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Saturation Throughput Analysis of the IEEE 802.11e EDCA Network with Contention Free Burst Under Fading Channel

Lina Bachiri · Djamil Aïssani · Louiza Bouallouche-Medjkoune

Abstract The 802.11 WLAN legacy standard cannot provide Quality of Service (QoS) support for multimedia applications because the 802.11 was initially developed for Best Effort services. Hence, the 802.11e amendment was published in order to provide the QoS support to WLANs. One of the most important functions in 802.11e is the contention based channel access mechanism called Enhanced Distributed Channel Access (EDCA), which provides a priority scheme by differentiating the Arbitration Inter Frame Space (AIFS), initial window size and Transmission OPportunity limit (TXOPlimit). In this paper, we propose a novel analytical model for the performance analysis of the IEEE 802.11e EDCA network with Contention Free Burst under fading channel and saturated traffic conditions. This new model captures all of the major QoS specific features, namely AIFS, minimum contention window size, maximum contention window size, virtual collision and TXOPlimit. So, we have analyzed the saturation system throughput of the basic access method of the IEEE 802.11e EDCA network.

Keywords IEEE 802.11e · EDCA · TXOPlimit · Throughput analysis · Markov chain · Fading channel

1 Introduction

IEEE 802.11 has become widely deployed that it becomes the dominating WLAN technology. This is mainly because the technology is reaching an unprecedented maturity in regard to providing ever-growing bitrates [1]. At the same time, multimedia applications require some quality of service support such as guaranteed bandwidth, bounded delay and jitter. But, the IEEE 802.11 protocol is unsuitable, for these multimedia applications [2]. The IEEE Task Group E has proposed a new MAC layer standard, namely IEEE 802.11e [3] to provide

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service differentiation. The IEEE 802.11e MAC layer defines a new method named hybrid coordination function (HCF) [1,4,5]. The HCF function uses two medium access schemes: contention based Enhanced Distributed Channel Access (EDCA) and centrally controlled Hybrid Coordination Channel Access (HCCA). In IEEE 802.11e, EDCA is the fundamental mechanism and HCCA is optional. In this paper, we propose an analytical model for EDCA with Contention Free Burst (CFB) under fading channel and finite load.

Many research efforts have been done to study the legacy IEEE 802.11 and IEEE 802.11e MAC layers, by both of analysis and simulation. In the following, we provide a brief summary of the proposed models for DCF and EDCA functions in the available literature.

Assuming constant collision probability for each station, Bianchi [6] analyzed the performance of the IEEE 802.11 DCF, and proposed a simple Markov chain to compute saturation throughput. In Ziouva and Antonakopoulos [7], modified the Bianchi's model [6] to derive the saturation delay. In Wu et al. [8], proposed an extension of Bianchi's model [6], to consider the retry limits. In [9], the authors proposed an analytical model to evaluate the system throughput and delay of DCF with different packet Hybrid Coordination Channel Accesserror rates. In [10], under fading channel the author presented a new analytical model to evaluate the performance of DCF. In Kosek-Szott [11] proposed a comprehensive analysis of heterogeneous traffic sources in saturated or nonsaturated with M/M/I/K queues. The authors in [12], proposed a new three-dimensional Markov chain of the IEEE 802.11b DCF networks with Packet Fragmentation Mechanism (PFM) in both Basic and RTS/CTS access methods under imperfect channel and finite load conditions.

Mangold et al. [13], provided performance evaluation for EDCA via simulations. Xiao [14] and Kong et al. [1] extended the Bianchi's model [6] to analyze the effect of CW and the AIFS differentiation; due to varying number of contending stations, these models ignore the correct treatment of varying collision probabilities at different AIFS slots. In [15,16], the authors studied the efficiency of burst transmissions with block acknowledgements. In [17,18], the authors presented the performance analysis of and EDCA. In [19,20], the authors proposed an analytical model to study the effect of burst transmissions. The authors in [21] Extended Bianchi model [6], to study the effect of the postcollision period and take a similar approach as [22]. The authors in [23], proposed a new analytical model for the TXOP service differentiation scheme in single hop ad hoc networks in the presence of unbalanced stations with different loads. Xiao [24] proposed a model to analyze the effect of contention window size differentiation in the EDCA mechanism. Xiao [2] developed an analytical model to evaluate the performance of the IEEE 802.11e in the saturated case. In [25], the authors modified the ZA's model [7] and extend the model to support EDCA. In Varposhti and Movahhedinia [26], developed an analytical model to derive an average delay for IEEE 802.11e over fading channel. Under saturated conditions Xu et al. [27], proposed an access delay model for EDCA with the AIFS, CW, and TXOP schemes. In [28], the performance evaluation of TXOP in EDCA are presented. In [29], the authors, proposed a novel mathematical model of the EDCA function. The authors in [30], enhanced the protocol IEEE 802.11e. In [31], the authors provide a survey of QoS provision in mobile multimedia, addressing the technologies at different network layers and cross layer design.

Although some efforts have been done for the performance analysis under a fading channel, e.g., [9,32,33], these efforts mainly focus on the legacy IEEE 802.11 MAC protocol. So, little works [26], have taken into account the channel errors when studied IEEE 802.11e performance but none of the above involves correctly all the parameters of IEEE 802.11e CW, AIFS and TXOPlimit.

In this paper, based on Bianchi's model [6], we propose a three-dimensional Markov chain model for IEEE 802.11e EDCA over fading channel. Based on this Markov model, we compute the throughput that different traffic classes can sustain. The main contribution of this new model is that it captures all QoS parameters: AIFS, CW and TXOPlimit.

The remainder of this paper is organized as follows. In Sect. 2, we give a brief introduction to IEEE 802.11 DCF and IEEE 802.11e EDCA. The proposed analytical model is presented in Sect. 3. Section 4 provides throughput analysis under fading channel and TXOPlimit parameter. Numerical and simulation results are given in Sect. 5. Finally, Sect. 6 concludes this paper.

2 DCF and EDCA Overview

We will briefly introduce DCF and EDCA mechanisms, which are useful for understanding our analytical model.

2.1 Distributed Coordination Function (DCF)

The IEEE 802.11 MAC defines two transmission modes for data packets: the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). In DCF, a station with a frame to transmit observes the channel activities until an idle period equal to a Distributed Inter Frame Space (DIFS) is detected. After sensing an idle DIFS, the station waits for a random backoff time before transmitting. After each DIFS, the backoff time counter is decremented in terms of slot time as long as the channel remains idle. The counter is stopped if a transmission is detected on the channel, and reactivated if the channel is sensed idle again. When the backoff time is zero, the station transmits its data frames. At each transmission, the backoff time is uniformly chosen from $(0, CW - 1)$ in terms of time slots, where CW is the current backoff window size. At the first transmission attempt, the initial CW is minimum backoff window size (CW_{min}). After each collision or error, CW is doubled until maximum backoff window size (CW_{max}) value, is reached. When the destination station successfully receives the frame, it replies with an ACKnowledgment (ACK) frame after waiting for a SIFS (Short Inter-Frame Space) period. If the transmitting station does not receive the ACK within a specified ACK Timeout, or detects the transmission of a different frame on the channel, it reschedules the frame transmission according to the previous backoff rules. The RTS/CTS mechanism is employed, to reduce collisions caused by hidden terminals and improve channel efficiency for long data transmissions [1,34].

2.2 Enhanced Distributed Channel Access (EDCA)

The IEEE 802.11 DCF does not support any type of priority. To overcome this drawback and enhance the traditional DCF, as an extension to the basic DCF mechanism of the legacy IEEE 802.11, IEEE 802.11e EDCA has been proposed to provide differentiated and distributed channel access.

As specified in the IEEE 802.11e standard, EDCA provide differentiated and distributed channel access for packets with eight different priorities, which are mapping into four different ACs at the MAC layer, using a mapping shown in Table 1. The user priority value is defined in the IEEE 802.1D bridge specification [35].

For a given station, traffic of different ACs are buffered in different queues as shown in Fig. 1. Each AC within a station behaves like a virtual station: it contends for access to the medium and independently starts its backoff after sensing the medium idle for at least AIFS period. When a collision occurs among different ACs within the same station, the higher

Table 1 Mapping between user priorities and access categories (ACs)

Priority	User priority	802.11D designation	Access category 802.11e	Designation
Lowest	1	BK	AC_BK	Background
	2	–	AC_BK	Background
	0	BE	AC_BE	Best effort
	3	EE	AC_BE	Best effort
	4	CL	AC_BI	Video
	5	VI	AC_BI	Video
	6	VO	AC_BO	Voice
Highest	7	NC	AC_BO	Voice

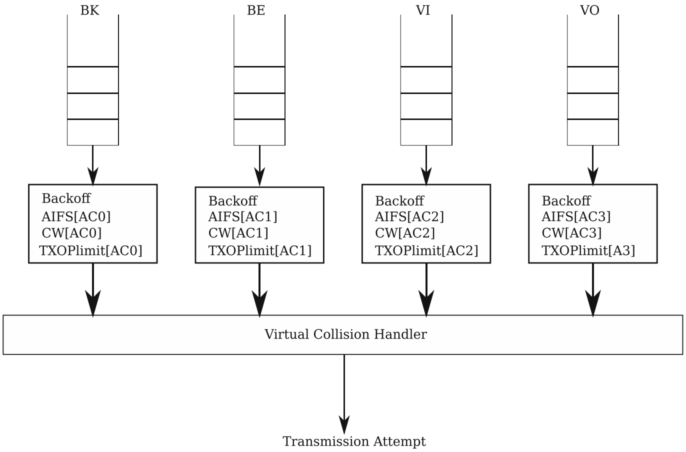

Fig. 1 ACs and virtual collision

priority AC is granted the opportunity for physical transmission, while the lower priority AC suffers from a virtual collision, which is similar to a real collision outside the station [1,4,5].

EDCA differentiates service classes through three parameters, namely AIFS (Arbitration InterFrame Space), minimum and maximum Contention Window size values CW_{min} and CW_{max}, and Transmission OPportunity limit TXOPlimit.

AIFS for a given AC is determined by the following equation:

$$AIFS = SIFS + AIFSN.aSlotTime$$

where AIFSN is called the arbitration IFS number, and aSlotTime is the duration of a time slot. The AC with the highest priority has the smallest AIFS (Fig. 2).

The backoff time is randomly chosen from $[0, CW - 1]$ in terms of slot time at each new transmission, where CW is the current backoff windows size. The initial CW is CW_{min}. After each collision, CW is doubled until a maximum backoff window size value CW_{max}.

EDCA also allows stations to transmit multiple frames without contending again, known as CFB (Contention-Free Bursting). CFB is limited by the TXOPlimit specified for each service class. A larger TXOPlimit allows the corresponding service class to transmit more frames in a burst, causing a better QoS in terms of throughput. As a conclusion, according to IEEE

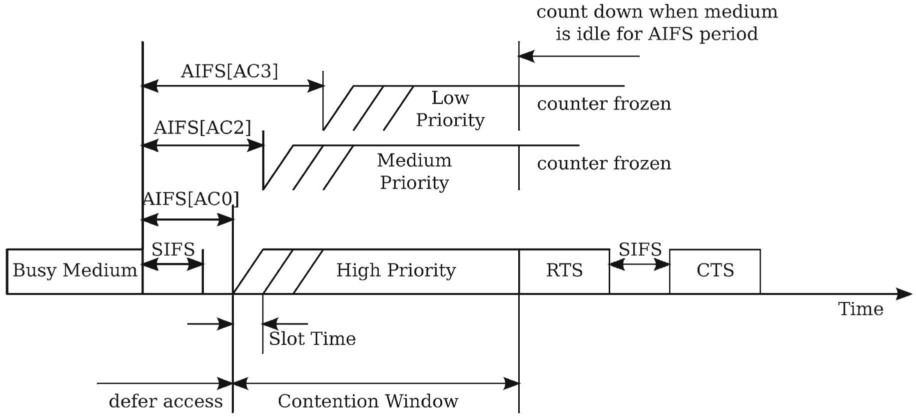

Fig. 2 IEEE 802.11e EDCA mechanism parameters

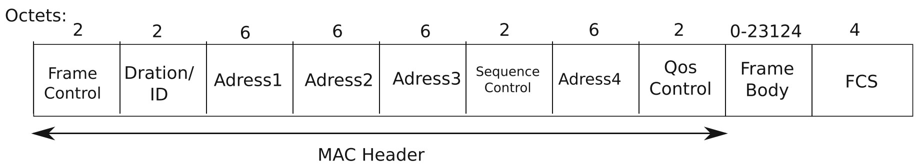

Fig. 3 Data frame format

802.11e, there are four ACs (Access Categories) with four priority levels; for $0 \leq j \leq i \leq 3$ we have the following inequalities:

$$(CW_{min})_i \leq (CW_{min})_j$$
$$(CW_{max})_i \leq (CW_{max})_j$$
$$AIFS_i \leq AIFS_j$$
$$(TXOP_{limit})_i \leq (TXOP_{limit})_j$$

which offers higher priority in gaining channel access for the ACs with higher indexes [26, 36,37].

- **Frame formats** [3]

In IEEE 802.11e a new set of frames is defined, which is similar to the IEEE 802.11 frames set but with a QoS attribute is added. It exist three classes of frames (data frames, management frames, control frames). In the following, we present the data frame format. The data frame format comprises a set of fields. Figure 3 shows the data frame format. Each frame consists of the following basic components:

1. A MAC header, which comprises frame control, duration, address, and sequence control information and QoS control information;
2. A variable length frame body, which contains information specific to the frame type and subtype;
3. A FCS (Frame Check Sequence), which contains an IEEE 32-bit CRC.

The data frame format comprises a set of fields:

– Frame control field depends on type frames (data frame, management frames and control frames).

- The Duration/ID field is 16 bits in length. The content of this field are varying with frame type (data, management).
- Address 1 always holds the receiver address of the intended receiver, and that Address 2 always holds the address of the station that is transmitting the frame. Address 3 and Address 4 depend on type of frames.
- The Sequence Number field is a 12-bit field indicating the sequence number of an MSDU (MAC Service Data Unit) or MMPDU (MAC Management Protocol Data Units). Each MSDU or MMPDU transmitted by a station is assigned a sequence number.
- The QoS Control field is a 16-bit, this field contains several information. In QoS field, the Traffic IDentifier (TID) subfield assigned to an MSDU in the layers above the MAC. TID indicate the type of traffic (background, best effort, video and voice).

3 Analytical Model

In this section, we present the proposed analytical model for the IEEE 802.11e EDCA function. In the following, we assume a fixed number of stations N. Each station has four ACs, and each AC always has a packet to transmit. This means that, the analysis is conducted under saturation conditions. The main contribution of this work is to consider all the features EDCA QoS (CW, AIFS, and TXOPlimit), under assuming fading channel environment which causes transmission errors.

3.1 Discrete Time Markov Chain Model

In this work, we extend the Markov chain proposed in [6], to evaluate EDCA under fading channel. We consider that undergo first frame can counter a collision or undergo noise errors while the others frames undergo noise errors since the channel is reserved after the first frame/ACK exchange sequence. Each state represents the remained time diagram for one $AC_i, i = (0, 1, 2, 3)$ per station. This is because each AC within a station behaves like a virtual station, and invokes its own AIFS and backoff procedure individually.

The discrete time Markov chain contains two parts: the first part represents the backoff procedure with the maximal allowable number of retransmission attempts of EDCA $(m+h)$. When reaching this limit, an AC_i will give up its current transmission and go to the first stage for the next transmission with probability of 1. The second part represents the states after reaching the zero backoff time. With probability $P_i = P_c + P_e$ (P_c probability of collision and P_e probability of error) it gos to a collision state. With probability $1 - P_i$ it will go to $(i, j, -1)$, and then with $1 - P_e$ probability, it will go to $(i, j, -2)$, with P_e probability it will go to collision state, and so on. If no error and no collision, the burst of frames is successfully transmitted. On the contrary, if there is any error occurred, the burst is terminated and the backoff procedure is restarted (Fig. 4).

To obtain the transmission probabilities τ_i with $i = (0, 1, 2, 3)$ for each AC_i and the transmission probability for a station τ, we use a simplified model shown in Fig. 5, we obtain the maximum achievable throughput. A simplified Markov chain is made here by merging the states after reaching the zero backoff time and the state $(i, j, 0)$ for each stage j as a virtual state $(i, j', 0')$ and renaming the other states $(i, j, k)s$ by $(i, j', k')s$.

With the simplified and equivalent model, for a given AC_i, let $s(i, t)$ be the stochastic process representing the backoff stage j' at time t, where $0 \leq j' \leq (m+h)'$. Let $b(i, t)$ the stochastic process that denotes the value of the backoff counter for a given AC_i at time t, and

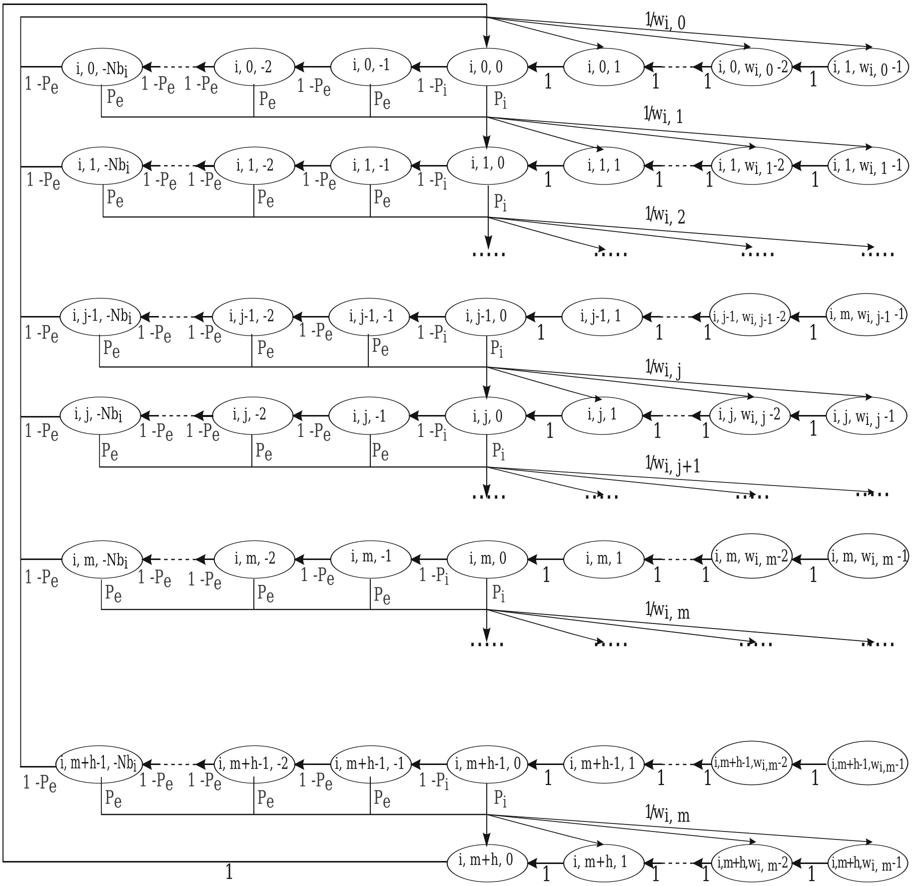

Fig. 4 Markov chain model of IEEE 802.11e EDCA with TXOPlimit for AC_i, $i = 0, 1, 2, 3$

the value of the backoff counter is uniformly drawn from $[0, W_{i,j'}]$, where $W_{i,j'}$ depends on the retransmission backoff stage j' and satisfies :

$$W_{i,j'} = \begin{cases} 2^{j'} W_{i,0'} & 0 \le j' \le (m-1)' \\ 2^{m'} W_{i,0'} & m' \le j' \le (m+h)'. \end{cases} \tag{1}$$

where $W_{i,0'}$ is the initial CW_{min} for each AC_i.

The process $(s(i,t), b(i,t))$ is a discrete time Markov chain under the assumption that P_c, the collision probability of AC_i, is independs of the backoff procedure. The probability P_c consists of two parts: the external collision probability caused by collisions with other transmissions from other stations, and the internal collisions caused by virtual collisions with higher ACs within the same station.

3.1.1 Transition Probabilities

The transition probabilities in this model are described as follows:

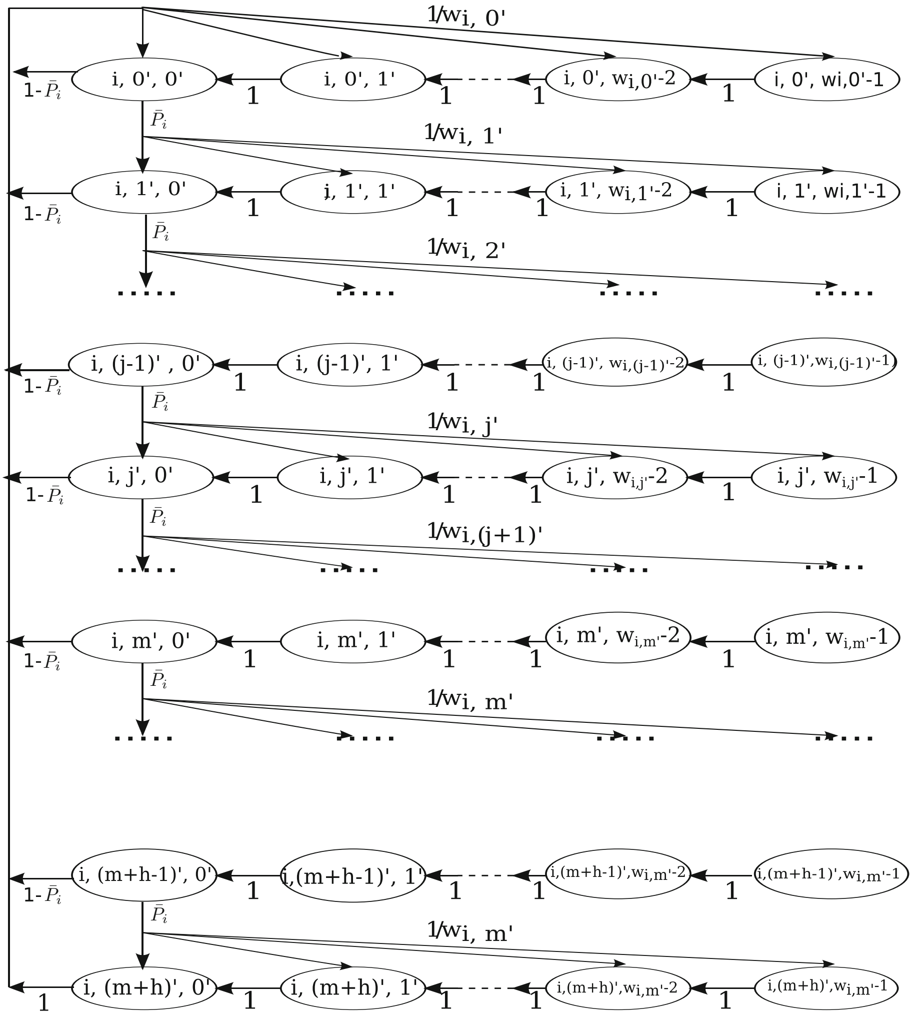

Fig. 5 A simplified Markov chain model for AC_i, $i = 0, 1, 2, 3$

1. The backoff counter decremented with probability 1 at each slot time:

$$p\{i, j', k'|i, j', (k+1)'\} = 1, 0 \leq k' \leq (w_{i,j'} - 1)', 0 \leq j' \leq (m+h)' \tag{2}$$

2. when the backoff counter is zero, the AC_i starts the transmission:

$$p\{i, 0', k'|i, j', 0'\} = \frac{1 - \bar{P}_i}{w_{i,0'}}, 0 \leq k' \leq (w_{i,j'-1})', 0 \leq j' \leq (m+h)' \tag{3}$$

3. the AC_i chooses a backoff delay of the next stage j' after an unsuccessful transmission at stage $(j-1)'$:

$$p\{i, j', k'|i, j', 0'\} = \frac{\bar{P}_i}{w_{i,j'}}, 0 \leq k' \leq (w_{i,j'} - 1)', 1 \leq j' \leq (m+h)' \tag{4}$$

4. when $(m+h)'$ retries have been exhausted, the AC_i will give up its current transmission with probability 1 and starts a new transmission:

$$p\{i, 0', k'|i, (m+h)', 0'\} = \frac{1}{w_{i,0}}, 0 \leq k' \leq (w_{i,j'} - 1)' \tag{5}$$

where

$$\bar{P}_i = 1 - (1 - P_i)(1 - P_e)^{Nb_i} \tag{6}$$

and $P_i = P_c + P_e$, P_c denotes the probability of collision and P_e denotes the probability of error, this probabilities can be calculated as follows:

$$P_c = 1 - (1 - \tau)^{N-1} \prod_{i > i'} (1 - \tau_i) \tag{7}$$

where i' means that $AC_{i'}$ has higher priority than AC_i.

$$P_e = 1 - (1 - BER)^l \tag{8}$$

with BER is the bit error rate and l is the frame size. N is the number of stations in the network. For each AC_i, Nb_i is the maximum number of frames transmitted in $TXOPlimit$.

3.1.2 Stationary Probabilities

let $b_{i,j',k'}$ be the steady probability of state (i, j', k') similar to [6], we have:

$$b_{i,j',k'} = \begin{cases} \bar{P}_i^{\,j'} b_{i,0',0'} & 0 \leq j' \leq (m+h)', k' = 0, \\ \frac{w_{i,j'}-k}{w_{i,j'}} b_{i,j',0'} & 0 \leq j' \leq (m+h)', 1 \leq k' \leq W_{i,j'} - 1. \end{cases} \tag{9}$$

by using the normalizing condition, we obtain:

$$\begin{aligned} 1 &= \sum_{j'=0}^{(m+h)'} \sum_{k=0}^{w_{i,j'}-1} b_{i,j',k'} \\ &= \sum_{j'=0}^{(m+h)'} b_{i,j',0'} \sum_{k=0}^{w_{i,j'}} \frac{w_{i,j'} - k}{w_{i,j'}} \\ &= \sum_{j'=0}^{(m+h)'} b_{i,j',0'} \frac{w_{i,j'} + 1}{2} \\ &= \frac{b_{i,0',0'}}{2} \left[\sum_{j'=0}^{m'} \bar{P}_i^{\,j'} (2^{j'} w + 1) + \sum_{j'=m'}^{(m+h)'} \bar{P}_i^{\,j'} (2^{m'} w + 1) \right] \end{aligned}$$

$$b_{i,0',0'} = \left[\frac{1 - \bar{P}_i^{\,(m+h+1)'}}{2(1 - \bar{P}_i)} + \frac{w}{2} \frac{[1 - (2\bar{P}_i)^{(m+1)'}](1 - \bar{P}_i) + \bar{P}_i (2\bar{P}_i)^{m'} (1 - \bar{P}_i^{\,h'})(1 - 2\bar{P}_i)}{(1 - \bar{P}_i^{\,(m+h+1)'})(1 - 2\bar{P}_i)} \right]^{-1} \tag{10}$$

$$\tau_i = \sum_{j'=0}^{(m+h)'} b_{i,j',0'} = \sum_{j'=0}^{(m+h)'} \bar{P}_i^{\,j'} b_{i,0',0'} = \frac{1 - \bar{P}_i^{\,(m+h+1)'}}{1 - \bar{P}_i} b_{i,0',0'} \tag{11}$$

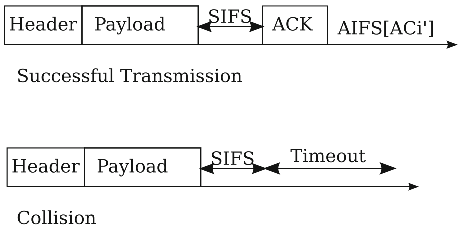

Fig. 6 Successful transmission time and collision time for one frame in basic access mode

from the viewpoint of a station, the probability τ that the station accesses to the channel is:

$$\tau = 1 - \prod_{j=0}^{3} (1 - \tau_i) \tag{12}$$

Equations (6), (7), (10) and (11) form a set of nonlinear equations. Means of numerical methods is used to solve it. All the transition probabilities and steady-state probabilities can be obtained.

4 Throughput Analysis

The normalized throughput of a given AC_i is calculated as the ration of time occupied by the transmitted information to the interval between two consecutive transmissions [1]. According to this definition, the throughput of AC_i, S_i is expressed as:

$$S_i = \frac{P_{tr} \cdot P_{si} \cdot E[N_s] \cdot E[P]}{(1 - p_{tr}) \cdot \delta + p_{tr} \cdot \sum_{i=0}^{3} Psi \cdot P_{succi} \cdot T_{s'} + p_{tr} \cdot (1 - \sum_{i=0}^{3} P_{si}) \cdot T_c + P_{tr} \cdot \sum_{i=0}^{3} P_{si} \cdot E[T_e]} \tag{13}$$

T_s is the average successful transmission time of one frame, $T_{s'} = Nb_i * T_s$ is the average successful transmission of burst frames, and T_c is the collision time. T_s' and T_c can be calculated from Fig. 6 as following:

$$\begin{cases} T_{s'} = Nb_i.(H + P + SIFS + ACK + AIFS[ACi']) \\ T_c = H + P + SIFS - Timeout \end{cases}$$

where

$Nb_i = TXOPlimit_i / T_s$, Nb_i is the number of the packets transmitted in burst for each AC_i.

$E[P]$ is the payload size, $E[N_s]$ is the average number of frames successfully transmitted in burst transmission, and P_{tr} is the probability that at least one station transmits in a time slot, and can be obtained by:

$$P_{tr} = 1 - (1 - \tau)^N \tag{14}$$

An AC_i frame can be transmitted successfully only when no other higher priority AC in the same station and no other station of the remaining $(N - 1)$ transmits. Therefore, the conditional successful transmission probability P_{si}, can be obtained by:

$$P_{si} = \frac{N \cdot \tau_i \cdot (1 - \tau)^{N-1} \cdot \prod_{i'>i} (1 - \tau_{i'})}{1 - (1 - \tau)^N} \tag{15}$$

$$E[N_s] = \sum_{j=2}^{Nb_i} (j - 1) \cdot (1 - P_e)^{j-1} \cdot P_e + P_{succi} \cdot Nb_i \tag{16}$$

where p_{succi} is the probability then all frames in the burst are successfully transmitted, it can be obtain by:

$$p_{succi} = (1 - P_e)^{Nb_i} \tag{17}$$

$$E[T_e] = \sum_{j=1}^{Nb_i} (1 - P_e)^{j-1} \cdot P_e \cdot T_e \tag{18}$$

where

$$T_e = T_s - SIFS + Timeout \tag{19}$$

$$Timeout = EIFS - DIFS + AIFSN[AC_i] \cdot \delta + SIFS - T_{turnaroundTime} \tag{20}$$

where $E[T_e]$ is the average time due to dropped frames during transmission by brust, and T_e is the time of loss of a single frame. We neglect $T_{turnaroundTime}$ because it is small compared with the other components.

5 Numerical and Simulation Results

In this section, we present the numerical and simulation results of the basic mode using NS2 [38]. We have calculated the normalized throughput under fading channel and we vary the number of stations (5 −35). This computation is made in both cases with and without TXOPlimit. The results show how the performance of the EDCA is affected by the TXOPlimit and transmission errors. For simplicity and without generality, we assume that there are two active ACs in each station, the first is $AC_3(Voice)$ with a higher priority, and the second is $AC_0(Background)$ with a lower priority. The following analytical and simulation results have been obtained assuming the parameters listed in Table 2.

In simulation we have used a traffic generated by each AC, following Poisson process traffic. This simulation was realized with high arrival rate (saturation region). The value of arrival rate equals to 1,800 Kb/s, this value leads to the saturation. To choose the arrival rate value, we varied the arrival rates from 20 (non-saturated) to 1,800 Kb/s (fully saturated) for each AC at each station, we noted that the saturation region starts from 800 Kb/s.

Figure 7 shows that when the number of stations increases, the normalized throughput available for each AC decreases slightly, also the total normalized throughput available in the network decreases slightly. The differentiation by TXOPlimit gives more priority for AC_3, because it is prioritized to transmit many frames in burst rather then AC_0, which is allowed to transmit a few number of frames. The Fig. 7 also shows the impact of fading channel on the performance of EDCA with TXOPlimit.

Figure 8 shows that when the number of stations increases, the normalized throughput available for each AC decreases slightly, also the total normalized throughput available in the network decreases slightly.

Figure 9 shows the total normalized throughput in both cases with and without TXOPlimit under ideal and fading channel. The normalized throughput of each AC and the total normalized throughput in an ideal ($BER = 0$) channel are higher than in fading channel. When the channel is ideal the normalized throughput can have a value 0.9 with 5 stations, whereas when the channel in non ideal ($BER = 10^{-5}$) the normalized throughput decreases in a remarkable way.

Figure 10, we compare our model with an existing validated model [1] in an ideal channel. We have chosen this model because it is the most cited in the literature. Our model with

Table 2 PYH and MAC IEEE 802.11e parameters

Parameter	Numerical value
Propagation delay	64 µs
Payload size	1,000 bytes
Phy Header (including preamble)	192 bits
Mac Header (including CRC bits)	272 bits
RTS Frame	Phy Header + 160 bits
CTS Frame	Phy Header + 112 bits
ACK Frame	Phy Header + 112 bits
CTS-timeout	DIFS + CTS
ACK-timeout	DIFS + ACK
Data rate	11 Mbps
Basic rate	2 Mbps
Time slot	20 µs
SIFS	1 Time slot
AIFS[AC3]	3 Time slot
AIFS[AC0]	4 Time slot
CW[AC3]	{7, 15, 31, 63}
CW[AC0]	{31, 63, 127, 255}
Nb0	1
Nb3	5

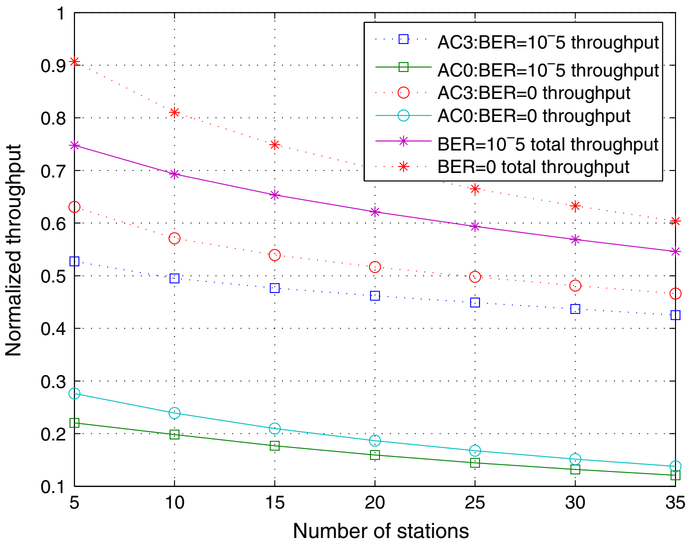

Fig. 7 Normalized throughput, with TXOPlimit ($Nb_0 = 1$, $Nb_3 = 5$)

TXOPlimit gives better performance by comparing it with the model [1], because it does not take into account the TXOPlimit parameter, which, once more, proves the importance of this

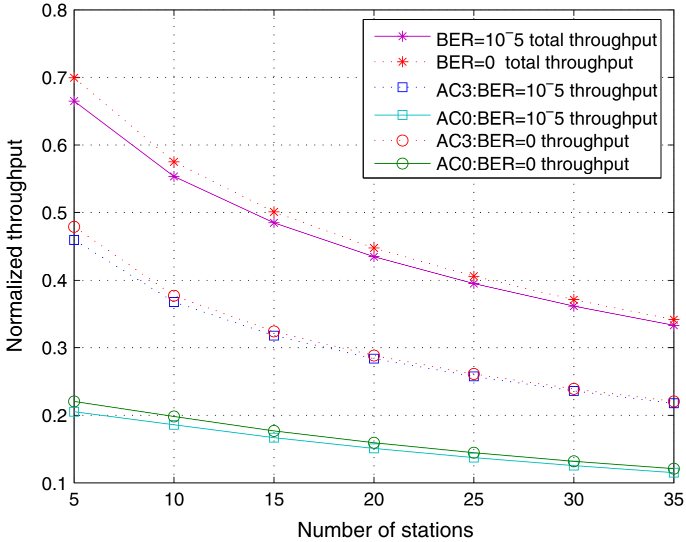

Fig. 8 Normalized throughput, without TXOPlimit

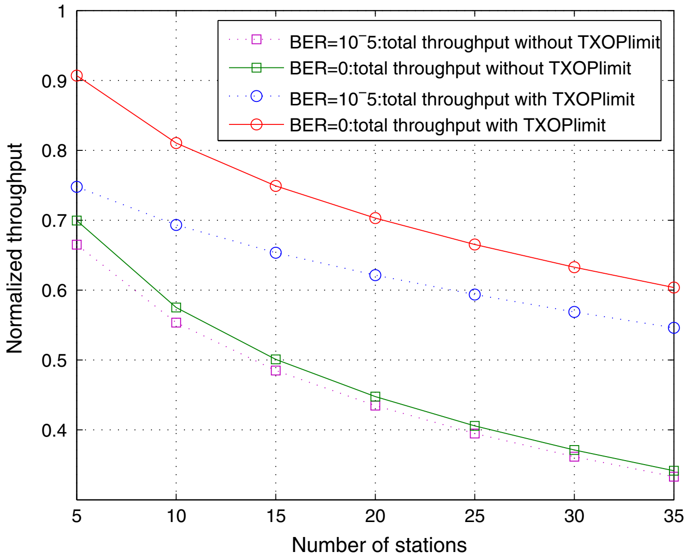

Fig. 9 Normalized throughput, with and without TXOPlimit

parameter to increase the occupation of channel and to decrease the collision. On the other hand, our model without TXOPlimit is similar to model [1].

The objective of our work is shown the impact of TXOPlimit parameter in both cases: ideal and non-ideal channel.

Figure 11 shows the normalized throughput of each AC without TXOPlimit in both cases of ideal channel ($BER = 0$) and fading channel ($BER = 3 * 10^{-5}$). The normalized throughput of each AC in an ideal channel is higher than the one in fading channel. When the

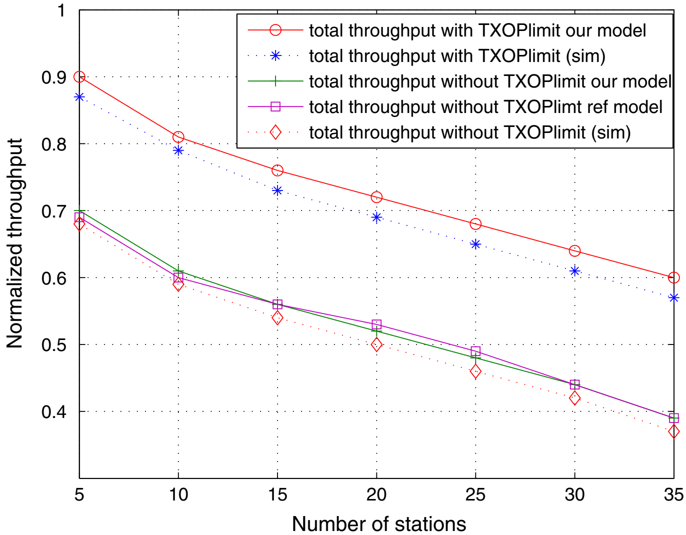

Fig. 10 Normalized throughput,with and without TXOPlimit of our model and reference model ($BER = 0$)

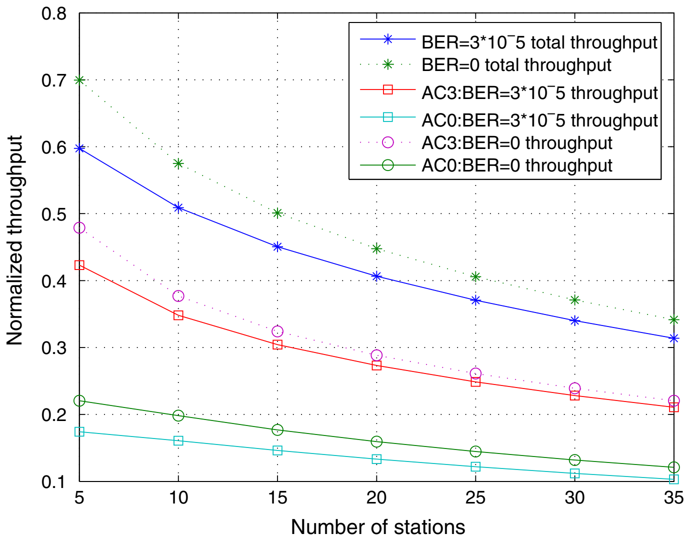

Fig. 11 Normalized throughput, without TXOPlimit

channel is ideal the normalized throughput can have a value of 0.7 with 5 stations, whereas when the channel in non ideal the normalized throughput decreases.

Figure 12 shows the normalized throughput of each AC with TXOPlimit in both cases of ideal channel ($BER = 0$) and fading channel ($BER = 3 * 10^{-5}$). The normalized throughput of each AC in an ideal channel is higher than the one in fading channel. When the channel is ideal the normalized throughput can have a value of 0.9 with 5 stations, whereas when the channel in non ideal the normalized throughput decreases.

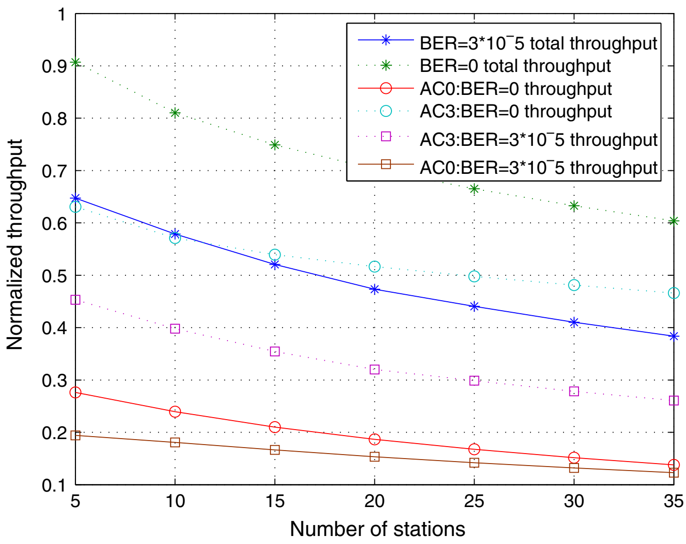

Fig. 12 Normalized throughput, with TXOPlimit ($Nb_0 = 1$, $Nb_3 = 5$)

- **Effects of the CW**

To investigate the effect of the CW on the performance of EDCA, there sets of CWs are used for AC3: $CW[AC3] = \{7, 15, 31, 63\}$, $CW[AC3] = \{15, 31, 63, 127\}$ and $CW[AC3] = \{31, 63, 127, 255\}$.

Figure 13 shows the normalized throughput of AC_3 and AC_0 against the number of stations in the network, without TXOPlimit and ideal channel ($BER = 0$).

Figure 14 shows the normalized throughput of AC_3 and AC_0 against the number of stations in the network, without TXOPlimit and fading channel ($BER = 3 * 10^{-5}$).

Figure 15 shows the normalized throughput of AC_3 and AC_0 against the number of stations in the network, with TXOPlimit and ideal channel ($BER = 0$).

Figure 16 shows the normalized throughput of AC_3 and AC_0 against the number of stations in the network, with TXOPlimit and fading channel ($BER = 3 * 10^{-5}$).

Figures 13, 14, 15 and 16 show that When the CW of AC_3 becomes smaller, AC_3 gains more opportunities for transmission and achieves a greater throughput. While the throughput of AC_0 follow the opposite trend.

In all the cases, with or without TXOPlimit and ideal or fading channel, when the CW of AC_3 is $\{31, 63, 127, 255\}$, and CW of AC_0 is $\{31, 63, 127, 255\}$, the throughput of the two ACs are different. This is because AC_3 has a smaller $AFIS$ than AC_0, which forces AC_0 to sense the channel for a longer time than AC_3. This helps AC_3 greatly after a successful transmission or after it finishes deferring. When the CW of AC_3 changes to $\{7, 15, 31, 63\}$, AC_3 obtains more chances to transmit. Thus, the throughput of AC_3 increases, while the throughput of AC_0 decrease.

We note that in all the cases, with or without and fading or ideal channel, when the CW of AC_3 is $\{7, 15, 31, 63\}$, the throughput of AC_3 is much higher than that of AC_0. However, as the number of stations increases, AC_3s throughput decreases slightly. This indicates that, as the number of stations increases, the differentiation effect of the CW size on the throughput becomes less and less important because most collisions occur among AC_3 flows.

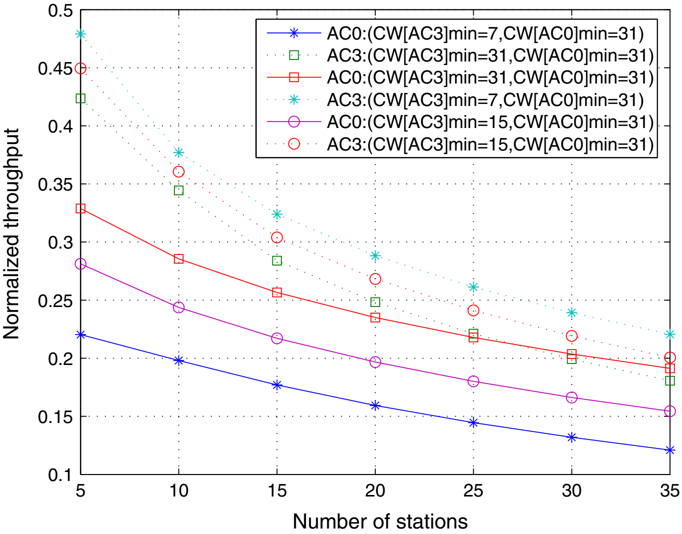

Fig. 13 Effects of different CWs, normalized throughput without TXOPlimit, ($BER = 0$)

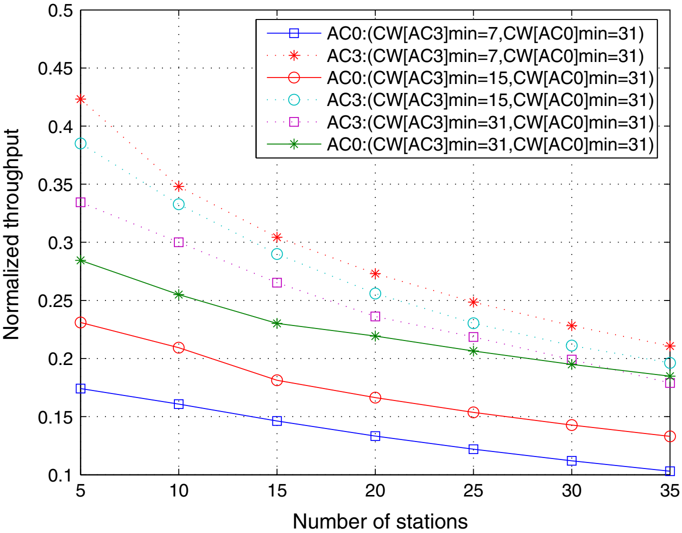

Fig. 14 Effects of different CWs, normalized throughput without TXOPlimit, ($BER = 3 * 10^{-5}$)

6 Conclusion

EDCA is the fundamental medium access control MAC scheme in IEEE 802.11e protocol. In this paper, we analyzed the performance of data burst transmissions, supported by the EDCA access mechanism. We developed an accurate analytical model to evaluate the performance of EDCA under fading channel. Compared with the existing analytical models of EDCA, the proposed model captures all of the major QoS specific features, namely AIFS, TXOPlimit, minimum contention window size CW_{min}, maximum contention window size CW_{max} and

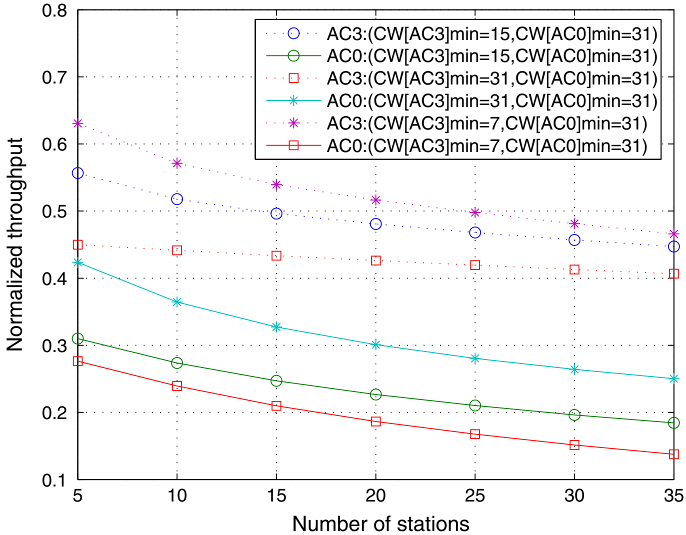

Fig. 15 effects of different CWs, normalized throughput with TXOPlimit, ($Nb_0 = 1, Nb_3 = 5$) and ($BER = 0$)

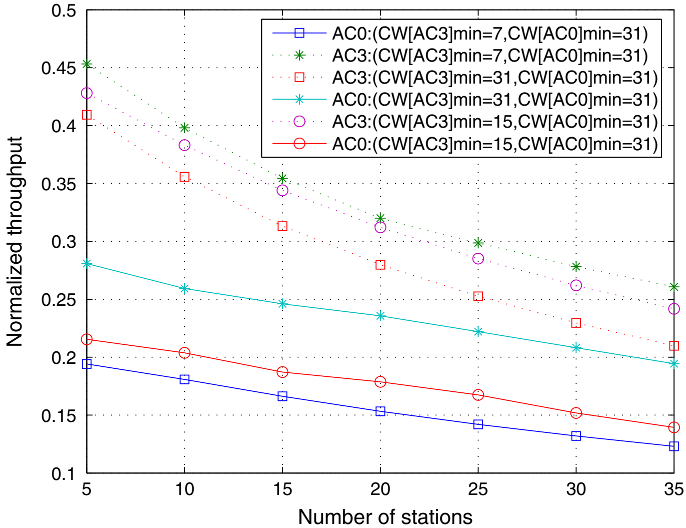

Fig. 16 effects of different CWs, normalized throughput with TXOPlimit, ($Nb_0 = 1, Nb_3 = 5$) and ($BER = 3 * 10^{-5}$)

virtual collision, introduced in EDCA. The main contribution of our study is that we consider the impact of TXOPlimit parameter under fading channel. The results show that our analytical model can accurately predict the throughput performance of IEEE 802.11e EDCA and also show the impact of the TXOPlimit parameter. As future work, we plan to investigate the delay performance of the EDCA mechanism.

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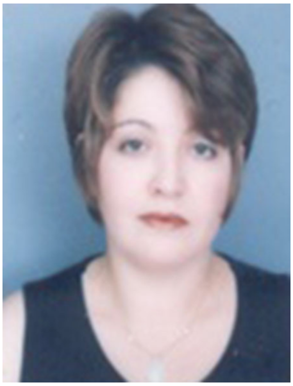

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