Performance Analysis of IEEE 802.11e EDCA with QoS Enhancements through TXOP based Frame-concatenation and Block-acknowledgement

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Abstract

Enhanced distributed channel access (EDCA) protocol of IEEE 802.11e WLAN standard supports access category (AC) wise quality of service (QoS) differentiation. But the EDCA does not fulfill the very stringent QoS requirements of hard real-time applications. Keeping this in mind, in this research article, we have enhanced the QoS feature of EDCA by adding transmission opportunity (TXOP) based frame-concatenation with block-acknowledgement scheme. Together with these enhancements, we have proposed an analytical model for the performance analysis of EDCA using three-dimensional Markov chain. The contemporary models of EDCA support only a small subset of features. Our analytical model covers all salient features of EDCA. Also, the enhanced frame-concatenation with block-acknowledgement feature is included. The computed throughput and delay characteristics for both EDCA and EDCA with enhanced frame-concatenation with block-acknowledgement scheme are thoroughly studied and compared. Analytical and simulation results match pretty well and validate our model.

Keywords: Enhanced Distributed Channel Access (EDCA), Access Category (AC), Contention Window (CW), Arbitration Interframe Space Number (AIFSN), Transmission Opportunity (TXOP).

1. Introduction

Recently, there is wide-spread use of wireless local area networks (WLAN) for high speed wireless internet connectivity, which is based on the distributed coordination function (DCF) protocol of IEEE 802.11 WLAN standard [1]. In the last few years, the performance analysis of DCF protocol has attracted the attention of several researchers.

1.1 Related work

The most pioneering work on the performance analysis of DCF was the analytical models proposed by Bianchi [2, 3], based on two dimensional Markov chain. But the models [2, 3] did not support saturation delay analysis. Also, in the throughput analysis, those models have not incorporated the back-off counter freezing and frame discarding after retry limit. Xiao and Rosdahl [4] studied the maximum throughput and throughput limits of DCF.

But, the aforesaid models [2]-[4], are legacy DCF models. According to IEEE 802.11standard, DCF does not support priority based service differentiation, which is indispensable for real-time applications.

The enhanced distributed channel access (EDCA) protocol of the emerging IEEE 802.11e standard [5] supports access category wise quality of service (QoS) differentiation between the real-time and the non real-time applications. The contemporary research articles [6-14] on EDCA are all based on simulations. The research articles [15]-[26] have presented analytical models of EDCA. But those models [15]-[26] have considered only one priority class access category (AC) or flow per station, whereas the IEEE 802.11e EDCA standard [5] has suggested four simultaneously active access categories (ACs) per station with internal collision handling feature. Also, the models [16], [18]-[19], [21]-[23], [25]-[26] have not implemented the back-off counter freezing. This has made the models less accurate. The frame discarding after retry limit that decreases excessive frame access delay, which is indispensable for real-time applications, has not been considered by the model [19]. Also, the post back-off after successful transmission, which reduces the starvation of the lower ACs, has not been implemented by anyone of the models [15]–[26].

The rest of the paper is organized as follows. The proposed analytical model is presented in section 2. Section 3 provides performance analysis. The validation of model is discussed in section 4. Finally, the conclusion is drawn in section 5.

2. Proposed Analytical Model

2.1 Model description

In this section, we have proposed an analytical model of EDCA with three-dimensional discrete-time Markov chain. We have considered all salient features of EDCA, like multiple numbers of simultaneously active access categories per station, which is theoretically unlimited in our model, with internal collisions handling feature for service differentiation between ACs and also to enhance the channel efficiency. The channel sensing with back-off counter freezing during back-off process is incorporated to add accuracy to the model. Post-back-off after successful transmission is implemented to add fairness to the model. The frame discarding after maximum retransmission limit is also included to reduce excessive frame access delay to suit the requirements of real-time applications.

Also, to meet the very stringent QoS requirements of the variable bit-rate, hard real-time applications like interactive multi-media, video-conferencing, we have enhanced the quality of service feature of EDCA by adding a novel scheme, *i.e.* TXOP-based frame-concatenation with block-acknowledgement. Simple EDCA does not satisfy the very stringent bandwidth and delay requirements of these applications which are now integral part of our modern life. In such environments, multiple picture frames in the form of medium access control (MAC) data frames, are very frequently needed to be exchanged by the peer applications running between a pair of computers in a delay bound fashion with high bit rate.

Also, client-server based applications like file transfer, web document transfer are very popular today. Here, a client computer with multi-tasking and multi-threaded operating systems environment can open multiple data connections with its remote server computer for frequent exchange of multiple MAC data frames for large file transfer.

In both the above examples, all those MAC data frames would have the same source and destination addresses. In the proposed frame-concatenation scheme, the expected value of the payloads $\mathrm{E(P)_k}$ $(1 \leq k \leq n_i)$ of all these n_i number of MAC data frames of the access category AC_i can be sent in a single concatenated MAC data frame with only a single physical and MAC frame header as shown in fig 1. This saves the overheads of $(n_i - 1)$ numbers of physical headers H_p (each 112 bits) and MAC headers H_m (each 256 bits), leading to higher throughput and lower delay.

In our proposed scheme, after winning the channel only once through a single EDCA contention procedure, the i_{th} access category AC_i transmits n_i number of payloads of its n_i number of MAC data frames within its $TXOP_i$ time in the payload field *E (P)* of the single concatenated MAC frame with a single physical and MAC header. Simple EDCA would have required n_i numbers of EDCA contentions, for n_i numbers of individual frames. Each of these contentions would have its own overheads like *AIFS* channel sensing, random back-off process, RTS, CTS and SIFS overheads. By saving the overheads of $(n_i - 1)$ numbers of headers and contentions, the proposed scheme enhances the throughput and delay performance of all ACs and also improves the system performance. In order to improve the throughput and delay performance of the higher ACs, which run the hard real-time applications; higher *TXOP* times are allocated to them.

In the concatenation scheme, as shown in the fig 1, the receiver access category AC_i recovers the payload fields $E(P)_k$ $(1 \leq k \leq n_i)$ of all the original n_i number of MAC data frames from the payload field *E (P)* of the concatenated frame, using the 8 bit counter field. The counter field counts the number of payloads being concatenated. Subsequently, it performs the error-detection on every individual payload field $\mathrm{E(P)_k}$, using its corresponding 16 bits long Frame Check Sequence (FCS) field, denoted as FCS_{16}. This is done for fixed length payloads. For variable length payloads, instead of the counter field, a special bit pattern *FLAG* may be used as payload separators in the concatenated frame. If *FLAG* pattern appears in the payloads, the situation can be managed by bit-stuffing and bit-de-stuffing mechanism. Also, in our new concatenated frame structure (fig 1), there is a single 16 bits long *FCS* field, denoted by FCS_{16}, as trailer to take care of header. After the error detection, when the receiver access category AC_i receives a block acknowledgement request from the original sender, the former sends only a single block- acknowledgement frame in bit-map form for all the n_i number of MAC data frames to the latter. This single block acknowledgement saves $(n_i - 1)$ numbers individual acknowledgements and SIFS overheads. This further improves systems performance without compromising the reliability aspect.

2.2 Model Implementation

For the implementation of the proposed scheme, a new concatenated QoS data frame (CON-QoS-DATA) as shown in fig 1, is created with the reserved type field value of 11 and sub-type value of 1000 of the frame control field of MAC frame structure. We have also created a new block-acknowledgement request frame (CON-BLOCK-ACK-REQ) and a new block-acknowledgement frame (CON-BLOCK-ACK) with type 01 (control) for both the frames and subtype 0000 and 0001 for the respective frames from reserved values.

Their frame structure is similar to standard EDCA. The activation of our frame concatenation and block-acknowledgement scheme is through the same procedure of activation of the existing scheme i.e. through the ADDBA (Add Block Acknowledgement) frame. Also, in the implementation of the proposed scheme, only some additional new code is required to be added to the existing EDCA protocol software to interpret these new CON-QoS-DATA, CON-BLOCK-ACK-REQ and CON-BLOCK-ACK frames as per the semantics of their frame structure, discussed earlier. The existing EDCA protocol code will interpret its own QoS, non-QoS data and control frames as usual. Therefore, the implementation mechanism of our proposed frame-concatenation with block-acknowledgement scheme would maintain the backward compatibility with the existing EDCA protocol software.

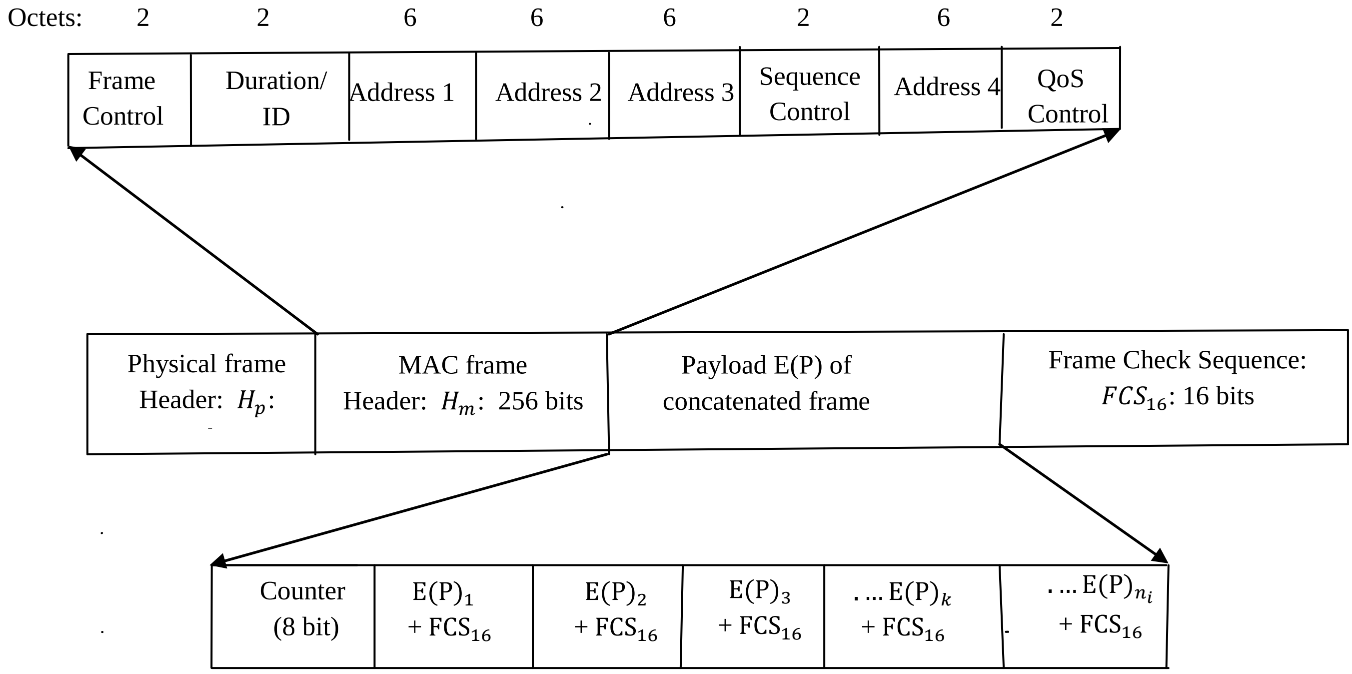

Fig 1: Structure of Concatenated MAC Data Frame (CON-QoS-DATA) of the i_{th} Access Category.

2.3 Markov Chain Formulations

In this section, we have formulated the discrete-time, three-dimensional Markov chain (fig 2) of our proposed model discussed in section 2.1 for the i_{th} access category AC_i within a station. The Markov chain formulated by Xiao [17] is primarily for priority based DCF, where each station has only one priority class. The Markov chain of our proposed model incorporates multiple priority class *ACs* per station with post-back-off after successful transmission. We have assumed ideal channel and saturation traffic condition for each *AC*. Each access category AC_i for $0 \leq i \leq ac_m - 1$, has its own minimum contention window $W_{i,0}$, transmission opportunity $TXOP_i$ and retry limit parameter $r_{i,max}$. Here, ac_m is the maximum number of simultaneously active access categories per station which is theoretically unlimited in our solution framework.

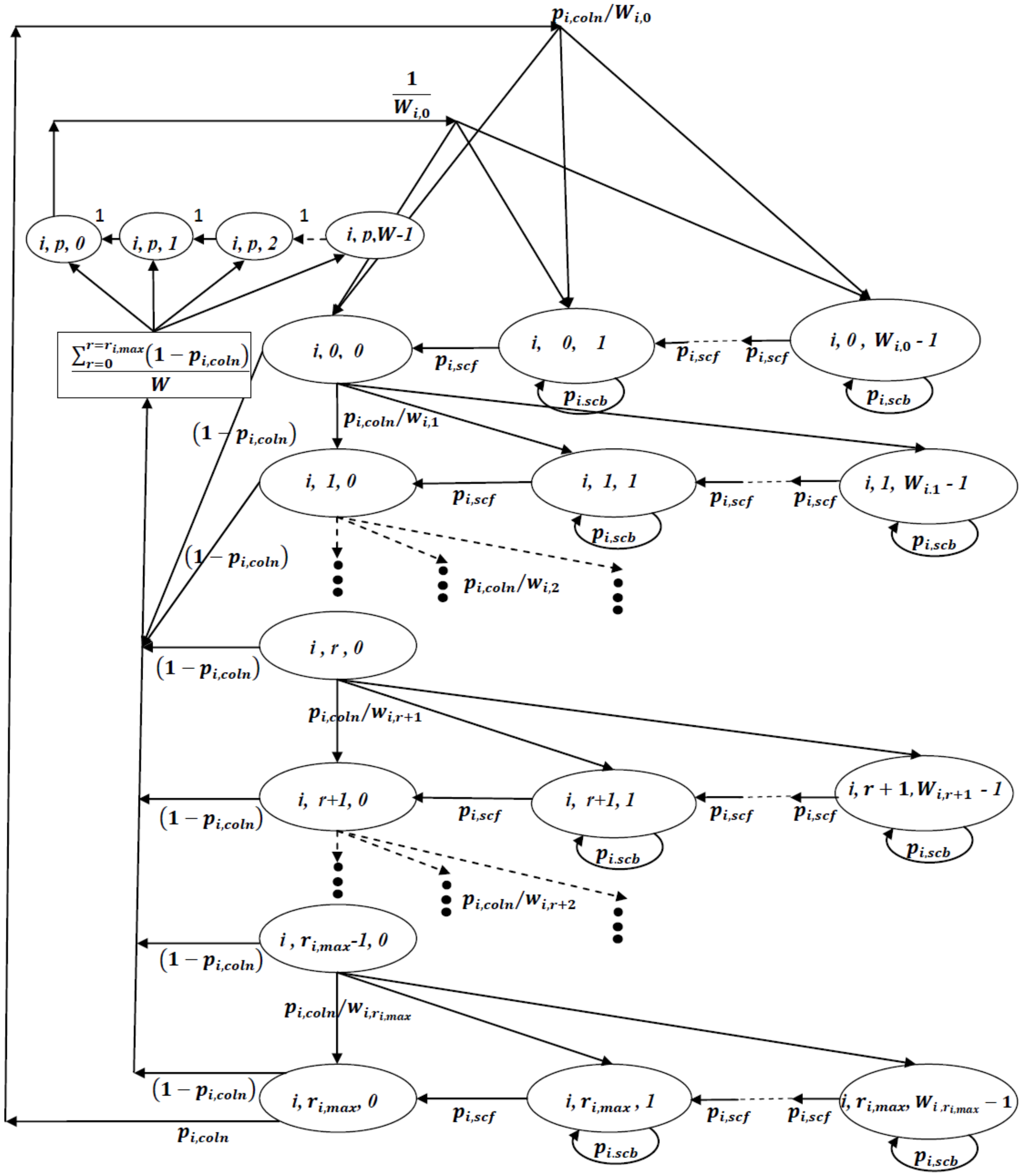

Fig 2: Markov Chain for the i_{th} Access Category

Each AC_i has its own queue and independently performs its back-off procedure like a virtual station. During back-off process, it either decrements or freezes its back-off counter at each slot time, by virtue of sensing the channel free or busy respectively with the probability of $p_{i,scf}$ or $p_{i,scb}$. The frame is transmitted when the back-off counter reaches zero. In case of collision, the frame is retransmitted. The retransmission proceeds up to $r_{i,max}$

attempts, after which frame is discarded. In our model, time is considered to be slotted. At each slot time, any one of the events like decrementing or freezing of back-off counter, successful transmission or collision triggers a transition from current state to next state as explained in subsequent section *2.5.*

Let *s(i, t)* and *b(i, t)* be the stochastic processes respectively to represent the back-off stage *r* and the back-off counter value k of an access category AC_i at slot time *t*. For pre-transmission back-off stage: $r \in [0, r_{i,max}]$ and for post-back-off stage: *r = p*. In the pre-transmission back-off stage *r*, the value of k of AC_i is randomly drawn from the range 0 to $W_{i,r} - 1$, using uniform distribution. Here, $W_{i,r}$ is the contention window of AC_i at pre-transmission back-off stage *r* and is given by: $W_{i,r} = (2)^r W_{i,0}$. We assume that the conditional collision probability $p_{i,coln}$ of AC_i is constant and independent of the back-off stage. Accordingly, the three-dimensional process *{i, s(i, t), b(i, t)}* for each access category AC_i becomes a discrete-time Markov chain. At slot time *t*, the state of AC_i within a station can be described by *(i, r, k).*

2.4 Post-back-off Stage

After each successful transmission, the post-back-off process at stage *r = p*, compels all ACs to go for a random wait. This wait interval is drawn uniformly from the range *0* to *W-1* time slots, where *W* denotes the post-back-off window. We have chosen the same post-back-off window *W* for all ACs to satisfy the inequality: $W_{3,0} < W_{2,0} < W < W_{1,0} < W_{0,0}$ with the pre-transmission back-off windows variables $W_{3,0}, W_{2,0}, W_{1,0}, W_{0,0}$. Due to this carefully chosen inequality, the post-transmission back-off process reduces the starvation of the lower ACs (*AC0, AC1*) by decreasing their post-transmission back-off delay compared to that of pre-transmission back-off process. Also, unlike pre-transmission back-off process, the transitional probability of decrementing the back-off counter during the post-transmission back-off is considered one, since the channel sensing is not implemented during this stage. This is because of the fact that, post-transmission back-off is not really meant for the frame transmission like the pre-transmission back-off process. It is performed only for adding some random wait to the recently successfully transmitting access categories to defer their next transmission.

2.5 Transition Probabilities

The non-null transition probabilities of i_{th} access category AC_i for $0 \le i \le ac_m - 1$, with the notational meaning of the parameters, as discussed in section 2.3 and 2.4 are listed below.

(1) In case of successful transmission, transition takes place to post back-off stage *p* for random wait

$$P\{(i, p, k)|(i, r, 0)\} = \frac{(1-p_{i,coln})}{W}, \quad 0 \le r \le r_{i,max}, 0 \le k \le W - 1.$$

(2) During collision, except during maximum back-off stage $r_{i,max}$, transition takes place to next stage by doubling the contention window

$$P\{(i, r+1, k)|(i, r, 0)\} = \frac{p_{i,coln}}{W_{i,r+1}}, \quad 0 \le r < r_{i,max}, \quad 0 \le k \le W_{i,r+1} - 1.$$

(3) During collision at maximum back-stage $r_{i,max}$, the frame is discarded and transition takes place to pre-transmission back-off stage 0 to transmit a new frame

$$P\{(i, 0, k) / (i, r_{i,max}, 0)\} = \frac{p_{i,coln}}{W_{i,0}}, \quad 0 \le k \le W_{i,0} - 1.$$

(4) During pre-transmission back-off process, the back-off counter is decremented by 1, if channel is free

$$P\{(i, r, k-1) / (i, r, k)\} = p_{i,scf}, \; 1 \le k \le W_{i,r} - 1, \; 0 \le r \le r_{i,max}.$$

(5) During pre-transmission back-off, the back-off counter is not decremented if channel is busy

$$P\{(i, r, k) / (i, r, k)\} = p_{i,scb}, \; 1 \le k \le W_{i,r} - 1, \; 0 \le r \le r_{i,max}.$$

(6) During post-back-off stage p, as there is no channel sensing, the back-off counter is always decremented

$$P\{(i, p, k-1) / (i, p, k)\} = 1, \; 1 \le k \le W - 1.$$

(7) After post-back-off, transition takes place to pre-transmission back-off stage 0 to transmit a new frame

$$P\{(i, 0, k) / (i, p, 0)\} = \frac{1}{W_{i,0}}, \; 0 \le k \le W_{i,0} - 1.$$

2.6 Systems Equations

Let $b_{i,r,k} = lim_{t\to\infty} P\{(i, s(i,t) = r, b(i,t) = k\}$ be the steady state probability of the state (i, r, k) for the i_{th} access category AC_i, $for\ 0 \le i \le ac_m - 1$. Similar to [2], we have

$$b_{i,r,0} = (p_{i,coln})^r \, b_{i,0,0}, \quad 0 \le r \le r_{i,max}. \tag{1}$$

Due to chain regularities, for pre-transmission back-off stage we can also derive

$$b_{i,r,k} = \frac{W_{i,r} - k}{W_{i,r}} \frac{b_{i,r,0}}{p_{i,scf}}, \quad 0 \le r \le r_{i,max}, \quad 1 \le k \le W_{i,r} - 1. \tag{2}$$

For post-back-off stage p, similar to Eq.(2), we derive

$$b_{i,p,k} = \frac{W-k}{W} \, b_{i,p,0}, \quad 0 \le k \le W - 1. \tag{3}$$

Also,

$$b_{i,p,0} = \sum_{r=0}^{r_{i,max}} (1 - p_{i,coln}) \, b_{i,r,0}. \tag{4}$$

Now, the sum total of the steady state probabilities of all the states of the chain is equal to 1. Therefore

$$\sum_{r=0}^{r_{i,max}} \sum_{k=0}^{W_{i,r}-1} b_{i,r,k} + \sum_{k=0}^{W-1} b_{i,p,k} = 1. \tag{5}$$

Using equations (1) to (5) and simplifying we get

$$b_{i,0,0} = \begin{bmatrix} \sum_{r=0}^{r_{i,max}} \left[\frac{p_{i,scf} + \left(\frac{W_{i,r}-1}{2}\right)}{p_{i,scf}} \right] (p_{i,coln})^r \\ + (1 - p_{i,coln}) \sum_{r=0}^{r_{i,max}} (p_{i,coln})^r \frac{W+1}{2} \end{bmatrix}^{-1}. \tag{6}$$

Let τ_i be the probability, that an AC_i within a station transmits in the channel in a randomly chosen slot time. Since a transmission occurs in state *(i,r,0)* for transmission stages: $r \in [0, r_{i,max}]$, τ_i may be expressed as the sum of steady state probabilities of all the corresponding *(i,r,0)* states. Therefore

$$\tau_i = \sum_{r=0}^{r_{i,max}} b_{i,r,0} = \sum_{r=0}^{r_{i,max}} b_{i,0,0} \left(p_{i,coln}\right)^r = \frac{\left(1-(p_{i,coln})^{(r_{i,max}+1)}\right)}{(1-p_{i,coln})} b_{i,0,0}. \quad (7)$$

Let τ be the probability that a station transmits in the channel in a randomly chosen slot time. A station transmits, when at least one of the access categories within that station transmits. Therefore

$$\tau = 1 - \prod_{i=0}^{ac_m-1} (1-\tau_i). \quad (8)$$

Let $p_{i,scf}$ be the probability that an AC_i within a station senses the channel free during pre-transmission back-off process. The AC_{i} would sense the channel free, if none of the *ACs* from the set of remaining *(N-1)* stations and none from the set of *ACs* excluding AC_{i}, within the same station transmit. Here N is the total number of stations in the WLAN. Therefore

$$p_{i,scf} = (1-\tau)^{N-1} \prod_{i' \neq i} (1-\tau_{i'}), \qquad 0 \le i \le ac_m - 1. \quad (9)$$

Therefore, the probability $p_{i,scb}$, that an AC_i within a station senses the channel busy be given as

$$p_{i,scb} = 1 - p_{i,scf}, \quad \text{since } p_{i,scb} + p_{i,scf} = 1. \quad (10)$$

Let $p_{i,coln}$ be the conditional collision probability *i.e*. the probability that an access category AC_i within a station, while transmitting, sees collision in the channel. Considering both external and internal collisions, such collision would occur when at least one of the access categories (*ACs*) from the set of remaining *(N-1)* stations or from the set of higher *ACs* than this AC_i within the same station transmits. Therefore

$$p_{i,coln} = 1 - (1-\tau)^{N-1} \prod_{i'>i} (1-\tau_{i'}). \quad (11)$$

Now Eq. (6) to (11), for $0 \le i \le (ac_m - 1)$, give rise to a total of $(5*ac_m+1)$ non-linear equations with equal number of unknown variables, depending on the value of ac_m. These variables are given by the set: $\{ b_{i,0,0}, \tau_i, p_{i,scf}, p_{i,scb}, p_{i,coln} \mid (0 \le i \le ac_m - 1)\}$ and τ. Here, $W, W_{i,0}, W_{i,r}, r_{i,max}$ are known constants for $0 \le r \le r_{i,max}$ and ac_m is numbers of simultaneously active access categories per stations, which is theoretically unlimited in our model. By numerical methods, we have solved the above equations for variables: $\{ \tau_i \mid (0 \le i \le ac_m - 1)\}$ and τ for any value of ac_m in the same solution framework. Knowing the values of above variables, the subsequent equations are solved easily by simple substitutions.

Let $p_{i,suc}$ be the successful transmission probability of an access category AC_i. Considering AC_i of all *N* stations, $p_{i,suc}$ can be calculated as *N* times the joint probabilities of the three independent events: (i) only this AC_i is transmitting in the channel, (ii) none of the *AC*s from the remaining *(N-1)* stations are transmitting and (iii) considering internal collision handling, none of the higher access categories than this AC_i in the same station are transmitting. Therefore

$$p_{i,suc} = N\tau_i (1-\tau)^{N-1} \prod_{i'>i} (1-\tau_{i'}) . \quad (12)$$

Now, considering all ACs, total successful transmission probability P_{suc} can be computed as the sum total of the successful transmission probabilities of the individual *ACs*. Therefore

$$P_{suc} = \sum_{i=0}^{ac_m - 1} p_{i,suc}. \tag{13}$$

Let P_{idle} be the probability that the channel is idle, *i.e*. the probability that none of the *N* stations in the WLAN are transmitting. Therefore

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

Finally, the probability $P_{coln,}$ that collision is taking in the channel, is given by

$$P_{coln} = 1 - P_{suc} - P_{idle} . \tag{15}$$

3. Performance Analysis

3.1 Saturation Throughput Computation without Frame-concatenation and Block-acknowledgement

The normalized saturation throughput of the access category AC_i *i.e.* $Throughput_i$ is defined as the ratio of the expected value of the successful transmission time of the payload (*P*), transmitted at the MAC speed ($speed_{mac}$), to the expected value of the total time of transmission. Therefore

$$Throughput_i = \frac{p_{i,suc}\frac{E(P)}{speed_{mac}}}{P_{idle}\,\delta + \sum_{i=0}^{ac_m-1}(p_{i,suc}\,T_{i,suc}) + P_{coln}T_{coln}} \tag{16}$$

Here, δ is the slot-time, $T_{i,suc}$ is the average successful transmission time of a frame of an AC_i and T_{coln} is the average collision time of a frame, as formulated in the subsequent equations.

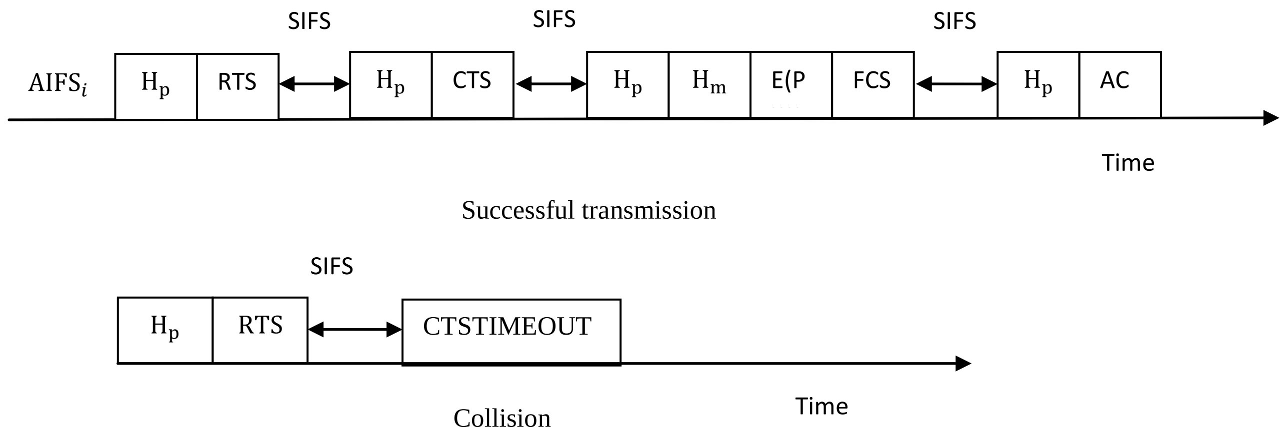

Fig 3(a): Timing Sequence for Transmission of RTS/CTS Mode of Standard EDCA for i_{th} AC.

Now, $T^{rts}{}_{i,suc}$ and $T^{rts}{}_{coln}$ (used in Eq. (16) as $T_{i,suc}$ and T_{coln}) are formulated for RTS/CTS mode, according to Figure 3(a).

$$T^{rts}{}_{i,suc} = AIFS_i + \left(\frac{H_p}{speed_{phy}} + \frac{RTS}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{CTS}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{H_m+E(P)+FCS}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{ACK}{speed_{mac}}\right) + 3\,SIFS\,. \tag{17}$$

Similarly,

$$T^{rts}{}_{coln} = \left(\frac{H_p}{speed_{phy}} + \frac{RTS}{speed_{mac}}\right) + SIFS + CTSTIMEOUT. \tag{18}$$

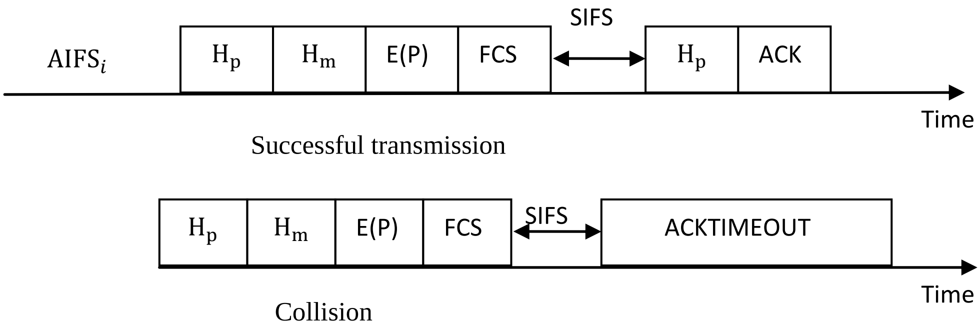

Fig 3(b): Timing Sequence for Transmission of Basic Mode of Standard EDCA for i_{th} AC.

Similarly, for the basic access scheme, according to Fig. 3(b)

$$T^{bas}{}_{i,suc} = AIFS_i + \left(\frac{H_p}{speed_{phy}} + \frac{H_m+E(P)+FCS}{speed_{mac}}\right) + SIFS + \left(\frac{H_p}{speed_{phy}} + \frac{ACK}{speed_{mac}}\right). \tag{19}$$

$$T^{bas}{}_{coln} = \left(\frac{H_p}{speed_{phy}} + \frac{H_m+E(p)+FCS}{speed_{mac}}\right) + SIFS + ACKTIMEOUT. \tag{20}$$

The notational meaning and the values above parameters are presented in table1 in section 4.

3.2 Saturation Throughput Computation with Frame-concatenation and Block-acknowledgement

For the proposed frame-concatenation and block-acknowledgement scheme, the saturation throughput of AC_i i.e.$Throughput_i{}^{fc}$ is given by

$$Throughput_i{}^{fc} = \frac{p_{i,suc}\; n_i \frac{E(P)}{speed_{mac}}}{P_{\;idle}\,\delta + \sum_{i=0}^{acm-1}\left(p_{i,suc}\,T^{fc}{}_{i,suc}\right) + P_{coln}\left(T^{fc}{}_{coln}\right)}\,. \tag{21}$$

The rationale behind the formulation of the above equation is similar to that of the equation (16), except the presence of the frame concatenation multiplication factor n_i, which is the number of payloads which are being transmitted in a single concatenated frame. Since, multiple numbers of payloads are transmitted in the single concatenated frame, $n_i > 1$. Here $T^{fc}_{i,suc}$ is the average successful transmission time of a concatenated frame-burst of an access category AC_i and $T^{fc}{}_{coln}$ is the average collision time. Since $n_i > 1$, the throughput of all ACs will be enhanced with the proposed frame-concatenation and block-acknowledgement scheme. As higher $TXOP_i$ times are allocated to higher *ACs*, the multiplication factor n_i (as per equation 22) will be greater for them compared to the lower *ACs*. Accordingly, the throughput of higher *ACs* will be higher. This is necessary as the higher *ACs* run the hard real-time applications.

For the RTS/CTS mode of the proposed concatenation scheme, the sender would set the Network Allocation Vector (NAV) for other stations to $TXOP_i$ time value of the AC_i in the duration field of the RTS and CTS frame. For the formulation of the equations for i_{th} access category AC_i of the aforesaid scheme, we replace the payload *E(P)* part of the timing sequence for the RTS/CTS mode of the EDCA of fig 3(a), by the expanded structure of the payload *E(P)* of concatenated frame *CON-QoS-DATA* of fig 1. Then we insert *CON-BLOCK-ACK-REQ* and *CON-BLOCK-ACK* frame with *SIFS* gap in the same timing sequence. Accordingly, to calculate frame concatenation multiplication factor n_i, we can equate

$$TXOP_i = \left(\frac{H_p}{speed_{phy}} + \frac{RTS}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{CTS}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{H_m+8+n_i(E(P)+FCS_{16})+FCS_{16}}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{CON-BLOCK-ACK-REQ}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{CON-BLOCK-ACK}{speed_{mac}}\right) + 4\,SIFS. \quad (22)$$

Here, FCS_{16} is the 16 bits long *FCS* field which is inserted with each payload field $E(P)_k (1 \le k \le n_i)$ within the single concatenated frame. FCS_{16} field is also inserted at the end of the frame (Fig 1). After calculating the value of n_i from the equation (22) for the proposed frame concatenation and block-acknowledgement scheme for RTS/CTS mode, the average successful transmission time $T_{i,suc}^{rts-fc}$ for AC_i is given by

$$T_{i,suc}^{rts-fc} = AIFS_i + \left(\frac{H_p}{speed_{phy}} + \frac{RTS}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{CTS}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{H_m+8+n_i(E(P)+FCS_{16})+FCS_{16}}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{CON-BLOCK-ACK-REQ}{speed_{mac}}\right) + \left(\frac{H_p}{speed_{phy}} + \frac{CON-BLOCK-ACK}{speed_{mac}}\right) + 4\,SIFS\,. \quad (23)$$

For collision, similar to equation (18), we can formulate

$$T_{coln}^{rts-fc} = \left(\frac{H_p}{speed_{phy}} + \frac{RTS}{speed_{mac}}\right) + SIFS + CTSTIMEOUT. \quad (24)$$

3.3 Saturation Delay Computation without Frame-concatenation and Block-acknowledgement

For saturation delay computation we have followed Xiao [17] with substantial modifications.

Let $P_{i,sf}$ be the probability, that a frame of access category AC_i, is successfully transmitted within $r_{i,max}$ number of re-transmissions. Therefore

$$P_{i,sf} = \sum_{r=0}^{r_{i,max}} (p_{i,coln})^r \left(1 - p_{i,coln}\right) = 1 - (p_{i,coln})^{r_{i,max}+1} \;. \quad (25)$$

Let $B_{i,slot}$ be a random variable denoting the total number of back-off slots, a frame of AC_i, goes through during the pre-transmission back-off stage within the retry limit $r_{i,max}$, before its successful transmission (denoted by B_i) and also during post-transmission back-off stage p, for random wait. Therefore

$$E\,(B_{i,slot}) = \left(\sum_{r=0}^{r_{i,max}} \frac{p_{i,coln}{}^{r}\,(1-p_{i,coln})}{\left(1-(p_{i,coln})^{r_{i,max}+1}\right)} \sum_{u=0}^{r} \sum_{n=1}^{W_{i,u}-1} \frac{n}{W_{i,u}}\right) + \left(\frac{W-1}{2}\right) = B_i + \left(\frac{W-1}{2}\right). \quad (26)$$

Let $F_{i,slot}$ be a random variable denoting the total instances of freezing during pre-transmission back–off stage for a frame of AC_i, before its successful transmission. Since the $E\,(F_{i,slot})$ is proportional to the expected value of the total pre-transmission back-off slots B_i (Eq. (26)), and $p_{i,scb}$ (Eq.(10)), therefore

$$E(F_{i,slot}) = B_i \frac{p_{i,scb}}{(p_{i,scb}+p_{i,scf})}. \quad (27)$$

Let $R_{i,retrans}$ be a random variable denoting the total number of retransmissions for a frame of access category AC_i, before its successful transmission. Hence

$$E\left(R_{i,retrans}\right) = \sum_{r=0}^{r_{i,max}} \frac{r\,(p_{i,coln})^{r}\,(1-p_{i,coln})}{1-(p_{i,coln})^{r_{i,max}+1}}. \quad (28)$$

Let $FRAME_{i,delay}$ be a random variable denoting the total saturation frame access delay for a frame of access category AC_i, before its successful transmission. Therefore, for the RTS/CTS and basic mode

$$E\,(FRAME_{i,delay}) = E(B_{i,slot})\,\delta + E\left(F_{i,slot}\right) T_i + E\left(R_{i,retrans}\right) T_{coln} + T_{i,suc}. \quad (29)$$

Here $$T_i = \frac{\sum_{j=0,j\neq i}^{ac_m-1} (p_{j,suc}\,T_{j,suc}) + P_{coln} T_{coln}}{\sum_{j=0,j\neq i}^{ac_m-1} (p_{j,suc}) + P_{coln}}. \quad (30)$$

is the average transmission time including the successful transmission and collision time of other *ACs* that makes the channel busy for the access category AC_i during its freezing of back-off counter.

3.4 Saturation Delay Computation with Frame-concatenation and Block-acknowledgment

For the proposed frame- bursting with block-acknowledgement scheme, let $FRAME_{i,delay}^{rts-fc}$ be a random variable denoting the total saturation frame access delay of a single frame of AC_i before its successful transmission for RTS/CTS mode. Therefore, through the similar computation presented in section 3.3, we get

$$E\,[FRAME_{i,delay}^{rts-fc}] = \frac{[\,E(B_{i,slot})]\delta + E(F_{i,slot})\,T^{rts-fc}{}_{i} + E\left(R_{i,retrans}\right) T_{coln}^{rts-fc} + T_{i,suc}^{rts-fc}\,]}{n_i}. \quad (31)$$

Where $$T^{rts-fc}{}_{i} = \frac{\sum_{j=0,\ j\neq i}^{ac_m-1} \left(p_{j,suc}\,T_{j,suc}^{rts-fc}\right) + P_{coln}\,T_{coln}^{rts-fc}}{\left(\sum_{j=0,\ j\neq i}^{ac_m-1} p_{j,suc} + P_{coln}\right)}. \quad (32)$$

The notational meaning of $T^{rts-fc}{}_{i}$ is similar to T_i of section 3.3 and n_i is the number of frames in the concatenated frame-burst.

4. Validation of Model

The number of simultaneous active ACs within a station in our model is theoretically unlimited. But for simplicity and without the loss of generality, we have considered four *ACs i.e. AC0*, *AC1*, *AC2* and *AC3* to satisfy the requirement of IEEE 802.11e EDCA standard. Here *AC0* is the lowest and *AC3* is the highest priority *AC*. For service differentiation, each access category AC_i ($0 \leq i \leq 3$) has its own parameter values like arbitration inter-frame space number$AIFSN_i$, minimum contention window $W_{i,0}$, transmission opportunity time $TXOP_i$ and retry limit value $r_{i,max}$. These parameters are presented in the following sets: $AIFSN$ set = $\{AIFSN_0, AIFSN_1, AIFSN_2, AIFSN_3\}$; W_0set = $\{W_{0,0}, W_{1,0}, W_{2,0}, W_{3,0}\}$; *TXOP set* = $\{TXOP_0, TXOP_1, TXOP_2, TXOP_3\}$ and R_{max} set $= \{r_{0,max}, r_{1,max}, r_{2,max}, r_{3,max}\}$. We have incorporated the following inequalities for service differentiation between ACs: $AIFSN_0 > AIFSN_1 > AIFSN_2 > AIFSN_3$; $W_{0,0} > W_{1,0} > W_{2,0} > W_{3,0}$ and $TXOP_0 < TXOP_1 < TXOP_2 < TXOP_3$.

4.1 Comparison of Simulation and Analytical results

The simulation of the proposed model has been carried in NS2 [27] network simulator which is the most popular network simulator among the researchers. For implementing frame-concatenation with block-acknowledgement scheme, we have extended NS2 by incorporating additional code in C++ and linking it to the existing code. For simulation purpose, we have considered four *ACs* per station. We have used constant bit rate traffic with its rate higher than the link capacity to implement the saturation traffic condition. Also, each *AC* within a station transmits fixed size user datagram protocol (UDP) packets. For performance measurement, we have repeated simulations 25 times for each case. The final results of simulations are obtained by taking their average. All the parameters used for analysis and simulation purpose are listed in Table 1. The physical header is transmitted at 1 mbps, physical /channel speed. The AC transmits the MAC header, payload and FCS at 11 mbps (MAC) speed.

Table 1 802.11e PHY/MAC Parameters for Analysis and Simulation

Payload size [E(P)]	1024	Bytes	Physical/Channel Speed [$speed_{phy}$]	1	Mbps
Physical Header [H_p]	192	bits	MAC speed [$speed_{mac}$]	11	Mbps
Data Frame MAC Header [H_m]	256	bits	Slot-time [δ]	20	μs
			SIFS	10	μs
RTS Frame [RTS]	160	bits	DIFS = $2^* \delta$ + SIFS		μs
CTS Frame [CTS]	112	bits	ACKTIMEOUT = DIFS + $\frac{H_p}{speed_{phy}} + \frac{ACK}{speed_{mac}}$		μs
ACK Frame [ACK]	112	bits	CTSTIMEOUT = DIFS + $\frac{H_p}{speed_{phy}} + \frac{CTS}{speed_{mac}}$		μs
CON-BLOCK-ACK-REQ	192	bits	$AIFS_{AC}$ = SIFS + $AIFSN_{AC}{}^* \delta$		μs
CON-BLOCK-ACK	1216	bits			

We have considered RTS/CTS mode of simple EDCA with W_0 set = {8,6,4,2}, R_{max} set = {8,8,8,8}, *AIFSN* set = {7,5,3,2} in Fig 4 and Fig 5. We have compared simulation values of throughput and delay denoted by AC0-simu, AC1-simu, AC2-simu, AC3-simu of Fig 4 for throughput and Fig 5 for delay to the analytical values of throughput and delay denoted by AC0, AC1, AC2 and AC3 of Fig.4 for throughput and Fig 5 for delay. The comparisons show that the simulation results of throughput and delay obtained through NS2 simulator matches pretty well to the corresponding analytical values.

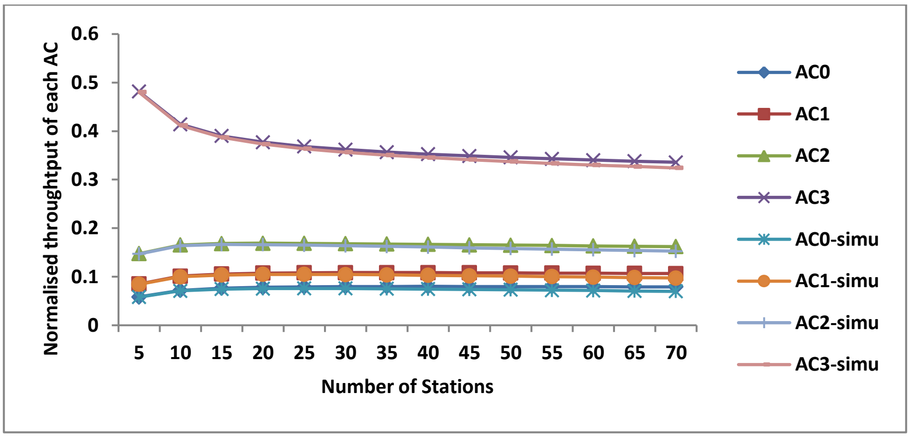

Fig 4: Comparison of Analytical Throughput Value with Simulation Result for RTS-CTS Mode.

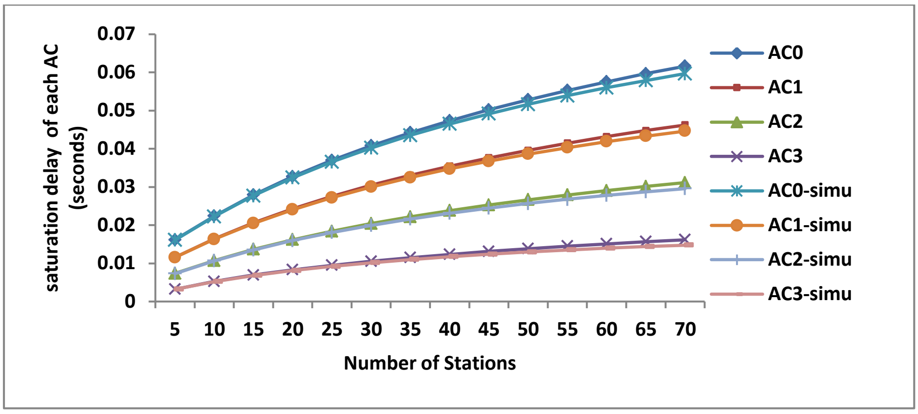

Fig 5: Comparison of Analytical Delay Value with Simulation Result for RTS-CTS Mode.

4.2 Throughput and Delay Characteristics with the Variation of Number of Stations

For RTS/CTS mode of standard EDCA, we observe that $Throughput_{AC3}$ (denoted by AC3 of Fig 4) is highest at lower number of stations i.e. at 5 due to higher favor of internal collision handler to highest priority AC3. Afterwards it decreases exponentially as the number of stations increases above 5 to about 70, due to more external collisions and finally reaches the saturation value. $Throughput_{AC2}$, $Throughput_{AC1}$, $Throughput_{AC0}$ (denoted by AC2, AC1 and A0 of Fig 4) is lower at lower number of stations due to lesser favor of internal collision handler to the lower priority ACs. Those throughputs then increase slowly and finally reach saturation value. Also, as the number of stations increases from 5 to 70, the delay of all ACs *i.e.* $Delay_{AC3}$, $Delay_{AC2}$, $Delay_{AC1}$ *and* $Delay_{AC0}$ (denoted by AC3, AC2, AC1 and AC0 of Fig 5) increases due to more collisions.

4.3 Service Differentiation

For the particular W_0, R_{max} and $AIFSN$ set, for any number of stations, it is observed that $Throughput_{AC3} > Throughput_{AC2} > Throughput_{AC1} > Throughput_{AC0}$ (Fig 4) and $Delay_{AC3} < Delay_{AC2} < Delay_{AC1} < Delay_{AC0}$ (Fig 5). This is because of the inequalities $W_{3,0} < W_{2,0} < W_{1,0} < W_{0,0}$; $AIFSN_3 < AIFSN_2 < AIFSN_1 < AIFSN_0$ and also due to the implementation of the internal collision handler in our model.

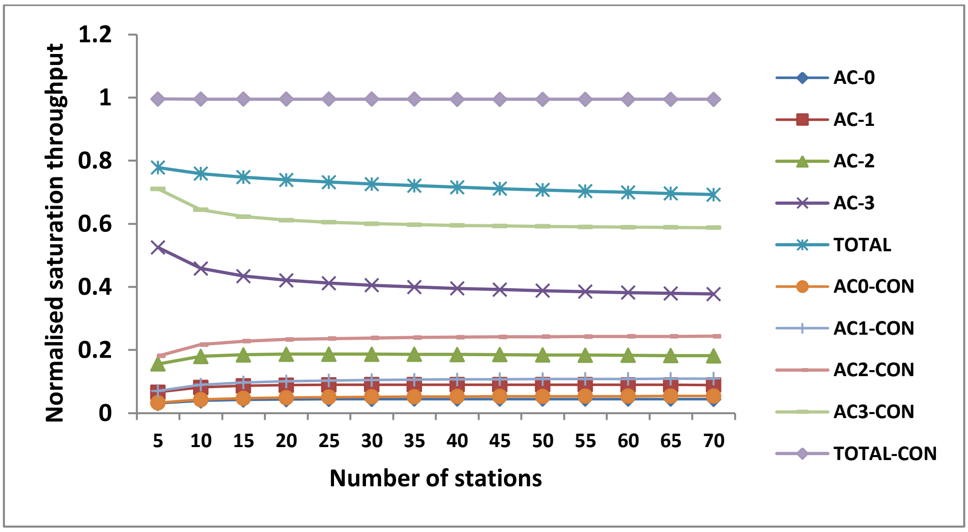

Fig 6: RTS/CTS throughput of standard EDCA (AC-0, AC-1, AC-2, AC-3, TOTAL) and EDCA with frame-concatenation and block-acknowledgement (AC0-CON, AC1-CON, AC2-CON, AC3-CON, TOTAL-CON).

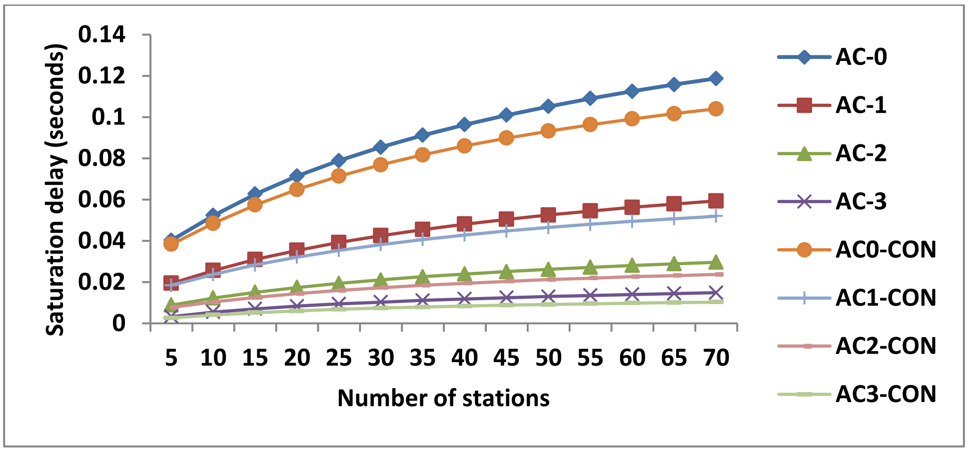

Fig 7: RTS/CTS delay of standard EDCA (AC-0, AC-1, AC-2, and AC-3) and EDCA with frame-concatenation and block-acknowledgement (AC0-CON, AC1-CON, AC2-CON, AC3-CON)

4.4. Performance Enhancement of Frame-concatenation and Block-acknowledgement Scheme

Here, we have considered RTS/CTS mode with W_0 set = {16,8,4,2}, AIFSN set = {7,5,3,2}, R_{max} set = {8, 8, 8, 8} and TXOP set ={ 0.050, 0.055, 0.060, 0.070 seconds.}.The comparison of AC0-CON, AC1-CON, AC2-CON, AC3-CON, TOTAL-CON **(**Fig 6 and

Table 2) with AC-0, AC-1, AC-2, AC-3, TOTAL (Fig 6) shows that the throughput with the proposed frame-concatenation and block-acknowledgement scheme, compared to the same of standard EDCA increases remarkably for higher ACs: by +55.76% for AC3-CON, +33.99% for AC2-CON and moderately for lower ACs: by +22.27% for AC1-CON and +22.26% for AC0-CON and there is a total increase of +43.59% of throughput TOTAL-CON, even when the number of stations is 70.

Also the comparison of AC0-CON, AC1-CON, AC2-CON & AC3-CON (Fig. 7 and Table 3) with AC-0, AC-1, AC-2, AC-3 (Fig 7) shows that the delay with the proposed frame-concatenation and block-acknowledgement scheme, compared to the same of standard EDCA decreases remarkably for higher ACs: by 44.20% for AC3-CON, 25.16% for AC2-CON and moderately for lower ACs: by 14.28% for AC1-CON and 14.14% for AC0-CON even when the number of stations is 70.

Table 2 Percentage Increase of Saturation Throughput of Proposed Frame-concatenation With block-acknowledgement Scheme Compared to standard EDCA

Number of Stations ↓	Percentage increase of normalized saturation throughput of frame-concatenation with block-acknowledgement scheme				
	AC0-CON	AC1-CON	AC2-CON	AC3-CON	TOTAL-CON
10	10.36%	10.37%	20.95%	40.60%	31.14%
20	14.06%	14.06%	24.99%	45.31%	34.61%
30	16.34%	16.35%	27.51%	48.22%	37.01%
40	18.14%	18.15%	29.48%	50.51%	38.96%
50	19.66%	19.67%	31.15%	52.46%	40.66%
60	21.02%	21.03%	32.63%	54.19%	42.18%
70	22.26%	22.27%	33.99%	55.76%	43.59%

Table 3 Percentage Decrease of Saturation Delay of Proposed Frame-concatenation with Block-acknowledgement Scheme Compared standard EDCA

Number of Stations ↓	Percentage decrease of saturation delay of frame-concatenation with block-acknowledgement scheme			
	AC0-CON	AC1-CON	AC2-CON	AC3-CON
10	07.87%	08.22%	18.47%	34.67%
20	09.96%	10.21%	20.66%	38.15%
30	11.16%	11.37%	21.94%	40.01%
40	12.07%	12.26%	22.92%	41.34%
50	12.84%	13.01%	23.75%	42.42%
60	13.51%	13.68%	24.49%	43.36%
70	14.14%	14.28%	25.16%	44.20%

Table 4 Total normalized Saturation Throughput of EDCA for RTS/CTS Mode without Frame-concatenation and Block- acknowledgement Scheme with W_o and R_{max} Set Variation

W_0 set →	{16,12,8,4}	{16,8,4,2}	{16,8,4,2}
R_{max} set →	{8,8,8,8}	{8,8,8,8}	{12,12,12,12}
Number of Stations ↓	Throughput Total	Throughput Total	Throughput Total
10	0.7589	0.7646	0.7696
30	0.7262	0.7381	0.7502
50	0.7072	0.7232	0.7409
70	0.6927	0.7119	0.7343

4.5 Total Throughput Variation

It is observed from Table 4 and Table 5 that with the variation of W_0 and R_{max} set, the higher ACs steal throughput from the lower ACs. But the total throughputs almost remain same at an average value of 0.7348 for standard EDCA without frame-concatenation and block-acknowledgement scheme (Table 4) and the total throughputs also remain almost same but at an higher average value of 0.9950 with the enhanced frame-concatenation and block-acknowledgement scheme (Table 5)**.** Hence**,** on the average, the total throughput, irrespective of window parameter variations, has increased remarkably by 35.41 % (from 0.7348 to 0.9950) due to our proposed scheme in comparison to standard EDCA. This affirms the superior QoS enhancement of the proposed frame-concatenation and block-acknowledgement scheme and its suitability for hard real-time applications.

Table 5 Total normalized saturation throughput of RTS/CTS mode for proposed frame-concatenation and block-acknowledgement scheme with W_o and R_{max} set variation

W_0 set →	{16,12,8,4}	{16,8,4,2}	{16,8,4,2}
R_{max} set →	{8,8,8,8}	{8,8,8,8}	{12,12,12,12}
Number of Stations ↓	Throughput Total	Throughput Total	Throughput Total
10	0.9951	0.9952	0.9952
30	0.9949	0.9950	0.9951
50	0.9947	0.9947	0.9951
70	0.9946	0.9946	0.9950

5. Conclusion

In this research article, we have studied the performance features of IEEE 802.11e EDCA with QoS enhancements through TXOP based frame-concatenation and block-acknowledgement scheme. From the analytical and simulation results discussed in section 4, we draw the following conclusions:

1. Analytical and simulation results match pretty well for both normalized saturation throughput and saturation delay and validate our model.

2. The throughput and delay pattern of standard EDCA show the access category wise QoS differentiation between the ACs, with higher ACs having higher throughput and lower delay. This shows that EDCA is suitable for soft real-time application when the latter is run through higher ACs.

3. Because of throughput stealing by higher ACs from the lower ACs, it is also revealed that, W_0 and R_{max} set variation does not improve the performance of standard EDCA to satisfy hard real-time applications like video-conferencing, interactive multi-media. The throughput and delay performance of our proposed model with the frame-concatenation and block-acknowledgement scheme has greatly out-performed standard EDCA, especially for the higher ACs. This establishes the fact that our model is suitable for hard real-time applications which are run through higher ACs.

Our key research contributions are:

(i) The contemporary EDCA models have implemented only one priority class active access category per station whereas, we have incorporated multiple number of simultaneously active access categories per station, denoted by the variable ac_m, which is theoretically unlimited in our solution framework

(ii) To implement these ac_m number of simultaneously active access categories per station, we have solved a total of ($5*ac_m+1$) non-linear equations depending on the value of ac_m, in the same solution framework.

(iii) We have implemented the frame-concatenation and block-acknowledgement scheme and have established the fact that it is a feasible solution for enhancing QoS requirements of hard real-time applications.

(iv) We have implemented channel sensing and back-off counter freezing during pre-transmission back-off process to make the model more accurate.

(v) We have included frame discarding after retry limit to remove excessive frame access delay, which is unsuitable for real-time applications.

(vi) We have also incorporated post-back-off after successful transmission, which reduces starvation of lower access categories.

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