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Modeling and Analysis of the TXOPLimit Efficiency with the Packet Fragmentation in an IEEE 802.11e-EDCA Network Under Noise-Related Losses

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Abstract Analytical modeling and performance study of the Enhanced Distributed Channel Access (EDCA) function of the IEEE 802.11e standard has been the topic of various works available in the literature. Nevertheless, the Packet Fragmentation (PF) conceived by the IEEE 802.11 work group for decreasing the effect of noise-related losses on the performances of IEEE 802.11 networks, has not at all been taken into account in the analytical models proposed for evaluating the performance of the Opportunity Transmission Limit (TXOPLimit), which is a key parameter of the EDCA function for a Differentiated Service in an IEEE 802.11e network. While, the PF can be employed with the TXOPLimit, in order to boost the efficiency of the Contention Free Burst of both Voice and Video streams under noise-related losses. In this paper, we aim at extending the Markov chain models proposed for the IEEE 802.11e-EDCA network, in order to especially model the TXOPLimit, the PF and the Packet Error Rate. Besides, we elaborate a mathematical model to compute the saturation throughput of Access Categories, Voice, Video, Best Effort and Background. The achieved numerical results indicate, for the first time that, the PF permits boosting the TXOPLimit efficiency under noise-related losses. Thus, the saturation throughputs of both Voice and Video access categories are substantially enhanced.

Keywords IEEE 802.11e-EDCA network · TXOPLimit · Packet fragmentation · Noise-related losses · Modeling · Markov chains · Throughput analysis

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1 Introduction

Nowadays, the IEEE 802.11 Wireless Local Area Network (WLAN) is one of the widespread wireless networks to the general public [1]. It enables easy and reliable management of local, broadband networks at the house, in workplaces, or in public spaces and tremendously promotes access to the Internet [2]. Due to a strong request of wireless technologies (mainly IEEE 802.11 standard), ensuring the Quality of Service (QoS) is now a crucial challenge in the accomplishment of IEEE 802.11 Medium Access Control (MAC) protocols for the next generation WLANs. Accordingly, the IEEE 802.11e standard has been specified for holding the QoS needs over IEEE 802.11 WLANs [3]. 802.11e provides differentiated service classes at medium access layer level for supporting the delivery of priority packets. This is possible by introducing the Hybrid Coordination Function (HCF) access method, which defines the Enhanced Distributed Channel Access (EDCA) method and HCF Controlled Channel Access (HCCA) method [4].

The EDCA function specifies numerous QoS refinements compared to the basic 802.11 channel access, which is the Distributed Coordination Function (DCF). The functioning of the EDCA relies on the concept of Access Categories (ACs), where four ACs (every one with a distinct waiting queue) are defined as follows: Voice—VO, Video—VI, Best Effort—BE, and Background—BK [3]. To enable data stream differentiation, the EDCA function defines for each AC the following QoS settings: the Contention Window minimum (CW_{min}) and maximum (CW_{max}) size, the Arbitration Inter-Frame Space Number (*AIFSN*), and the Transmission Opportunity Limit (TXOPLimit). Each of the latter QoS settings has a special role to play, namely: CW_{min} and CW_{max} respectively corresponding to the original length of the contention window and the highest backoff value, *AIFSN* denotes the lowest number of empty slots prior to the commencement of the actual transmission, and TXOPLimit provides an opportunity for a given AC to subsequently transmit a burst of frames upon obtaining the right of access to channel [2]. A full specification of EDCA function may be obtained in [3].

Different approaches may be adopted towards performance evaluation of the EDCA function of the IEEE 802.11e standard, including: simulation/experiment (please, refer to: [5–19]) and mathematical modeling (please, refer to: [20–38]). Mathematical modeling is a formal approach for abstractly depicting the proper functioning of a system, usually in stationary state [39]. Resolving the mathematical models leads to accurate numerical results for system performance measurements [40]. The most basic method of mathematical modeling is Markov chains. Other high level methods based on Markov chains theory are also available, including: Queues and Queuing Networks, Petri Nets and stochastic Process Algebras [41]. Different criteria are used to select an appropriate method of mathematical modeling, namely: the type of analysis (quantitative or qualitative), the desired objectives, the level of detail required, etc. A mathematical model of a discrete event system, produced with one of said high level methods, may be correlated with a Markov chain Model using a process commonly called: state space generation [42]. So, Markov chains allow a lowest level of abstraction, that's what makes them the broadest method of mathematical modeling [43]. In particular, Discrete Time Markov Chains (DTMCs) are advisable for modeling a broad range of concurrent and stochastic computer systems [44]. In case of IEEE 802.11 networks, Markov chains set up very flexible, powerful, and efficient ways for modeling and evaluating the dynamic properties of such systems. In fact, the state space of a 802.11 network can be viewed as a graph, where the transitions between the 802.11 states are mentioned with directed arcs [45]. Accordingly, the majority of performance metrics (mainly, throughput and delay) can be readily computed.

Since the EDCA function has been introduced in the IEEE 802.11 standard, the Markov chain models formerly developed for the DCF function have become inadequate in evaluating 802.11 network with QoS. However, while these models lack data stream differentiation, they offer a solid basis for subsequent work, by showing how multiple states of the channel access method can be depicted with a Markov chain [2]. The work in this area is vast and important: Kong et al. [21] developed a mathematical model of the IEEE 802.11e network considering particularly the following EDCA parameters: *AIFS* and *CW*. On the one hand, the achievable throughput of the EDCA function is computed and, on the other hand, a recursive method able to calculate the mean access delay is proposed. Vassis and Kormentzas [22] elaborated a mathematical model of the EDCA function over unsaturated traffic conditions, in order to derive and evaluate different kinds of delay metric, namely: queuing delay, access delay, and total delay. Xiao [23] presented a mathematical model to investigate backoff-based priority procedures for both IEEE 802.11 standard and IEEE 802.11e amendment by adjusting the following settings: the minimum backoff window size, the backoff window-increasing factor, and the retransmission limit. Banchs and Vollero [24] proposed a mathematical model of the 802.11e network for identifying the optimal values of the EDCA parameters (namely, *AIFS*, CW_{min}, CW_{max} and TXOPLimit) capable of attaining a maximum throughput of the network. Tao and Panwar [25] designed a three-dimensional Markov chain modeling the EDCA function under infinite load conditions, to thereby determine the maximum sustainable throughput and service delay distribution of each 802.11e access category. Serrano et al. [27] provided analysis for throughput and delay metrics of the EDCA function under a finite load conditions, by proposing a mathematical model without making any assumption on the source's arrival process, and without needing to put all frames at the same length. Varposhti and Movahhedinia [14] exhibited an enhanced channel access method, known as Collision Avoidance with Fading Detection (CAFD), for reducing the impact of noise-related losses on EDCA performance (loss rate and packet delay). Pan and Wu [30] developed an analytical model of the EDCA function, which is based on the differentiated *IFS*, in order to evaluate the saturation throughput of the 802.11e network under heterogeneous traffic scenarios. In addition, the discrete time slot is considered for analyzing the external collision time. Hu et al. [31] presented a mathematical model of the EDCA function for specifically studying the TXOPLimit parameter in a single-hop 802.11e network under the existence of unbalanced stations with various traffic loads. The following performance measurements are given: throughput, end-to-end delay, frame dropping probability, and energy consumption. Hu et al. [34] accommodated, through a mathematical model, the integration of the EDCA parameters (namely: *AIFS*, *CW* and TXOPLimit) in an 802.11e network with finite buffer capacity under a finite load conditions. The proposed model derives the following performance metrics: throughput, delay, delay jitter, and frame loss probability.

Mathematical modeling and performance evaluation of the EDCA function of the IEEE 802.11e standard, while have been the subject of numerous studies from both the scientific and industrial communities, have generally occurred independently of concerns for noise-related losses. In particular, the efficiency of the TXOPLimit which is a relevant parameter for service differentiation between the different data streams in an IEEE 802.11e network, is also contestable when considering noise-related losses. Indeed, noise-related losses are very frequent in big towns and cities, they therefore induce additional delays and low throughput [46]. To deal with noise-related losses, the Packet Fragmentation (PF) is introduced in the MAC layer of the IEEE 802.11 standard [1] for enhancing the 802.11 performance under the influence of Packet Error Rate (PER) parameters, namely: Bit Error Rate (BER) and packet length (please, refer to: [36, 37, 47–50]). In this paper, we aim at studying how the Packet Fragmentation introduced in the IEEE 802.11 standard may be applied for improving the efficiency of the TXOPLimit in an IEEE 802.11e-EDCA network under the effect of noise-related losses. The goals sought to be attained in the present paper are defined as follows:

1. Firstly, we propose a new two-dimensional Markov chain modeling the EDCA function of the IEEE 802.11e standard, especially taking account of the TXOPLimit, the Packet Fragmentation and the Packet Error Rate.
2. Secondly, we develop a mathematical model to derive a new formulae capable of estimating the saturation throughput of the 802.11e-EDCA network enabling the TXOPLimit and the Packet Fragmentation under noise-related losses.
3. Finally, we conduct a throughput study of the IEEE 802.11e-EDCA network to demonstrate, for the first time ever, the essential role of Packet Fragmentation in improving TXOPLimit efficiency under noise-related losses.

This paper is structured as follows: in Sects. 2 and 3, we respectively provide an overview of the TXOPLimit and the Packet Fragmentation. In Sect. 4, we give a detailed description of the proposed mathematical model for EDCA function including TXOPLimit and Packet Fragmentation. In Sect. 5, we present and discuss the obtained numerical results about the sustainable throughput of the IEEE 802.11e-EDCA network. In Sect. 6, we conclude the paper.

2 Description of TXOPLimit Operation

The performance of the 802.11 network is negatively impacted by the overheads inherent to DCF function. The overheads of the 802.11 MAC layer arise from several well-known factors, including: physical (PHY) and MAC layer headers, control frames, backoff time, and inter-frame spaces. The higher the physical data rate, the more significant is the overheads generated by the 802.11 MAC layer. To address this issue, the TXOPLimit parameter has been introduced in the EDCA function of the IEEE 802.11e standard for enhancing the network performance. Indeed, the TXOPLimit parameter allows a 802.11e-EDCA station to transmit a burst of frames in a single channel access, unlike the basic 802.11-DCF station which may not exceed one frame after accessing the transmission channel [32].

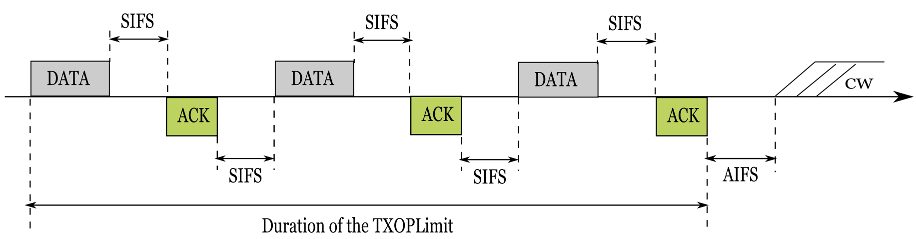

Fig. 1 Operating principle of TXOPLimit

In Fig. 1, we illustrate the operating principle of TXOPLimit. After having obtained access to a transmission channel, a 802.11e-EDCA station enabling the TXOPLimit parameter has the right to perform a succession of several DATA/ACKnowledgement (ACK) sequences. A Short Inter-Frame Space (SIFS) is then used to separate not only sending DATA and receiving ACK, but also the different DATA/ACK sequences. The number of DATA/ACK sequences that can be executed by a 802.11e-EDCA station depends on the duration of the TXOPLimit to be allocated for the 802.11e-EDCA station concerned. The transmission of a data burst containing several frames immediately stops if an ACK of a given frame is not received, even if the duration of the TXOPLimit has not yet expired. In this case, it would be necessary to regain access to the channel in order to resume the transmission of the data burst from the failed frame.

The TXOPLimit parameter allows a better efficiency of 802.11e-EDCA network by optimizing the bandwidth utilization. This is accomplished by transmitting all the frames contained in the data burst with one access to a transmission channel, namely by sharing the same contention overheads. By means of the TXOPLimit parameter, quality of service differentiation can also be realized between the different data streams by assigning to the different access categories different TXOPLimit durations. In addition, the TXOPLimit parameter is suggested in multi-rate 802.11 networks to ensure an equitable distribution of the transmission channel, by allocating long TXOPLimit durations for faster stations and short TXOPLimit durations for slower stations [32].

3 Description of Packet Fragmentation Operation

The partitioning process of a data packet into several data fragments is known as Packet Fragmentation. The purpose of this process is to produce smaller size data fragments, in order to increase the reliability of transmission of the original data packet in an environment affected by noise errors.

3.1 Basic Principle of Packet Fragmentation

A data packet is subdivided into several portions corresponding to different data fragments, if and only if the size of the data packet exceeds a certain predetermined value known as Fragmentation Threshold. In fact, the MAC layer of the IEEE 802.11 standard subdivides each data packet which has exceeded Fragmentation Threshold prior to inserting the MAC header and Frame Check Sequence (FCS), in such a manner that the size of the resulting data fragments does not exceed Fragmentation Threshold. The basic principle of Packet Fragmentation is illustrated in Fig. 2. The data fragments obtained after fragmentation of the data packet are subsequently transmitted in a single channel access. An individual ACK is then employed for acknowledging each received data fragment. In case of loss of a data fragment, the data packet transmission stops. The retransmission of the data packet will resume from the failed data fragment [1].

3.2 Detailed Operations of the Packet Fragmentation

After winning access to a transmission channel, a 802.11 station enabling the Packet Fragmentation transmits its data fragments one after another until all these data fragments are transmitted, or that an expected ACK for whatever data fragment has not been received

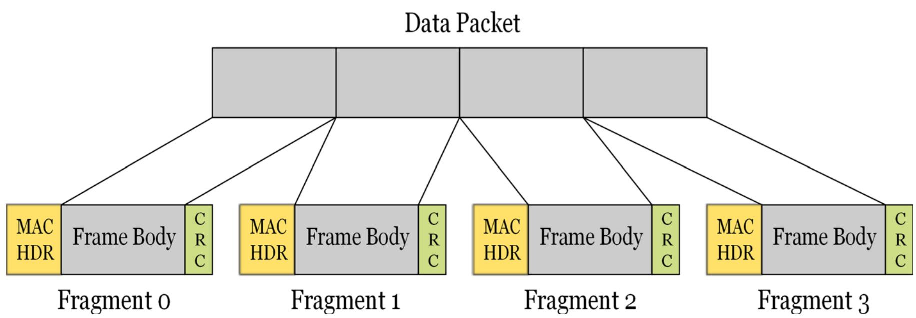

Fig. 2 Basic principle of packet fragmentation

at a predetermined time. The only thing that allows 802.11 station to monopolize the transmission channel during the transmission of the data fragments is the use of SIFS duration, as shown in Fig. 3. Each time a sending station transmits a data fragment, it starts listening to the transmission channel for receiving an ACK. After waiting a SIFS duration, the receiving station having successfully received a data fragment, in turn, responds by returning an ACK. If the sending station does not receive an ACK for a data fragment, it considers that the latter suffered a transmission failure. For retransmitting a lost data fragment and continuing the transmission of the next data fragments, the sending station has to win again the transmission channel [1].

4 Modeling 802.11e EDCA with TXOPLimit and PF

In this section, we propose a new two-dimensional discrete time Markov chain modeling the EDCA function of the IEEE 802.11e standard, especially taking account of the TXOPLimit, the Packet Fragmentation and the Packet Error Rate. Resolving the equations of the stationary probabilities of this Markov chain hence enables us to determine the packet transmission probability $\tau[h]$ of each Access Category h ($AC[h]$), where $h \in \{VO, VI, BE, BK\}$ knowing that VO, VI, BE and BK represent respectively the following data streams: Voice, Video, Best Effort and Background. This probability will then be used for developing mathematical models, in order to compute the saturation throughput of each $AC[h]$ in the IEEE 802.11e-EDCA network.

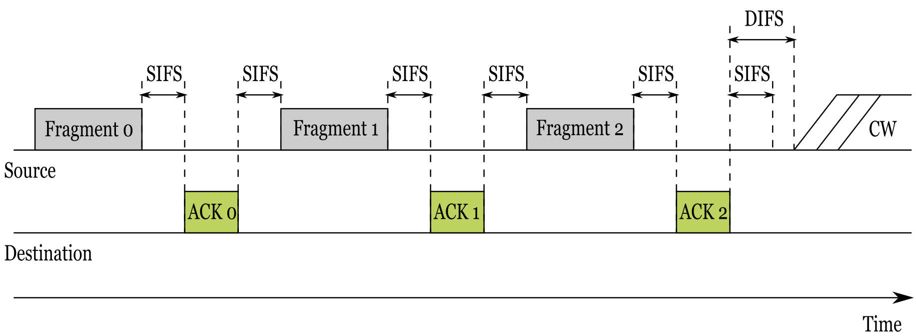

Fig. 3 Detailed operations of the packet fragmentation

4.1 Hypothesis of the 802.11e ECDA Mathematical Model

In what follows, we provide a detailed listing of all of the basic underlying hypothesis for the purposes of modeling the EDCA function of the IEEE 802.11e standard with TXO-PLimit and Packet Fragmentation under noise-related losses. Tables 1 and 2 respectively defining all the parameters and the basic probabilities necessary for modeling the 802.11e-EDCA network.

1. Each station that wins the transmission channel consecutively sends the packets available in its queue, given that the transmission time does not exceeds its specified TXOPLimit duration.
2. The transmission channel is error-prone, which means that noise-related losses may happen during the transmission of data.
3. At MAC level, the length of data is identical for all packets. If this exceeds Fragmentation Threshold, the packets are then fragmented.
4. The network comprises a constant number of stations, where transmission queues always contain packets to be transmitted on the network.
5. The collision probability of a packet is constant for whatever access category h, and it is also independent of the number of transmission failures.

Table 1 Parameters of the 802.11e EDCA mathematical model

Parameter	Description
n	Number of stations in the network
$m[h]$	Maximum backoff stage of the $AC[h]$
$W_0[h]$	Minimum contention window of the $AC[h]$
$W_m[h]$	Maximum contention window of the $AC[h]$
$W_i[h]$	Contention window size of the $AC[h]$ at the ith transmission attempt
$TXOPLimit[h]$	Time duration during which an $AC[h]$ is allowed to consecutively transmit a burst of packets
$TL[h]$	Maximum number of packets can be transmitted in burst during the $TXOPLimit[h]$ of the $AC[h]$
$NF[h]$	Maximum number of fragments can be transmitted in burst during the $TXOPLimit[h]$ of the $AC[h]$
P	Packet payload length
F	Fragment payload length
T_P	Transmission time of a packet payload
T_F	Transmission time of a fragment payload
T_{MAC}	Transmission time of the MAC layer header
T_{PHY}	Transmission time of the PHY layer header
ACK	Transmission time of an acknowledgment
$AIFSN[h]$	Minimum number of idle slots before a frame transmission of the $AC[h]$ may begin
$AIFS[h]$	Arbitration inter-frame space of the $AC[h]$
$SIFS$	Short inter-frame space
δ	Signal propagation time
σ	Time slot

Table 2 Probabilities of the 802.11e EDCA mathematical model

Probability	Definition
τ	Packet transmission probability of a station
$\tau[h]$	Packet transmission probability of the $AC[h]$
$P[h]$	Packet collision probability of the $AC[h]$
P_e	Packet error probability
P_p	Probability of achieving the end of a packet transmission after having transmitted all its fragments

4.2 Packet Transmission Probability

For estimating the stationary probability $\tau[h]$ that the $AC[h]$ transmits a packet in an arbitrary time slot, we propose to model the operation of a single access category h by a Markov chain. Thereafter, this probability will be needed in determining the saturation throughput of the $AC[h]$.

Let $S_{[h]}(t)$ be the stochastic process modeling the backoff stage i of the $AC[h]$ at a given time t (where, $i \in \{0, 1, \ldots, m[h]\}$).

Let $B_{[h]}(t)$ be the stochastic process modeling either the backoff time counter j or the kth transmitted packet during the $TXOPLimit[h]$ of the $AC[h]$ at a given time t (where, $j \in \{0, 1, \ldots, W_i[h]\}$ and $k \in \{-1, -2, \ldots, -TL[h]\}$).

For each access category h:

- The size of the contention window $W_i[h]$ at the ith transmission attempt is determined using the Eq. (1), which is illustrated by Fig. 4.

$$W_i[h] = 2^i \times W_0[h]. \tag{1}$$

- The maximum number of packets $TL[h]$ that can be transmitted in burst during the $TXOPLimit[h]$ is determined using the Eq. (2), which is illustrated by Fig. 5.

$$TL[h] = \frac{TXOPLimit[h]}{T_{PHY} + T_{MAC} + T_P + ACK + 2 \times SIFS + 2 \times \delta}. \tag{2}$$

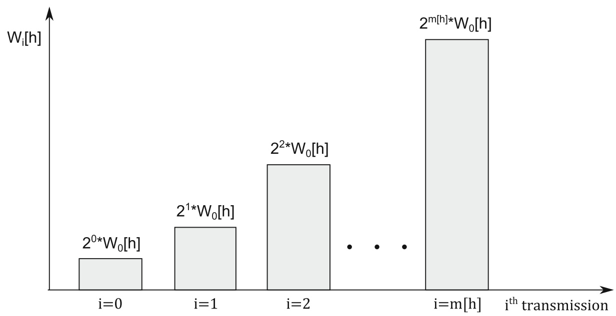

Fig. 4 Contention window size ($W_i[h]$) of the $AC[h]$ at ith transmission attempt

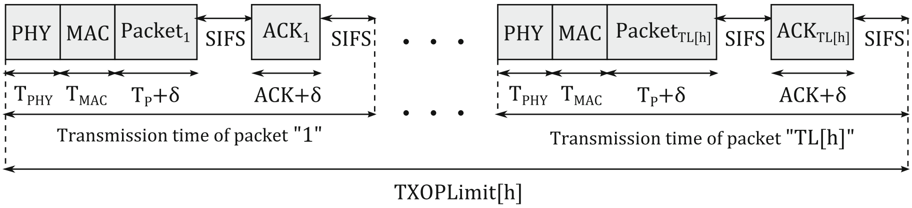

Fig. 5 Maximum number of packets (*TL*[*h*]) can be transmitted in burst during the *TXOPLimit*[*h*] of the *AC*[*h*]

The bi-dimensional process $\{S_{[h]}(t), B_{[h]}(t)\}$ can be modeled by the discrete-time Markov chain represented in Fig. 6, upon adoption of the well-known hypothesis of Bianchi's model [45]. This hypothesis is defined as follows: at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant and independent probability [45].

In the following, we list all non-zero transition probabilities of the proposed Markov chain:

$$P\{i,k/i,k+1\} = 1 - P[h],\ i \in (0, m[h]),\ k \in (-1, W_i[h] - 2). \tag{3a}$$

$$P\{i,k/i,k\} = P[h],\ i \in (0, m[h]),\ k \in (1, W_i[h] - 1). \tag{3b}$$

$$P\{i,k/i,k+1\} = (1 - P_e)P_p,\ i \in (0, m[h]),\ k \in (-TL[h], -2). \tag{3c}$$

$$P\{i,k/i,k\} = (1 - P_e)(1 - P_p),\ i \in (0, m[h]),\ k \in (-TL[h], -1). \tag{3d}$$

$$P\{i,k/i-1,0\} = P[h]/W_i[h],\ i \in (1, m[h]),\ k \in (0, W_i[h] - 1). \tag{3e}$$

$$P\{m[h],k/m[h],0\} = P[h]/W_m[h],\ k \in (0, W_m[h] - 1). \tag{3f}$$

$$P\{0,k/i,-TL[h]\} = P_p(1 - P_e)/W_0[h],\ i \in (0, m[h]),\ k \in (0, W_0[h] - 1). \tag{3g}$$

$$P\{i,k/i-1,k'\} = P_e/W_i[h],\ i \in (1, m[h]),\ k \in (0, W_i[h] - 1),\ k' \in (-TL[h], -1). \tag{3h}$$

$$P\{m[h],k/m[h],k'\} = P_e/W_m[h],\ k \in (0, W_m[h] - 1),\ k' \in (-TL[h], -1). \tag{3i}$$

The meaning of each transition probability is given as follows:

- $1 - P[h]$ is the probability that the $AC[h]$ finds the channel idle for decrementing its backoff time or beginning its transmission.
- $P[h]$ is the probability that the $AC[h]$ finds the channel busy for freezing its backoff time or detecting a collision.
- $(1 - P_e)P_p$ is the transmission probability of the last fragment of a given packet without noise errors.
- $(1 - P_e)(1 - P_p)$ is the transmission probability of the next fragment of a given packet without noise errors.
- $P[h]/W_i[h]$ is the probability that the $AC[h]$ chooses a new backoff time in the contention window $W_i[h]$ for retransmitting a packet lost due to a collision.
- $P[h]/W_m[h]$ is the probability that the $AC[h]$ chooses a new backoff time in the maximum contention window $W_m[h]$ for retransmitting a packet lost due to a collision.

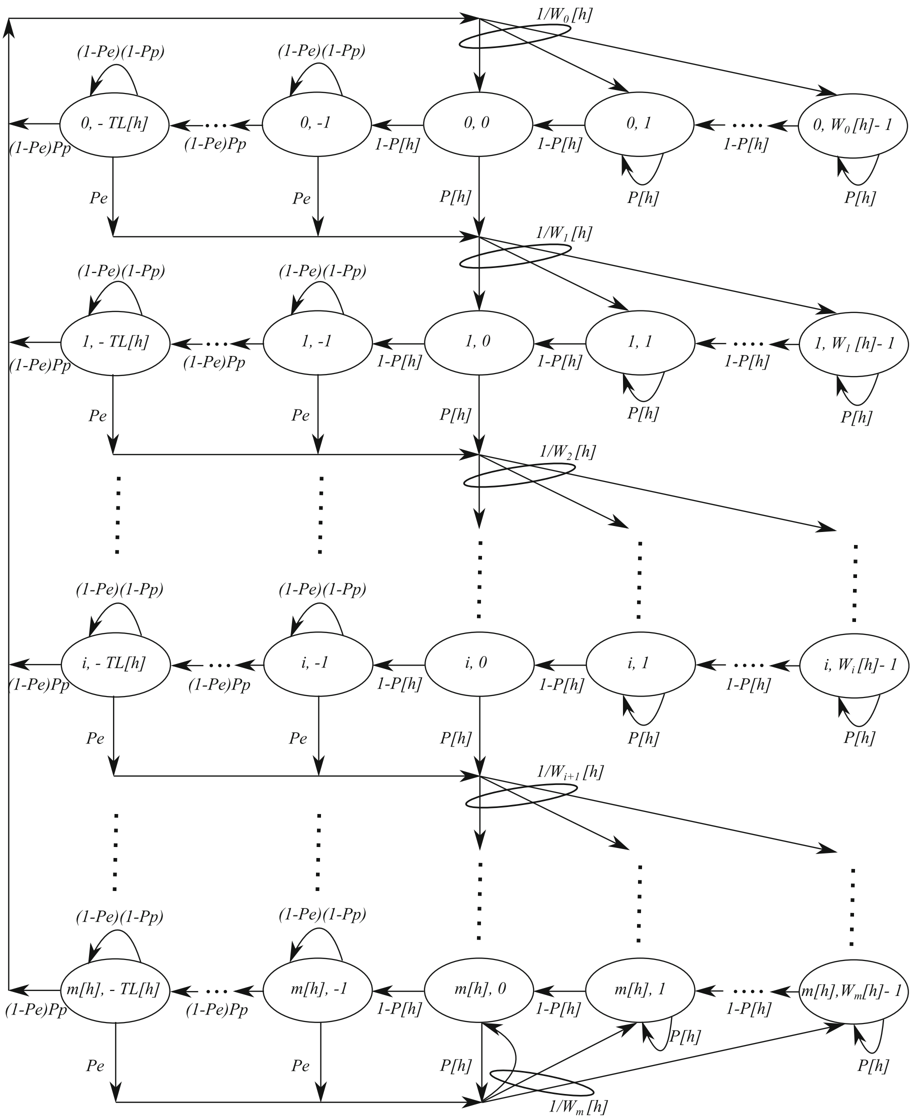

Fig. 6 Markov chain model of an access category h running the 802.11e EDCA function

- $P_p(1 - P_e)/W_0[h]$ is the probability that the $AC[h]$ chooses a new backoff time in the minimum contention window $W_0[h]$ after a successful transmission of all its packets.
- $P_e/W_i[h]$ is the probability that the $AC[h]$ chooses a new backoff time in the contention window $W_i[h]$ for retransmitting a packet lost due to noise errors.
- $P_e/W_m[h]$ is the probability that the $AC[h]$ chooses a new backoff time in the maximum contention window $W_m[h]$ for retransmitting a packet lost due to noise errors.

Let $\pi_{i,k} = lim_{t\to\infty} P\{S_{[h]}(t) = i, B_{[h]}(t) = k\},\ i \in (0, m[h]),\ k \in (-TL[h], W_i[h] - 1)$ be the stationary distribution of the proposed Markov chain modeling the 802.11e EDCA with

TXOPLimit and Packet Fragmentation under noise-related losses. In order to find the stationary distribution of our Markov chain, we apply the following *Balance* equation [51]:

$$\pi_i \times p_{ij} = \pi_j \times p_{ji}, \quad \forall i, j \in S.$$

where, S is the state space of the Markov chain, π_i is the stationary probability to be in state i, and p_{ij} is the transition probability from state i to state j.

The *Balance* equation has the following interpretation: it says that in the Markov chain, the flow from state i to state j is equal to that from state j to state i. For more details about the *Balance* equation, please refer to [51].

After applying the *Balance* equation on our Markov chain, we have obtained the following stationary distribution:

$$\pi_{i,k} = \begin{cases} \alpha^i \cdot \dfrac{W_i[h] - k}{W_i[h]} \cdot \dfrac{1}{1 - P[h]} \cdot \pi_{0,0}, & i \in (0, m[h]-1),\, k \in (0, W_i[h]-1); \\ \dfrac{\alpha^{m[h]}}{1-\alpha} \cdot \dfrac{W_i[h] - k}{W_i[h]} \cdot \dfrac{1}{1 - P[h]} \cdot \pi_{0,0}, & i = m[h],\, k \in (0, W_i[h]-1); \\ \alpha^i \cdot \dfrac{(1 - P[h]) \cdot \left[(1-P_e)P_p\right]^{(-k-1)}}{\left[(1-P_e)P_p + P_e\right]^{(-k)}} \cdot \pi_{0,0}, & i \in (0, m[h]-1),\, k \in (-1, -TL[h]); \\ \dfrac{\alpha^{m[h]}}{1-\alpha} \cdot \dfrac{(1 - P[h]) \cdot \left[(1-P_e)P_p\right]^{(-k-1)}}{\left[(1-P_e)P_p + P_e\right]^{(-k)}} \cdot \pi_{0,0}, & i = m[h],\, k \in (-1, -TL[h]). \end{cases} \tag{4}$$

where,

$$\alpha = 1 - \frac{(1 - P[h]) \cdot \left[(1-P_e)P_p\right]^{TL[h]}}{\left[(1-P_e)P_p + P_e\right]^{TL[h]}}. \tag{5}$$

According to Eq. (4), the stationary probabilities $\pi_{i,k}$ are expressed as a function dependent on the stationary probability $\pi_{0,0}$, and the packet collision probability $P[h]$. $\pi_{0,0}$ can then be found by imposing the normalization condition on our Markov chain. It is obtained as follows:

$$\begin{aligned} 1 &= \sum_{i=0}^{m[h]} \sum_{k=0}^{W_i[h]-1} \pi_{i,k} + \sum_{i=0}^{m[h]} \sum_{k=1}^{TL[h]} \pi_{i,-k}, \\ &= \pi_{0,0} \cdot \left[\frac{(W_0[h]+1) \cdot (1-2\alpha) + \alpha \cdot W_0[h] \cdot \left[1 - (2\alpha)^{m[h]}\right]}{2 \cdot (1-2\alpha) \cdot (1-\alpha) \cdot (1-P[h])} + \frac{\alpha - P[h]}{P_e \cdot (1-\alpha)} \right]. \end{aligned} \tag{6}$$

Hence, we have:

$$\pi_{0,0} = \frac{2 \cdot (1-2\alpha) \cdot (1-\alpha) \cdot (1-P[h])}{(1-2\alpha) \cdot \left[(W_0[h]+1) + \frac{2}{P_e} \cdot (\alpha - P[h]) \cdot (1-P[h])\right] + \alpha \cdot W_0[h] \cdot \left[1 - (2\alpha)^{m[h]}\right]}. \tag{7}$$

Now, the packet transmission probability $\tau[h]$ of the $AC[h]$ can be expressed as the sum of stationary probabilities $\pi_{i,k}$ of transmission states (i, k), where $i \in (0, m[h])$ and $k \in (-1, -TL[h])$. It is obtained as follows:

$$\tau[h] = \sum_{i=0}^{m[h]} \sum_{k=1}^{TL[h]} \pi_{i,-k} = \frac{\alpha - P[h]}{P_e \cdot (1-\alpha)} \cdot \pi_{0,0}, \\ = \frac{2 \cdot (1-2\alpha) \cdot (\alpha - P[h]) \cdot (1-P[h])}{(1-2\alpha) \cdot [P_e(W_0[h]+1) + 2(\alpha - P[h]) \cdot (1-P[h])] + P_e \cdot \alpha \cdot W_0[h] \cdot \left[1-(2\alpha)^{m[h]}\right]}. \tag{8}$$

Let τ denotes the probability that a given station of the 802.11e-EDCA network accesses the transmission channel. It may be found as the probability that at least one of the access categories (each with its packet transmission probability $\tau[h]$) of the station in question accesses the transmission channel. τ is given by the Eq. (9) wherein the values 3, 2, 1 and 0 are used to respectively represent the access categories VO, VI, BE and BK.

$$\tau = 1 - \prod_{h=0}^{3} (1 - \tau[h]) \tag{9}$$

The packet transmission probability $\tau[h]$ of the $AC[h]$, in turn, is based on the following probabilities:

- $P[h]$ (*packet collision probability of the* $AC[h]$); the probability that a packet of an $AC[h]$ is lost because of a collision in a given time slot, is expressed as the probability that at least one other station among $n-1$ stations of the network transmits, or at least one other $AC[i]$ (of the same station) having a higher priority ($i > h$) than that of $AC[h]$ transmits. It is obtained as follows:

$$P[h] = 1 - (1-\tau)^{n-1} \cdot \prod_{i>h} (1 - \tau[i]). \tag{10}$$

- P_e (*packet error probability*); the probability that a packet of any access category is lost because of noise errors in a given time slot, is expressed as a function of the BER and packet length. It is obtained as follows:

$$P_e = 1 - (1 - BER)^P. \tag{11}$$

- P_p (*probability of achieving the end of packet transmission*); the probability of achieving the transmission end of a packet of any access category after transmitting all its fragments, is expressed as the ratio of fragment payload length (F) to packet payload length (P). It is obtained as follows:

$$P_p = \frac{F}{P}. \tag{12}$$

The resolution of the Eqs. (8), (9) and (10), which together form a system of nonlinear equations, by means of numerical methods allows us to obtain the numerical values of the transition probabilities and stationary probabilities.

4.3 Saturation Throughput (*TH*[*h*])

The saturation throughput ($TH[h]$) that may be achieved by an $AC[h]$ in an IEEE 802.11e-EDCA network, is determined from the various events happening on the transmission channel during an arbitrary time slot. In the following, we provide the basic parameters required for developing $TH[h]$:

- Let P_{tr} be the probability that there is at least one station transmitting data in a given time slot. Since n stations contend on the channel, and each transmits with probability τ, P_{tr} is given as follows:

$$P_{tr} = 1 - (1 - \tau)^n. \tag{13}$$

- Let $P_s[h]$ be the probability that the $AC[h]$ wins the transmission channel. $P_s[h]$ is expressed by the fact that exactly one $AC[h]$ of a single station transmits on the transmission channel. It is given as follows:

$$P_s[h] = n\tau[h](1 - \tau[h])^{n-1} \times \prod_{i=0, i\neq h}^{3} (1 - \tau[i])^n. \tag{14}$$

- Let $T_c[h]$ be the sensing time of a collided transmission of the first fragment of the $AC[h]$ on the transmission channel. $T_c[h]$ is determined using the Eqs. (15) and (16), which are respectively illustrated by Figs. 7 and 8.

$$T_c[h] = T_{PHY} + T_{MAC} + T_F + \delta + AIFS[h]. \tag{15}$$

where,

$$AIFS[h] = AIFSN[h] \times \sigma + SIFS. \tag{16}$$

- Let $T_e[h]$ be the sensing time of an erroneous transmission of the first fragment of the $AC[h]$ on the transmission channel. $T_e[h]$ is determined using the Eq. (17), which is illustrated by Fig. 9.

$$T_e[h] = T_{PHY} + T_{MAC} + T_F + \delta + AIFS[h]. \tag{17}$$

- Let $T_j[h]$ be the sensing time of a transmission of j fragments successfully and the $(j+1)$th with error of the $AC[h]$ on the transmission channel. $T_j[h]$ is determined using the Eq. (18), which is illustrated by Fig. 10.

$$T_j[h] = j \times [T_{PHY} + T_{MAC} + T_F + ACK + 2 \times SIFS + 2 \times \delta] + T_e[h]. \tag{18}$$

- Let $T_s[h]$ be the sensing time of a successful transmission of all fragments of the $AC[h]$ on the transmission channel. $T_s[h]$ is determined using the Eqs. (19) and (20), which are respectively illustrated by Figs. 11 and 12.

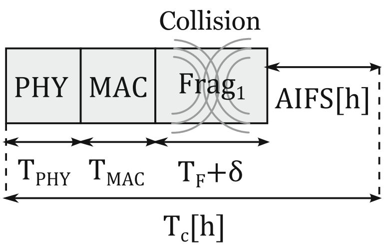

Fig. 7 Time of activity of the channel ($T_c[h]$) by a collision on the first fragment of the $AC[h]$

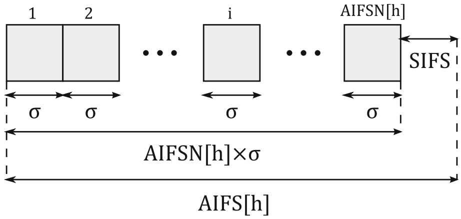

Fig. 8 Arbitration inter-frame space of the $AC[h]$ (AIFS[h])

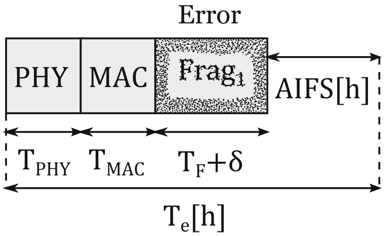

Fig. 9 Time of activity of the channel ($T_e[h]$) by an erroneous transmission on the first fragment of the $AC[h]$

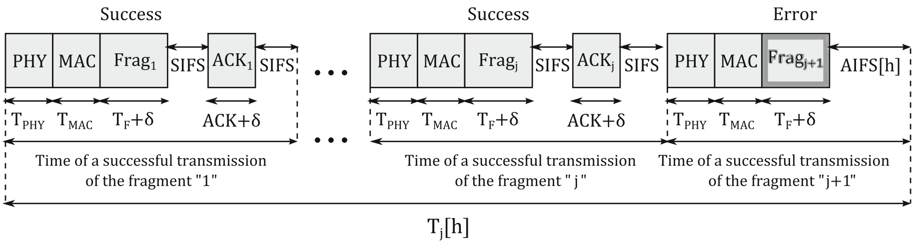

Fig. 10 Time of activity of the channel ($T_j[h]$) by a transmission of j fragments successfully and the $(j+1)$th with error of the $AC[h]$

$$T_s[h] = NF[h] \times [T_{PHY} + T_{MAC} + T_F + ACK + 2 \times SIFS + 2 \times \delta] \\ - SIFS + AIFS[h]. \tag{19}$$

where,

$$NF[h] = \frac{TXOPLimit[h]}{T_{PHY} + T_{MAC} + T_F + 2 \times SIFS + ACK + 2\delta} \tag{20}$$

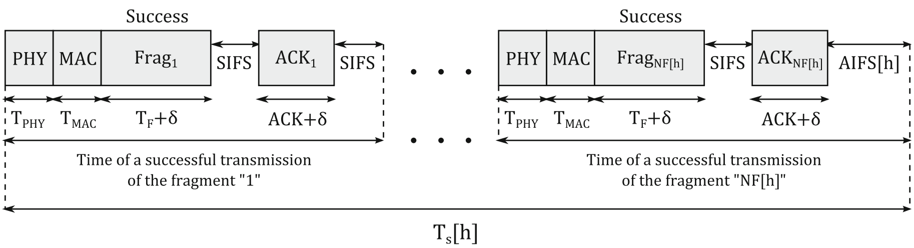

Fig. 11 Time of activity of the channel ($T_s[h]$) by a successful transmission of all the fragments of the $AC[h]$

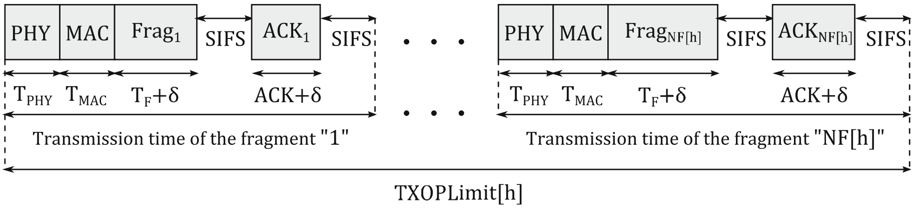

Fig. 12 Maximum number of fragments (*NF*[*h*]) can be transmitted in burst during the *TXOPLimit*[*h*] of the *AC*[*h*]

The saturation throughput *TH*[*h*] of the *AC*[*h*] can be expressed as the fraction of time that the transmission channel is employed to successfully transmit useful bits (payload). To determine *TH*[*h*], let us analyze the different events which can happen in a randomly chosen time slot (these events are illustrated in Fig. 13):

Event "1" with the probability $(1 - P_{tr})$, the transmission channel is idle [P_{tr} is given in Eq. (13)]. The time duration of this event is σ, and the amount of payload bits successfully transmitted during this event is equal to 0.

Event "2" with the probability $P_{tr} \times (1 - \sum_{h=0}^{3} P_s[h])$, the transmission channel contains a collision [$P_s[h]$ is given in Eq. (14)]. The time duration of this event is $T_c[h]$ [$T_c[h]$ is given in Eq. (15)], and the amount of payload bits successfully transmitted during this event is equal to 0.

Event "3" with the probability $P_{tr} \times \sum_{h=0}^{3} P_s[h] \times P_e$, the transmission channel contains an erroneous fragment [P_e is given in Eq. (11)]. The time duration of this event is $T_e[h]$ [$T_e[h]$ is given in Eq. (17)], and the amount of payload bits successfully transmitted during this event is equal 0.

Event "4" with the probability $P_{tr} \times \sum_{h=0}^{3} P_s[h] \times (1 - P_e)^j \times P_e$, the transmission channel contains j fragments successfully transmitted and the $(j + 1)$th is an erroneous

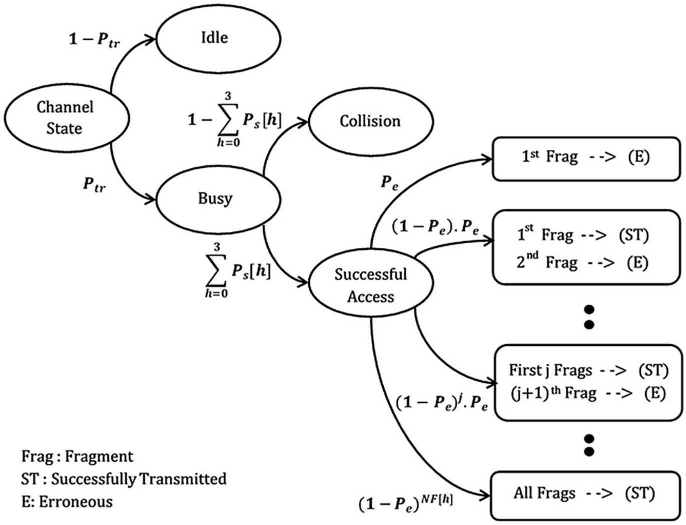

Fig. 13 Different events which can happen in a randomly chosen time slot

fragment. The time duration of this event is $T_j[h]$ [$T_j[h]$ is given in Eq. (18)], and the amount of payload bits successfully transmitted during this event is equal to $j \times F$ (where, F is the fragment payload length).

Event "5" with the probability $P_{tr} \times \sum_{h=0}^{3} P_s[h] \times (1-P_e)^{NF[h]}$, the transmission channel contains $NF[h]$ fragments successfully transmitted [$NF[h]$ is the maximum number of fragment that can be transmitted during the $TXOPLimit[h]$ of the $AC[h]$, it is given in Eq. (20)]. The time duration of this event is $T_s[h]$ [$T_s[h]$ is given in Eq. (19)], and the amount of payload bits successfully transmitted during this event is equal to $NF[h] \times F$.

Let $E[\sigma]$ denotes the average duration of a time slot. It is obtained as follows:

$$\begin{aligned}
E[\sigma] &= \sigma \times (1-P_{tr}) + T_c[h] \times P_{tr}\left(1 - \sum_{h=0}^{3} P_s[h]\right) + T_e[h] \times P_{tr} \sum_{h=0}^{3} P_s[h] \cdot P_e \\
&\quad + T_1[h] \times P_{tr} \sum_{h=0}^{3} P_s[h] \cdot (1-P_e)P_e + T_2[h] \times P_{tr} \sum_{h=0}^{3} P_s[h] \cdot (1-P_e)^2 P_e \\
&\quad + \cdots + T_j[h] \times P_{tr} \sum_{h=0}^{3} P_s[h] \cdot (1-P_e)^j P_e + \cdots \\
&\quad + T_s[h] \times P_{tr} \sum_{h=0}^{3} P_s[h] \cdot (1-P_e)^{NF[h]}. \\
E[\sigma] &= \sigma \times (1-P_{tr}) + T_c[h] \times P_{tr}\left(1 - \sum_{h=0}^{3} P_s[h]\right) + P_{tr} \sum_{h=0}^{3} P_s[h] \Big[T_e[h] \times P_e \\
&\quad T_1[h] \times (1-P_e)P_e + T_2[h] \times (1-P_e)^2 P_e + \cdots + T_j[h] \times (1-P_e)^j P_e \\
&\quad + \cdots + T_s[h] \times (1-P_e)^{NF[h]} \Big]. \\
E[\sigma] &= \sigma \times (1-P_{tr}) + T_c[h] \times P_{tr}\left(1 - \sum_{h=0}^{3} P_s[h]\right) + P_{tr} \sum_{h=0}^{3} P_s[h] \\
&\quad \times \left[T_e[h] \times P_e + \sum_{j=1}^{NF[h]-1} T_j[h] \times (1-P_e)^j P_e + T_s[h] \times (1-P_e)^{NF[h]} \right].
\end{aligned} \tag{21}$$

Let $E_I[h]$ denotes the average amount of payload bits successfully transmitted on the transmission channel by the $AC[h]$ in a randomly chosen time slot. It is obtained as follows:

$$\begin{aligned}
E_I[h] &= F \times P_s[h](1-P_e)P_e + 2F \times P_s[h](1-P_e)^2 P_e + \cdots \\
&\quad + jF \times P_s[h](1-P_e)^j P_e + \cdots + NF[h]F \times P_s[h](1-P_e)^{NF[h]}. \\
E_I[h] &= F \times P_s[h]\Big[(1-P_e)P_e + 2 \times (1-P_e)^2 P_e + \cdots + j \times (1-P_e)^j P_e \\
&\quad + \cdots + NF[h] \times (1-P_e)^{NF[h]}\Big]. \\
E_I[h] &= F \times P_s[h]\left[P_e \sum_{j=1}^{NF[h]-1} j \times (1-P_e)^j + NF[h] \times (1-P_e)^{NF[h]} \right].
\end{aligned} \tag{22}$$

Finally, the saturation throughput ($TH[h]$) of the $AC[h]$ is obtained as the ratio of average amount of payload bits successfully transmitted on the transmission channel to average duration of a time slot $E[\sigma]$. It is given as follows:

$$TH[h] = \frac{E_I[h]}{E[\sigma]}. \tag{23}$$

5 Numerical Results and Performance Study

In this section, the aim is to examine the numerical results obtained after the implementation (with Matlab) of the mathematical model presented in the previous section. These results are generated using various criteria, including: the value of the BER, the length of the packet, the number of stations in the network, aggregation/non-aggregation of packets, and fragmentation/non-fragmentation of packets. To generate the figures below, we have used the values presented in Tables 3 and 4. The ultimate objectives of this section are organized as follows:

- Firstly, we show the effect of noise-related losses on the saturation throughput attainable in an IEEE 802.11e-EDCA network that does not enable neither TXOPLimit nor Packet Fragmentation.
- Secondly, we show the effect of noise-related losses on the decrease in the efficiency of the TXOPLimit parameter, which is initially intended to optimize the bandwidth utilization.
- Finally, we show, for the first time, how the Packet Fragmentation allows increasing the efficiency of the TXOPLimit parameter under the effect of noise-related losses.

Figure 14 represents the saturation throughput of a given $AC[h]$ according to the BER value. This figure shows that, the saturation throughput of the IEEE 802.11e-EDCA network is decreasing along BER values. This is due to the PER which increases with the increase of BER [see Eq. (11)]. We note that, the decrease of throughput between the lower and the higher value of BER (10^{-5} and 10^{-4}, respectively) is about 50%. So, the BER is an important factor that should be considered when evaluating the performance of an IEEE 802.11 network, because if this does not happen this performance is overstated.

In Fig. 15, we have chosen a moderate BER (5×10^{-5}) and based on this value, we have computed the saturation throughput of a given $AC[h]$ according to the packet length. We show in this figure an increase of the throughput until the packet length reaches 1024 bytes. After this packet length, the obtained throughput is decreasing with the increase of

Table 3 802.11b PHY and MAC parameters

Parameter	Numerical value
δ	1 µs
σ	20 µs
$SIFS$	10 µs
Basic rate (PHY header)	1 Mbits/s
Basic rate (MAC header)	2 Mbits/s
Data rate	11 Mbits/s
PHY header length	192 bits
MAC header length	34 bytes
ACK length	14 bytes
Maximum payload length	2304 bytes

Table 4 802.11e-EDCA default parameters

$AC[h]$	m	AIFSN	W_0	W_m	TXOPLimit
AC[BK]	5	7	32	1024	0
AC[BE]	5	3	32	1024	0
AC[VI]	1	2	16	32	6016 s
AC[VO]	1	2	8	16	3264 s

the packet length. We note that, the decrease of the saturation throughput between its maximum and minimum value is about 27 and 30% for $AC[VO]$ and $AC[VI]$, respectively. The decrease of the saturation throughput is caused by the PER, which increases with the increase of the packet length [see Eq. (11)]. So, the packet length is an another critical issue which causes losses and degrades the performance of the IEEE 802.11e-EDCA network.

In Fig. 16, we have put the BER to a moderate value of 5×10^{-5}, the packet length to a mean value of 1024 bytes, and we have calculated the saturation throughput of a given $AC[h]$ according to the network size. This figure shows that, the saturation throughput of the IEEE 802.11e-EDCA network is decreasing with the increase of the number of stations in the network. This degradation of the throughput is related to the number of collisions, which becomes more important when the network size increases.

In Fig. 17, we have considered the TXOPLimit for both $AC[VI]$ and $AC[VO]$, each of them are respectively allowed to consecutively transmit 6 and 3 MPDUs. In case of moderate BER and middle packet length, we show that, the burst transmission of Video and Voice streams has considerably improved the saturation throughput of both $AC[VI]$ and $AC[VO]$. We note that, the obtained saturation throughput by the $AC[VO]$ is better than that of the $AC[VI]$, although the TXOPLimit assigned to the $AC[VI]$ is longer than that of the $AC[VO]$. This is due to the PER which terminates the burst transmission of $AC[VI]$ at each time the transmission of any video packet is failed. So, the $AC[VI]$ again accesses the transmission channel to retransmit the failed video packet.

In Fig. 18, we study the achievable saturation throughputs with TXOPLimit in cases of low and high BER (10^{-5} and 10^{-4}, respectively), and we compare them to the obtained throughputs without TXOPLimit in case of low BER. In case of low BER, we show that, the TXOPLimit permits to highly improve the saturation throughputs of $AC[VI]$ and

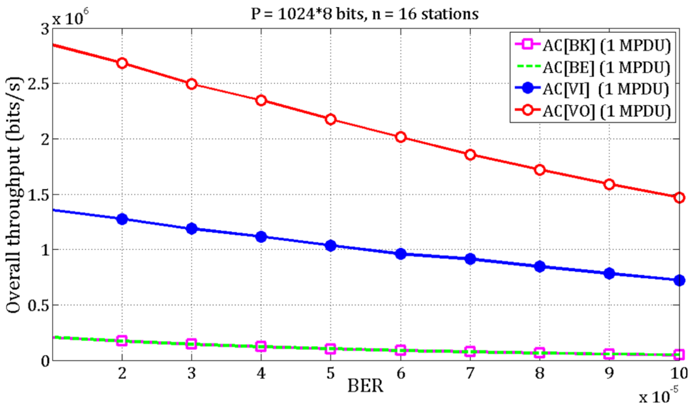

Fig. 14 Saturation throughput versus BER

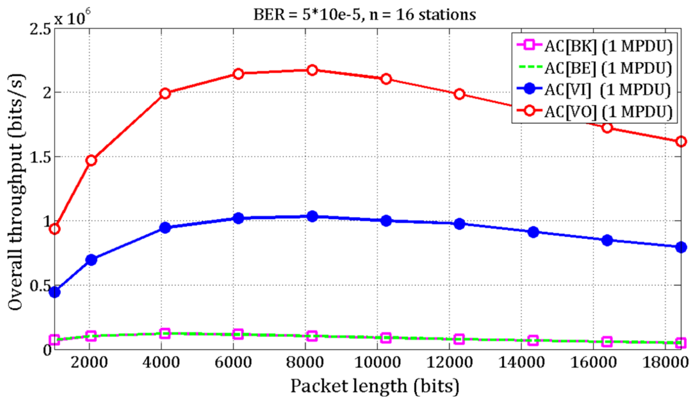

Fig. 15 Saturation throughput versus packet length

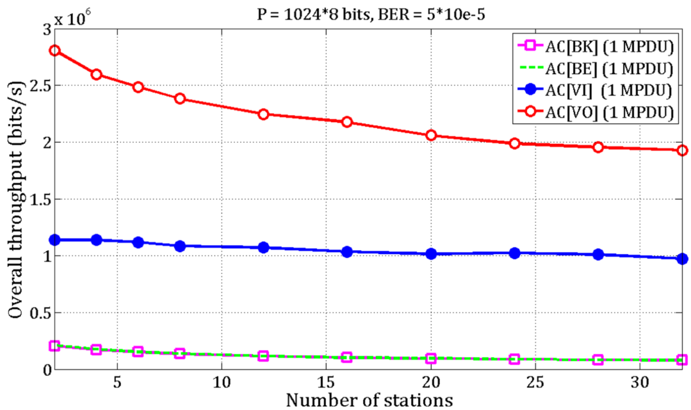

Fig. 16 Saturation throughput versus network size

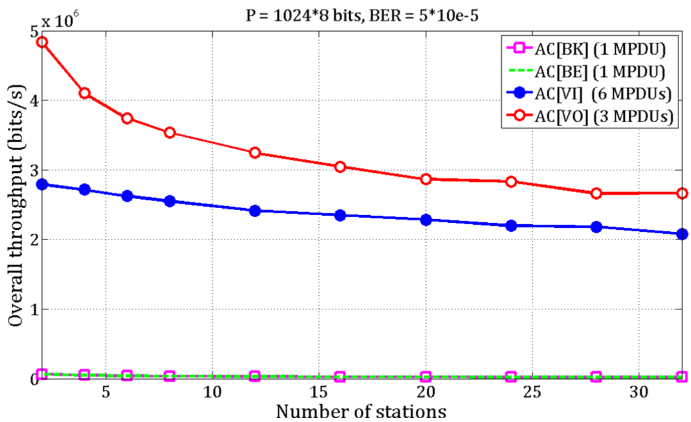

Fig. 17 Saturation throughput achieved with TXOPLimit according to the network size

AC[*VO*] compared to the obtained throughputs without TXOPLimit. The improvement level is about 78% for *AC*[*VI*] and 40% for *AC*[*VO*]. We note that, the throughput improvement of the *AC*[*VI*] is more important than that of the *AC*[*VO*], because the *AC*[*VI*] is allowed to transmit (in burst) more MPDUs than the *AC*[*VO*]. Since the BER is low (the effect of BER is negligible), the *AC*[*VI*] transmits all its authorized MPDUs during its own TXOPLimit. However, in case of high BER, the achievable saturation throughputs of *AC*[*VI*] and *AC*[*VO*] with TXOPLimit are highly degraded. They are below of the obtained throughputs without TXOPLimit in case of low BER. This is due to the burst transmission of *AC*[*VI*] and *AC*[*VO*] which is frequently stopped at each time the transmission of any packet (in burst) is failed. We can conclude that, when the BER is low, the TXOPLimit is a relevant parameter for service differentiation and improving the bandwidth utilization in an IEEE 802.11e network. However, when the BER is high, the TXOPLimit has any effect neither to improve the channel utilization nor to achieve QoS differentiation.

In Fig. 19, we consider a moderate BER (5×10^{-5}) in order to study the impact of the packet length on the achievable saturation throughputs of *AC*[*VI*] and *AC*[*VO*] with TXOPLimit. Therefore, we compute the achievable throughputs of *AC*[*VI*] and *AC*[*VO*] with TXOPLimit in cases of middle and maximum packet length (1024 and 2304 bytes, respectively) and we compare them to the obtained throughputs without TXOPLimit in case of middle packet length. When the packet length is middle, the TXOPLimit allows increasing the throughputs of *AC*[*VI*] and *AC*[*VO*] compared to the obtained throughputs without TXOPLimit. Whereas, when the maximum packet length is used with the TXO-PLimit, we note that, the throughputs of both *AC*[*VI*] and *AC*[*VO*] are decreased. This is due to the PER which is highly increased with the maximum packet length. The achievable throughputs of *AC*[*VI*] and *AC*[*VO*] with TXOPLimit in case of maximum packet length is below than the obtained throughputs without TXOPLimit in case of middle packet length. So, we also can affirm that, when the BER is moderate and the packet length is great, the TXOPLimit is not efficient neither for achieving service differentiation nor for enhancing the bandwidth utilization.

In Fig. 20, we study the achievable saturation throughputs of *AC*[*VI*] and *AC*[*VO*] with TXOPLimit in cases of non-fragmented and fragmented packets under a high BER value (10^{-4}), and we compare them to the obtained throughputs with TXOPLimit in case of non-

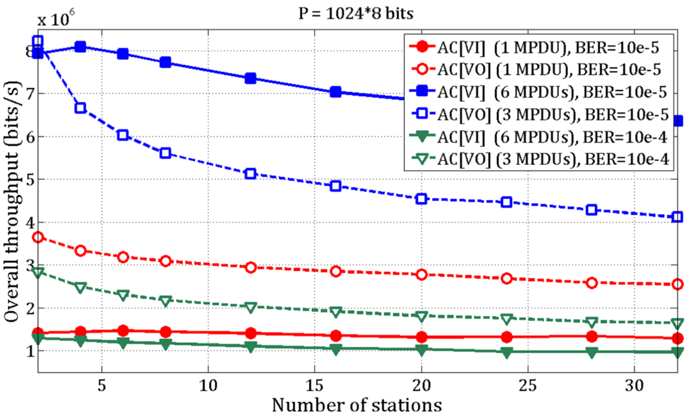

Fig. 18 Saturation throughput achieved with TXOPLimit in cases of low and high BER according to the network size

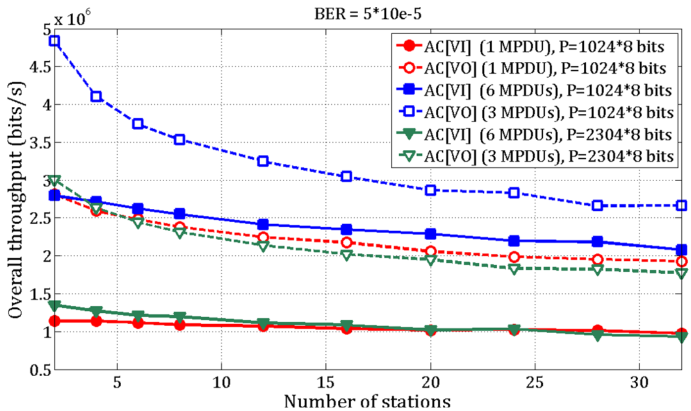

Fig. 19 Saturation throughput achievable with TXOPLimit in cases of middle and maximum packet length according to the network size

fragmented packets under a low BER value (10^{-5}). We show that, applying Packet Fragmentation with TXOPLimit allows increasing the throughputs of $AC[VI]$ and $AC[VO]$ under a high BER value. We note that, the improvement level is about 33% for $AC[VI]$ and 29% for $AC[VO]$ compared to the case of TXOPLimit with non-fragmented packets under a high BER value. This improvement level is due to the PER which is decreased once the Packet Fragmentation is used. Thereby, with the Packet Fragmentation, the $AC[VI]$ and $AC[VO]$ are able to transmit more frames during their TXOPLimits. So, we can affirm that, using the Packet Fragmentation in an IEEE 802.11e-ECDA network is an unquestionable solution for increasing the TXOPLimit efficiency under the impact of BER.

In Fig. 21, we have put the BER to a moderate value of 5×10^{-5}, and we have computed the achievable saturation throughputs of $AC[VI]$ and $AC[VO]$ with TXOPLimit by using the maximum packet length in cases of non-fragmented and fragmented packets. These results are compared with those of TXOPLimit in case of non-fragmented packets when the packet length is middle. We show that, using the Packet Fragmentation with

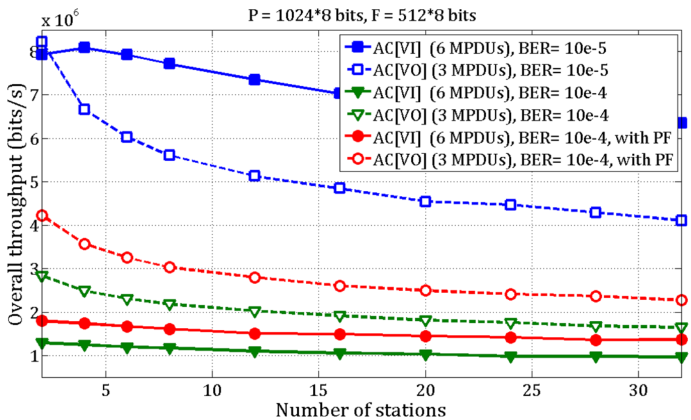

Fig. 20 Saturation throughput achievable with TXOPLimit and Packet Fragmentation in cases of low and high BER according to the network size

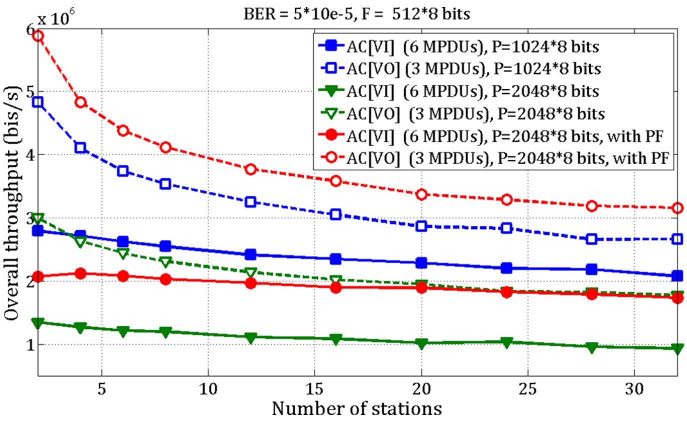

Fig. 21 Saturation throughput achievable with TXOPLimit and Packet Fragmentation in cases of middle and maximum packet length according to the network size

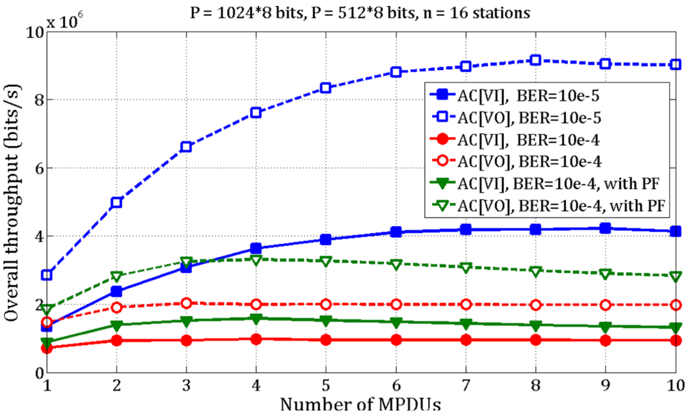

Fig. 22 Saturation throughput achievable with Packet Fragmentation in cases of low and high BER according to the network size

TXOPLimit, allows considerably improving the throughputs of both $AC[VI]$ and $AC[VO]$ when the maximum packet length is used under a moderate BER. The improvement level is about 50% for $AC[VI]$ and 47% for $AC[VO]$. This improvement level is due to the PER which is become a constant value for a given BER value whatever the packet length. Once the packets are subdivided into fragments, the PER does not increase although the increase of packet length. So, we also can affirm that, the Packet Fragmentation is an unquestionable solution for increasing the TXOPLimit efficiency under noise-related losses, mainly when the packet length is great.

In Figs. 22 and 23, we extend and approve the results presented in Figs. 20 and 21 for different number of MPDUs authorized to be transmitted during the TXOPLimit durations assigned to the $AC[VI]$ and $AC[VO]$. We show in Fig. 22 that, the TXOPLimit allows achieving service differentiated and enhancing the bandwidth utilization when the channel is ideal ($BER = 10^{-5}$). However, when the channel is disturbed ($BER = 10^{-4}$), the TXOPLimit efficiency is highly degraded. We note that, using the Packet Fragmentation

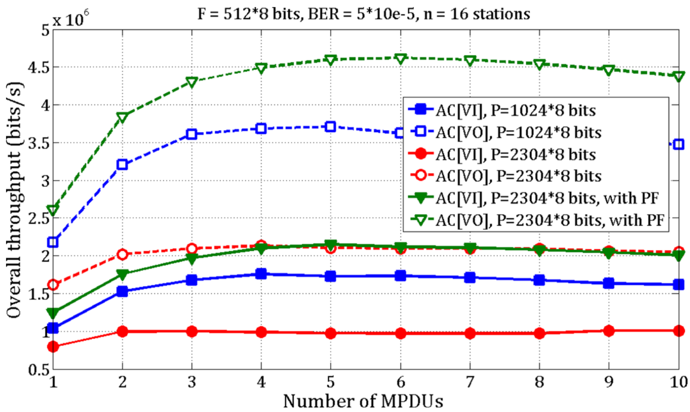

Fig. 23 Saturation throughput achievable with Packet Fragmentation in cases of middle and maximum packet length according to the network size

allows increasing the TXOPLimit efficiency under the impact of BER. We show in Fig. 23 that, the TXOPLimit efficiency is highly affected when the packet length is great. This issue is solved by using the Packet Fragmentation. We note that, the TXOPLimit with the Packet Fragmentation is become more efficient than the case without Packet Fragmentation whatever the packet length.

6 Conclusion

In this paper, we are interested in showing the relevance of the Packet Fragmentation, which is proposed for enhancing the performance of the legacy IEEE 802.11 standard under noise-related losses, towards improving the efficiency of the TXOPLimit, which is a key parameter proposed in the EDCA function of the IEEE 802.11e standard for service differentiation and enhancing the bandwidth utilization. For this purpose, we have proposed a new two-dimensional discrete time Markov chain modeling the 802.11e EDCA with TXOPLimit and Packet Fragmentation under noise-related losses. Thus, based on the computed stationary probability $\tau[h]$, means the probability that a given $AC[h]$ transmits a packet in a time slot, we have proposed a mathematical model to derive the saturation throughput of a given $AC[h]$. The presented numerical results, show on the one hand that the throughput of the IEEE 802.11e-EDCA network is highly degraded because of noise-related losses. Particularly, the efficiency of the TXOPLimit parameter has dropped significantly. On the other hand, our results show, for the first time that, the Packet Fragmentation combined with the TXOPLimit in an IEEE 802.11e-EDCA network under noise-related losses, allows achieving service differentiation and improving the bandwidth utilization. Consequently, we can reaffirm that the Packet Fragmentation is an unquestionable solution for improving the TXOPLimit efficiency in an error-prone channel.

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