p_{\mathrm{coll}})}+\dfrac{1-p_{\mathrm{f}}^{m+1}}{1-p_{\mathrm{f}}}, & m>m',\end{cases} \tag{18}$$

where

$$\begin{aligned}\Psi=&(1-p_{\mathrm{f}})W_0(1-(2p_{\mathrm{f}})^{m'+1})-(1-2p_{\mathrm{f}})(1-p_{\mathrm{f}}^{m+1})\\&+W_0 2^{m'}p_{\mathrm{f}}^{m'+1}(1-2p_{\mathrm{f}})(1-p_{\mathrm{f}}^{m-m'}).\end{aligned} \tag{19}$$

The probability of frame transmission τ is equal to $Pr\{$backoff timer equals 0$\}$ and thus

$$\begin{aligned}\tau&=\sum_{i=0}^{m}b_{i,0}\\&=\begin{cases}\left[\dfrac{(1-p_{\mathrm{f}})W_0(1-(2p_{\mathrm{f}})^{m+1})-(1-2p_{\mathrm{f}})(1-p_{\mathrm{f}}^{m+1})}{2(1-2p_{\mathrm{f}})(1-p_{\mathrm{f}})(1-p_{\mathrm{coll}})}\right.\\ \quad\left.+\dfrac{1-p_{\mathrm{f}}^{m+1}}{1-p_{\mathrm{f}}}\right]^{-1}\dfrac{1-p_{\mathrm{f}}^{m+1}}{1-p_{\mathrm{f}}}, & m\le m',\\ \left[\dfrac{\Psi}{2(1-2p_{\mathrm{f}})(1-p_{\mathrm{f}})(1-p_{\mathrm{coll}})}+\dfrac{1-p_{\mathrm{f}}^{m+1}}{1-p_{\mathrm{f}}}\right]^{-1}\\ \quad\cdot\dfrac{1-p_{\mathrm{f}}^{m+1}}{1-p_{\mathrm{f}}}, & m>m',\end{cases}\end{aligned} \tag{20}$$

For $p_{\mathrm{coll}}=0$ the above solution is the same as that presented in (Ni *et al*., 2005).

Probability of transmission failure p_{f} and probability of collision p_{coll}

The probability of transmission failure

$$p_{\mathrm{f}}=1-(1-p_{\mathrm{coll}})(1-p_{\mathrm{e}}), \tag{21}$$

where p_e is the frame error probability, and

$$p_e = 1-(1-p_{e\_data})(1-p_{e\_ACK}), \tag{22}$$

where p_{e_data} is FER for data frames and p_{e_ACK} is FER for ACK frames. p_{e_data} and p_{e_ACK} can be calculated from bit error probability (i.e., BER) p_b:

$$p_{e\_data} = 1-(1-p_b)^{L_{data}}, \tag{23}$$

$$p_{e\_ACK} = 1-(1-p_b)^{L_{ACK}}. \tag{24}$$

The probability of collision

$$p_{coll} = 1-(1-\tau)^{n-1}. \tag{25}$$

Finally

$$p_f = 1-(1-p_{coll})(1-p_e) = 1-(1-\tau)^{n-1}(1-p_e). \tag{26}$$

Eqs.(20) and (26) form a non-linear system with two unknown variables τ and p_f which may be solved numerically.

VALIDATION

The present model was validated with the use of simulation in two steps. The aim of Step 1 was to compare the proposed model with (1) models presented by (Bianchi, 2000; Wu *et al.*, 2002) in which channel errors are not taken into account, (2) the special case of (Ni *et al*., 2005)'s model in which BER is assumed zero, and (3) simulations [also presented by Heusse *et al.*(2005)]. In Step 2, channel errors were taken into account; the accuracy of the present model was evaluated with simulations presented by Lopez-Aguilera *et al.*(2006) and compared with the model presented in (Ni *et al*., 2005).

Step 1

The ns-2 simulator version 2.29 (http://nsnam.isi.edu/nsnam/index.php/Main_Page) was used. The IEEE 802.11 DSSS 1 Mbps PHY was simulated (OFDM PHY is not implemented in the standard version of ns-2). The simulation was performed for saturated conditions with static routing and for 1000 bytes MAC frames UDP traffic. The results are presented in Fig.3.

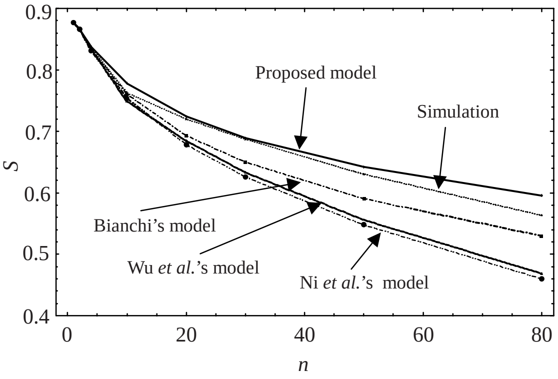

Fig.3 Normalized saturation throughput: analytical and simulation results for IEEE 802.11 DSSS 1 Mbps with *L*=1000 bytes and *BER*=0

The proposed model was also compared with simulation results presented by Heusse *et al.*(2005), which were obtained with the simulation tool created at Universitat Politècnica de Catalunya in Barcelona. In Table 1 the simulation conditions and simulation results are presented. Note that non-aggregated values of saturation throughput (*S*/*n*) are presented.

Table 1 Non-aggregated values (in Mbps) of saturation throughput for IEEE 802.11g 54 Mbps ERP-OFDM with *L*=1500 bytes and *BER*=0

n	Bianchi's model	Wu *et al.*'s model	Ni *et al.*'s model	Proposed model	Simulation
1	31.36	31.36	31.36	31.36	31.79
2	16.24	16.24	16.15	16.05	16.18
4	7.90	7.90	7.79	7.86	7.85
10	2.87	2.86	2.79	2.93	2.92
15	1.82	1.78	1.72	1.88	1.87
20	1.30	1.26	1.21	1.36	1.36
25	1.00	0.95	0.91	1.06	1.06
50	0.43	0.37	0.35	0.47	0.49
100	0.17	0.11	0.10	0.21	0.22

Step 2

Although the ns-2 simulator enables simulating channel errors, the mechanism of error occurrence is based on physical features and is thus different from the one assumed in the proposed analytical model (randomly distributed bit errors). For this reason the ns-2 simulator was not used.

The accuracy of the proposed model was compared with the results obtained by solving the model presented by Ni *et al*.(2005) for assumptions concerning PHY and its parameters which are presented in Fig.4. Fig.4 also presents simulation results obtained by Lopez-Aguilera *et al.*(2006), who used the same simulation tool as Heusse *et al.*(2005), i.e., the simulator mentioned above. In these simulations a random pattern of bit-error occurrence was assumed, as assumed in the model presented in this paper.

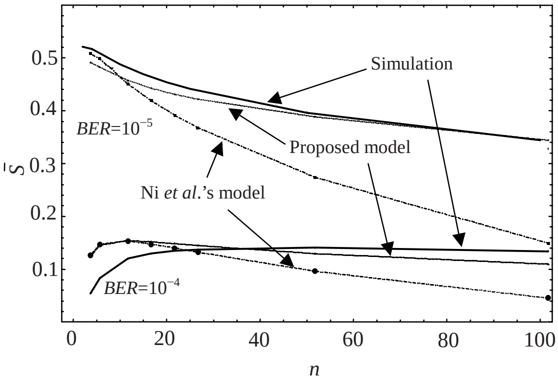

Fig.4 Normalized saturation throughput: analytical and simulation results for IEEE 802.11g 54 Mbps ERP-OFDM with L=1500 bytes and $BER=10^{-5}$ and 10^{-4}

ANALYSIS OF IEEE 802.11g 54 Mbps ERP-OFDM

All diagrams presented in this section show values of the normalized saturation throughput for IEEE 802.11g 54 Mbps ERP-OFDM. All calculations were made for $n\in\{1, 2, 3, 4, 5, 10, 15, 20, 30, 40\}$. For the frame with L=1000 bytes the following values of *BER* were used: 10^{-4}, 5×10^{-5}, 10^{-5}, 5×10^{-6}, 10^{-6}, and 0. For L=100, 250, 500, 1000, 1500, 2000 bytes, $BER\in\{0, 10^{-5}, 10^{-4}\}$. We considered IEEE 802.11g ERP-OFDM, i.e., "g" only mode and data rate R=54 Mbps (with the exception of the last diagram, which contains evaluation of R's impact on S).

Fig.5 presents normalized S as a function of n for L=1000 bytes frame and different values of *BER*. Along with increasing value of *BER*, saturation throughput S is reduced. Also the maximum of S is shifted from n=2 for two smallest *BER* 0 and 10^{-6}, through n=3 for *BER* 5×10^{-6} and 10^{-5}, n=5 for $BER=5\times10^{-5}$, into n=10 for $BER=10^{-4}$. Along with increasing value of *BER* the curves are flattened. For a given *BER*, reduction of S with increase of n is related to the increasing number of collisions in medium. Reduction of S between BER=0 and $BER=10^{-6}$ is very small.

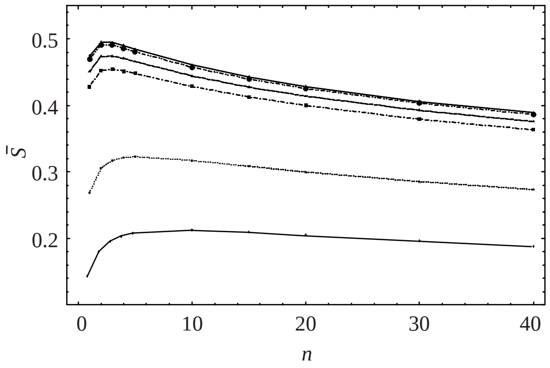

Fig.5 Normalized S as a function of n for L=1000 bytes and different values of *BER*. The curves from top down correspond to BER=0, 10^{-6}, 5×10^{-6}, 10^{-5}, 5×10^{-5}, and 10^{-4}, respectively

Figs.6 and 7 present normalized S as a function of n for different values of frame length and BER=0 and 10^{-5}, respectively. For a given n along with increase of frame length, the value of S increases. Maximum value of S depends on n and falls into [2, 5]. In comparison to BER=0 (Fig.6), when $BER=10^{-5}$ (Fig.7), S is reduced because of channel errors.

Fig.8 presents normalized S as a function of n for different values of frame length and $BER=10^{-4}$. For a given n along with increase of frame length, S increases but only to a limited level; S decreases for frames greater than 500 bytes and for $n\geq3$. This is an influence of increasing *FER* with frame length.

Finally, we evaluate normalized S as a function of n for different IEEE 802.11g data rates R=6, 9, 12, 18, 24, 36, 48, 54 Mbps. Results in Fig.9 show that the channel usage for lower rates is better than that for upper ones; for 6 Mbps and n=1 it is close to 85%, while for 54 Mbps and n=1 it is close to 47%.

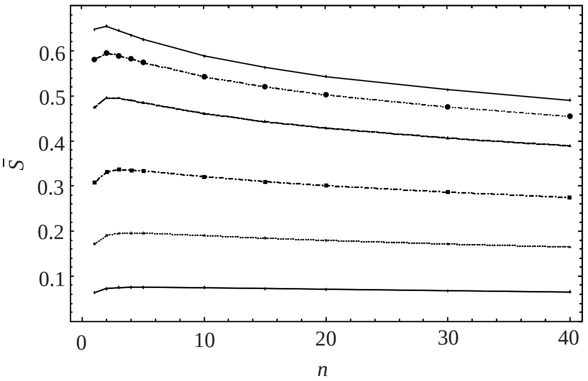

Fig.6 Normalized S as a function of n for different values of frame length L and BER=0. The curves from top down correspond to L=2000, 1500, 1000, 500, 250, and 100 bytes, respectively

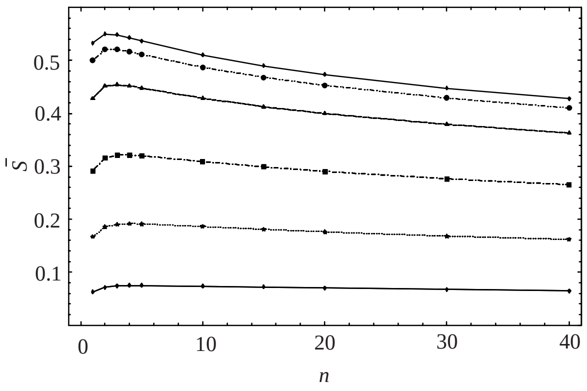

Fig.7 Normalized *S* as a function of *n* for different values of frame length *L* and *BER*=10^{-5}. The curves from top down correspond to *L*=2000, 1500, 1000, 500, 250, and 100 bytes, respectively

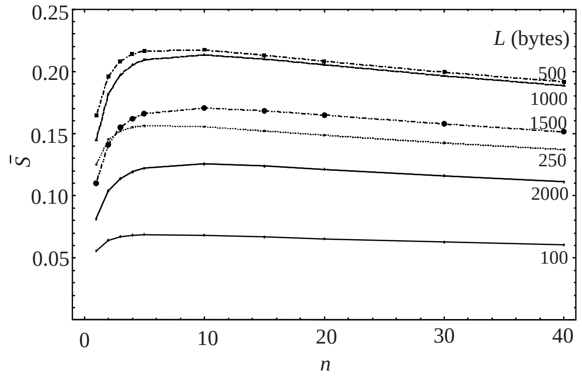

Fig.8 Normalized *S* as a function of *n* for different values of frame length *L* and *BER*=10^{-4}

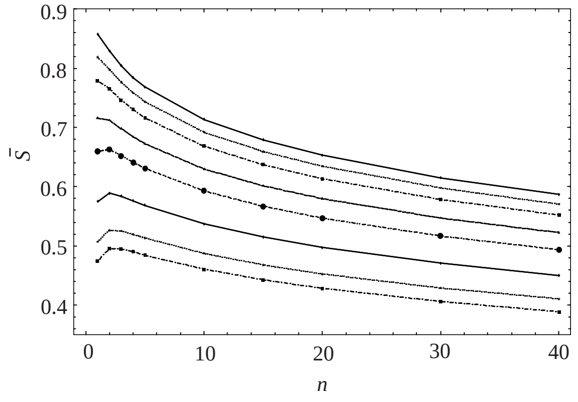

Fig.9 Normalized *S* as a function of *n* for *L*=1000 bytes, *BER*=0 and different values of *R*. The curves from top down correspond to *R*=6, 9, 12, 18, 24, 36, 48, and 54 Mbps, respectively

CONCLUSION

The present analysis shows that the saturation throughput *S* essentially depends on the bit error rate *BER*, i.e., for a given number of stations and a given frame length, the lower the *BER*, the greater the *S*. This is an influence of channel error on the effective volume of transmitted data. Increasing the number of stations implies collisions and finally reduces *S*. *S* depends on frame error rate *FER* because *FER* is a function of *BER* and *L*.

The results show that the proposed model has good accuracy in both error-free and error-prone channels. For error-free conditions the model yields some overestimation while other models known from literature tend to underestimate *S*. For both error-free and error-prone cases the proposed model shows better accuracy than models in the literature with which it was compared, especially for a large number of stations. The latter is the consequence of the fact that the proposed model takes into account freezing of the backoff timer; the impact of the freezing of the backoff timer on throughput evaluation increases with the increase of the number of stations competing for access to the transmission medium.

Future work could be focused on taking into account such features of the IEEE 802.11 protocol as the RTS/CTS and EDCA (enhanced distributed channel access).

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