Analytical Modeling of the IEEE 802.11e EDCA Network with Contention Free Burst

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Contention Free Burst (CFB) is a promising burst transmission scheme defined in the IEEE 802.11e Medium Access Control (MAC) protocol to achieve differentiated Quality of Service (QoS) and improve the utilization of the wireless scarce bandwidth. Although modeling and performance analysis of the IEEE 802.11e network have attracted tremendous research efforts from both the academia and industry, most existing analytical models do not give attention to the CFB QoS parameter. In this paper, we aim to propose a simple analytical model of the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) function including mainly the CFB, in order to study its effect on the improvement of the achievable throughput of Video and Voice Access Categories (ACs). Therefore, we propose a new two-dimensional Markov chain model of the IEEE 802.11e EDCA function with CFB. Then, we develop a mathematical model to derive the saturation throughput. Finally, performance analysis has allowed us to estimate the maximum sustainable throughput with CFB in an IEEE 802.11e-EDCA network under infinite load conditions.

IEEE 802.11e EDCA Function, CFB, Markov Chains, Modeling, Throughput Analysis

1. INTRODUCTION

The IEEE 802.11 standard is currently one of the most popular wireless access technologies. It allows for quick and simple configuration of local, broadband networks at home, in offices, or in public places and greatly facilitates Internet access (Kosek-Szott et al. (2011)). With the increasing demand of Wireless Local Area Networks (WLANs), especially of the IEEE 802.11 (IEEE 802.11 Standard (1999)), the support of differentiated Quality of Service (QoS) has become one of the recent critical challenges for the success of IEEE 802.11 Medium Access Control (MAC) protocols for the future wireless communications. It is important to develop a new medium access scheme that can support the differentiated QoS requirements over IEEE 802.11 WLANs, which is specified by the IEEE 802.11e (IEEE 802.11e Standard (2005)). The IEEE 802.11e standard specifies differentiated service classes in the MAC layer to enable different kind of packet priorities and have drawn tremendous interest from both industry and academia. IEEE 802.11e defines the Hybrid Coordination Function (HCF) access mechanism, which uses two mechanisms for the support of QoS differentiation. They are Enhanced Distributed Channel Access (EDCA) and HCF Controlled Channel Access (HCCA) (Lee et al. (2007)).

The EDCA function defines several QoS enhancements to the legacy IEEE 802.11 Distributed Coordination Function (DCF). EDCA operation is based on different priority levels through the definition of Access Categories (ACs). There are four ACs (Voice – VO, Video – VI, Best Effort – BE, and Background – BK), each with a separate queue. To provide traffic differentiation, the following medium access parameters are defined for each AC: the Contention Window minimum (CW_{min}) and maximum (CW_{max}) size, the Arbitration Inter-Frame Space Number ($AIFSN$), and the Contention Free Burst (CFB). The functions of the access parameters are as follows: CW_{min} and CW_{max} determine the initial size of the contention window and the maximum possible backoff value, respectively. $AIFSN$ determines the minimum number of idle slots before a frame transmission may begin. The CFB allows consecutive frame transmissions after gaining channel access (Kosek-Szott et al. (2011)). A comprehensive description of EDCA function can be found in (IEEE 802.11e Standard (2005)).

After the new EDCA function was defined, the previously proposed analytical models of the IEEE 802.11 DCF became unsatisfactory because they lacked traffic differentiation. However, they were a solid starting point for further research. Most of all, they resolved the complicated problem of representing multiple states of the channel access procedure by using Markov chains (Kosek-Szott et al. (2011)). In this area, Kong et al. (2004) presented an analytical model of the IEEE 802.11e EDCA taking into account AIFS and CW. The authors analyzed the throughput performance of differentiated service traffic and proposed a recursive method enable to provide the mean access delay. Vassis and Kormentzas (2005) presented an analytical model for the performance evaluation of IEEE 802.11e EDCA scheme under finite load conditions on the basis of various instances of delay metric (access delay, queuing delay and total delay). Banchs and Vollero (2006) presented an analytical model to analyze the throughput performance of an EDCA WLAN as a function of its parameters ($AIFS$, CW_{min}, CW_{max} and TXOPLimit). The authors searched for the optimal EDCA configuration which maximizes the throughput performance of the WLAN. Serrano et al. (2007) presented a model to analyze the throughput and delay performance of the EDCA mechanism under non-saturation conditions. The proposed model can be used to analyze generic source models, as it neither makes any assumption on the source's arrival process nor requires all packets be of the same length. Varposhti and Movahhedinia (2009) analyzed the effect of loss and delay caused by fading channel on EDCA performance. Then, they proposed a modification to the media access scheme, called Collision Avoidance with Fading Detection (CAFD) to enhance performance in wireless environments subject to failure. Hu et al. (2011) proposed an analytical model for the TXOP service differentiation scheme in single-hop ad hoc networks in the presence of unbalanced stations with different traffic loads. The QoS metrics including throughput, end-to-end delay, frame dropping probability, and energy consumption are derived. Hu et al. (2012) proposed an analytical model to accommodate the integration of the three QoS schemes including AIFS, CW and TXOPLimit in an IEEE 802.11e-EDCA network with finite buffer capacity under unsaturated traffic loads. The important QoS performance metrics in terms of throughput, delay, delay jitter, and frame loss probability are derived.

In this paper, we propose a simple analytical model of the IEEE 802.11e EDCA function with Contention Free Burst. Therefore, we use a two-dimensional Markov chain to model the behavior of a single access category. Then, we develop a mathematical model to derive the saturation throughput of a given access category.

The remainder of this paper is organized as following: an overview of the CFB scheme is given in section 2. In section 3, we describe the proposed analytical model of the IEEE 802.11e ECDA function with CFB. The obtained analytical results about the sustainable overall throughput in an IEEE 802.11e-EDCA network, are presented in section 4. In section 5, we conclude the paper.

2. OVERVIEW OF THE CFB SCHEME

In DCF, the system efficiency is considerably affected by various overheads referred to as Physical (PHY) layer headers, control frames, backoff, and inter-frame space. The overhead problem becomes more serious as the data rate increases. To mitigate the impact of the overheads and improve the system efficiency, the TXOP scheme has been proposed in the IEEE 802.11e protocol (Min et al. (2011)).

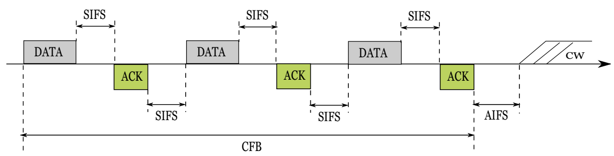

Figure 1: *Contention Free Burst scheme.*

Different from DCF where a station can transmit only one frame after winning the channel, the TXOP scheme allows a station gaining the channel to transmit the frames available in its buffer successively provided that the duration of transmission does not exceed a certain threshold, namely the CFB. As shown in Figure 1, each frame is acknowledged by an ACKnowledgement (ACK) after a Short Inter-Frame Space (SIFS) upon receiving this ACK. If the transmission of any frame fails, the burst is terminated and the station contends again for the channel to retransmit the failed frame. The TXOP scheme is an efficient way to improve the channel utilization because the contention overhead is shared among all the frames transmitted in a burst. Moreover, it enables service differentiation between multiple traffic classes by virtue of various CFBs. Another advantage of using the TXOP scheme is that the channel occupation time in multi-rate WLANs can be fairly distributed by allocating the larger CFB to faster stations. The slow stations, therefore, no longer severely degrade the performance of those with the higher rate (Min et al. (2011)).

3. MODELING 802.11E EDCA WITH CFB

In this section, we describe a new two-dimensional discrete time Markov chain model for the IEEE 802.11e EDCA function including the CFB. The resolution of stationary probabilities equations of this Markov chain model allows us to compute the packet transmission probability $\tau[h]$ of each access category h ($AC[h]$), where $h \in \{VO, VI, BE, BK\}$. This probability will be used to develop a mathematical model to derive the overall throughput of a given access category h in an IEEE 802.11e-EDCA network.

3.1. Assumptions of 802.11e ECDA Analytical Model

The following is a list of assumptions of our analytical model for the IEEE 802.11e EDCA function. Table 1 (resp. Table 2) includes Parameters (resp. Probabilities) of the 802.11e analytical model.

Table 1: *Parameters of the 802.11e analytical 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 i^{th} transmission attempt.
$TL[h]$	Maximum number of packets can be transmitted in burst during the $CFB[h]$ of the $AC[h]$.
P	Packet payload length.
T_P	Time of a packet payload transmission.
T_{MAC}	Time of a MAC layer header transmission.
T_{PHY}	Time of a PHY layer header transmission.
ACK	Time of an acknowledgment transmission.
$AIFS[h]$	Time interval of AIFS of the $AC[h]$.
$SIFS$	Time interval of SIFS.
δ	Time of a signal propagation.
σ	An empty slot time.

Table 2: *Probabilities of the 802.11e analytical model.*

Probability	***Definition***
τ	Packet transmission probability of a wireless station.
$\tau[h]$	Packet transmission probability of a $AC[h]$.
$P[h]$	Packet collision probability of a $AC[h]$.

1. All packets are of the same length. Each station that gains the channel access transmits the packets available in its queue consecutively, provided that the duration of transmission does not exceeds the specific CFB.
2. We assume a fixed number of wireless stations, where each access category h always having a packet available for transmission. In other words, we operate in saturation conditions.
3. The collision probability of a packet of any access category h is constant and is independent of the number of retransmissions.

3.2. Packet Transmission Probability

We study the behavior of a single access category h with a Markov chain model, and we obtain the stationary probability $\tau[h]$ that the $AC[h]$ transmits a packet in a generic slot time. This probability will be used to determine the saturation throughput of the IEEE 802.11e-EDCA network.

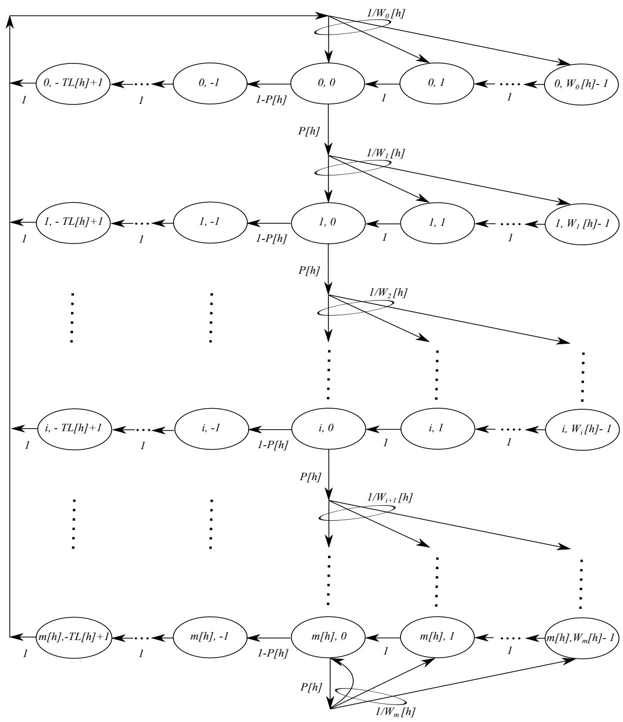

Figure 2: *Markov chain model of an access category h running the 802.11e EDCA function.*

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

Let $B_{[h]}(t)$ be the stochastic process representing either the backoff time counter j ($j = 0, 1, \ldots, W_i[h]$) or the k^{th} transmitted packet ($k = 0, -1, \ldots, -TL[h]+1$) during the $CFB[h]$ for a given $AC[h]$.

For a given $AC[h]$, the $W_i[h]$ and the $TL[h]$ are given by the Equations 1 and 2, respectively.

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

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

Once the key approximation in *Bianchi's* Markov chain model (Bianchi (2000)) is assumed (which means that, at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant and independent probability $P[h]$) it is possible to model the bi-dimensional process $\{S_{[h]}(t), B_{[h]}(t)\}$ with the discrete-time Markov chain depicted in Figure 2.

In this Markov chain, the only non null one-step transition probabilities are:

$$\begin{cases} P\{i,k/i,k+1\} = 1, \ i \in (0,m[h]), \ k \in (-TL[h]+1,-2). \\ P\{i,k/i,k+1\} = 1, \ i \in (0,m[h]), \ k \in (0,W_i[h]-2). \\ P\{i,-1/i,0\} = 1 - P[h], \ i \in (0,m[h]). \\ P\{0,k/i,-TL[h]+1\} = \dfrac{1}{W_0[h]}, \ i \in (0,m[h]), \ k \in (0,W_0[h]-1). \\ P\{i,k/i-1,0\} = \dfrac{P[h]}{W_i[h]}, \ i \in (1,m[h]), k \in (0,W_i[h]-1). \\ P\{m[h],k/m[h],0\} = \dfrac{P[h]}{W_m[h]}, \ k \in (0,W_m[h]-1). \end{cases} \tag{3a}$$

Let $\pi_{i,k} = lim_{t\to\infty} P\{S_{[h]}(t) = i, B_{[h]}(t) = k\}$, $i \in (0,m[h]), k \in (-TL[h]+1, W_i[h]-1)$ be the stationary distribution of the chain. The closed-form solution for this Markov chain is:

$$\pi_{i,k} = \begin{cases} \alpha^i \cdot \gamma \cdot \pi_{0,0}, & i \in (0,m[h]-1), k \in (0,W_i[h]-1); \\ \theta \cdot \gamma \cdot \pi_{0,0}, & i = m[h], k \in (0,W_i[h]-1); \\ \alpha^i \cdot \beta \cdot \pi_{0,0}, & i \in (0,m[h]-1), k \in (-1,-TL[h]+1); \\ \theta \cdot \beta \cdot \pi_{0,0}, & i = m[h], k \in (-1,-TL[h]+1). \end{cases} \tag{4}$$

Where,
- $\alpha = P[h]$.
- $\beta = 1 - P[h]$.
- $\gamma = \frac{W_i[h]-k}{W_i[h]}$.
- $\theta = \frac{P[h]^{m[h]}}{1-P[h]}$.

Thus, by the relation (4), all the values $\pi_{i,k}$ are expressed as a function of the value $\pi_{0,0}$ and packet collision probability $P[h]$. $\pi_{0,0}$ is finally determined by imposing the normalization condition, that can be simplified as follows:

$$\begin{aligned} 1 &= \sum_{i=0}^{m[h]} \sum_{k=0}^{W_i[h]-1} \pi_{i,k} + \sum_{i=0}^{m[h]} \sum_{k=1}^{TL[h]-1} \pi_{i,-k}, \\ &= \pi_{0,0} \cdot \left[\frac{\lambda_1 + \lambda_2}{\lambda_3} + (TL[h]-1)\right]. \end{aligned} \tag{5}$$

Where,
- $\lambda_1 = (W_0[h]+1) \cdot (1 - 2P[h])$.
- $\lambda_2 = P[h] \cdot W_0[h] \cdot \left[1 - (2P[h])^{m[h]}\right]$.
- $\lambda_3 = 2 \cdot (1 - 2P[h]) \cdot (1 - P[h])$.

Hence, we have:

$$\pi_{0,0} = \frac{\lambda_3}{\lambda_1 + \lambda_2 + \lambda_3 \cdot (TL[h]-1)}. \tag{6}$$

We can now express the probability $\tau[h]$ that an $AC[h]$ transmits in a random chosen slot time. It is the sum of all the steady-state probabilities of states $\pi_{i,k}$, $i = 0, 1, \cdots m[h]$, and $k = 0, -1, \cdots - TL[h] + 1$. In these states, an $AC[h]$ attempts to transmit its packets. Thus:

$$\begin{aligned} \tau[h] &= \sum_{i=0}^{m[h]} \sum_{k=1}^{TL[h]-1} \pi_{i,-k} + \sum_{i=0}^{m[h]} \pi_{i,0}, \\ &= \frac{TL[h] \cdot (1-P[h]) + P[h]}{1-P[h]} \cdot \pi_{0,0}, \\ &= \frac{\lambda_4}{\lambda_1 + \lambda_2 + \lambda_3 \cdot (TL[h]-1)}. \end{aligned} \tag{7}$$

Where,
- $\lambda_4 = 2 \cdot (1 - 2P[h]) \cdot (TL[h] \cdot (1 - P[h]) + P[h])$

From the viewpoint of a wireless station, the probability τ that the wireless station accesses the channel is given by the Equation 8, where the access categories VO, VI, BE and BK are represented by the priorities 3, 2, 1 and 0, respectively.

$$\tau = 1 - \prod_{h=0}^{3} (1 - \tau[h]) \tag{8}$$

The probability $P[h]$ that a transmitted packet of a given $AC[h]$ encounters a collision, is the probability that, in a time slot, at least one of $n-1$ remaining wireless stations transmits, or at least one of $AC[i]$ ($i > h$) of the same wireless station transmits. $i > h$ means that, $AC[i]$ has higher priority than $AC[h]$. Hence, we have:

$$P[h] = 1 - (1-\tau)^{n-1} \cdot \prod_{i>h} (1-\tau[i]). \quad (9)$$

Equations 7, 8 and 9 form a set of nonlinear equations. It can be solved by means of numerical methods. All the transition probabilities and steady-state probabilities can be obtained.

3.3. Saturation Throughput $(TH[h])$

We study the events that can occur within a generic slot time, and we express the saturation throughput of a given $AC[h]$ in an IEEE 802.11e-EDCA network, as a function of the computed value $\tau[h]$.

We express the elementary parameters of $TH[h]$:

• Let P_{tr} be the probability that there is at least a transmission in the considered slot time:

$$P_{tr} = 1 - (1-\tau)^n. \quad (10)$$

• Let $P_s[h]$ be the probability that the $AC[h]$ gets the channel access. It is given by the probability that exactly one $AC[h]$ transmits on the channel:

$$P_s[h] = n\tau[h](1-\tau[h])^{n-1} \cdot \prod_{i=0, i\neq h}^{3} (1-\tau[i])^n. \quad (11)$$

• Let T_c be the time that the channel is sensed busy by a collided transmission of the first packet of any $AC[h]$:

$$T_c = \min\{AIFS[h]\} + T_{MAC} + T_{PHY} + T_P + \delta \quad (12)$$

Where,

$$AIFS[h] = AIFSN[h] \times \sigma + SIFS. \quad (13)$$

• Let $T_s[h]$ be the time that the channel is sensed busy by a successful transmission of all the packets of the $AC[h]$:

$$\begin{aligned} T_s[h] =& AIFS[h] + TL[h] \cdot [T_{MAC} + T_{PHY} + T_P + \\ & 2SIFS + 2\delta + ACK] - SIFS. \end{aligned} \quad (14)$$

We define $E_I[h]$, as the average amount of useful information successfully transmitted by the $AC[h]$ in a slot time. It is given as follows:

$$E_I[h] = P_s[h] \cdot P \cdot TL[h]. \quad (15)$$

The average length of a slot time $E[\sigma]$, is obtained by considering that:

• With the probability $(1-P_{tr})$, the slot time is empty;

• With the probability $P_{tr}(1 - \sum_{h=0}^{3} P_s[h])$, the slot time contains a collision;

• With the probability $P_{tr} \sum_{h=0}^{3} P_s[h]$, the slot time contains $TL[h]$ packets successfully transmitted.

$$\begin{aligned} E[\sigma] =& (1-P_{tr}) \cdot \sigma + P_{tr} \left(1 - \sum_{h=0}^{3} P_s[h]\right) \cdot Tc + \\ & P_{tr} \left(\sum_{h=0}^{3} P_s[h]\right) \cdot T_s[h]. \end{aligned} \quad (16)$$

Now, we are able to express the saturation throughput $(TH[h])$ of a given $AC[h]$, as the ratio of the average amount of useful information successfully transmitted $E_I[h]$ to the average length of a slot time $E[\sigma]$:

$$TH[h] = \frac{E_I[h]}{E[\sigma]}. \quad (17)$$

4. SATURATION THROUGHPUT ANALYSIS

In this section, we present and analyze the obtained analytical results about the overall throughput of the IEEE 802.11e-EDCA network. These results are obtained after solving and programming the analytical model described in section 3 under Matlab software. The numerical values of parameters used to get the below figures, are listed in Tables 3 and 4.

The throughput analysis of the IEEE 802.11e-EDCA network provided in this section, is done with different BER values, packet lengths and network sizes, in cases of aggregated and non-aggregated packets. This analysis is original and leads to new conclusions that could not be intrusively expected.

In Figure 3, we compare the overall throughput of AC[VO] and AC[VI] obtained with and without CFB according to the number of stations in the network. We observe that, the overall throughput of both AC[VO] and AC[VI] is decreasing with the increase of the network size. This due to the number of collisions which increases with the increase of the number of stations in the network. We note on Figure 3 that, the use of CFB allows significant channel utilization improvement of both AC[VO] and AC[VI].

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	***CFB***
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

We also note that, when CFB is used, the overall throughput obtained with AC[VI] is greater than the one obtained with AC[VO]. This is due to the number of consecutive MPDUs sent by the AC[VI] which is greater than the one sent by the AC[VO].

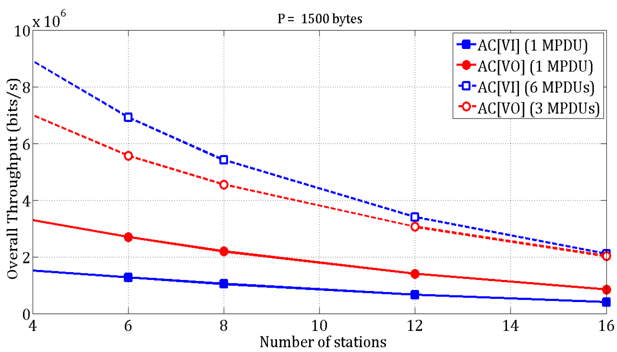

Figure 3: Overall throughput variation according to the network size.

In Figure 4, we compare the overall throughput of both AC[VO] and AC[VI] obtained with and without CFB according to the packet length. We show on this figure that, on one hand, the use of CFB permits considerably to improve the channel utilization compared to the case without CFB. On other hand, with CFB the overall throughput of AC[VO] and AC[VI] increases considerably with the increase of packet length. When the CFB is used, the collision can occur only on the first packet in burst and the other packets are spared from collision related losses. This is why the throughput in case of CFB increases significantly with the increase of the packet length.

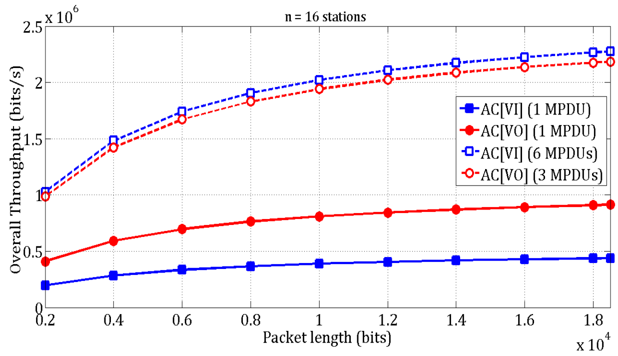

Figure 4: Overall throughput variation according to the packet length.

In Figure 5, we analyze the overall throughput of AC[VO] and AC[VI] according to the number of MPDUs in cases of middle and maximum packet length (1500 bytes and 2312 bytes, respectively). We show clearly that, the overall throughput of both AC[VO] and AC[VI] increases with the increase of the number of MPDUs allowed to be transmitted during a CFB. We also note that, increasing the packet length allows to increase the efficiency of CFB. Through the presented analytical results, we can affirm that, the CFB is a promising burst transmission scheme which allows to enhance the utilization of the bandwidth and to achieve QoS differentiation.

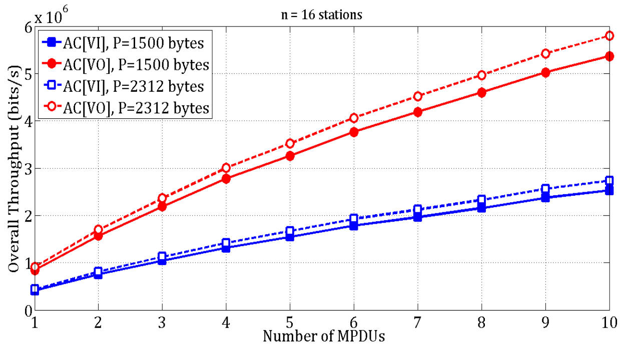

Figure 5: Overall throughput variation according to the CFB.

5. CONCLUSION

In this paper, we have proposed a simple analytical model of the IEEE 802.11e-EDCA network taking into account the CFB. So, we have proposed a new two dimensional discrete time Markov chain model. Then, we have developed a mathematical model to compute the saturation throughput with CFB of a given AC[h]. The obtained analytical results have allowed us to estimate the maximum throughput of the IEEE 802.11e-EDCA network with CFB. Particularly, the presented analytical results show how the Contention Free Burst permits to increase significantly the throughput of video and voice access categories.

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