

Analytical Modeling of IEEE 802.11e Enhanced Distributed Channel Access under a Non-Saturation Condition

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Abstract: Problem statement: The IEEE 802.11e EDCA protocol with different access Categories (ACs) supporting for Quality-of-Service (QoS). Due to internal or external packet collision, the Contention Window (CW) of the station increases the channel idle time under high Bit Error Rate (BER). **Approach:** In this study, we propose an analytical model for performance evaluation of IEEE 802.11e EDCA scheme under non-saturation condition and error prone channel. The new markov chain model have decrease the channel idle time in IEEE 802.11 EDCA and considerably increases the throughput for minimum number of station. **Results:** We develop an expression for the nonsaturation throughput as a function of the number of stations, packet sizes and BER. **Conclusion:** We validate the accuracy of our analysis with simulation expression. Using this model, the contention factors can be set appropriately to attain particular Quality-of-Service (QoS) requirements.

Key words: Enhanced Distributed Channel Access (EDCA), markov model, Contention Window (CW), non-saturation, Quality-of-Servi (QoS), Bit Error Rate (BER)

INTRODUCTION

In recent years, the IEEE 802.11 Wireless Local Area Network (WLAN) has been widely deployed in Indoor wireless Communication and it includes detailed specification of both medium access control and physical layer. The most research area of these two layers is Medium Access Control (MAC) layer in the first sub layer of data link layer. To access the medium from physical layer using MAC layer will be coordinating the random access of the medium. In wireless LAN MAC protocols is to coordinate the access of wireless client station in shared medium using carrier sense multiple Access/Collision Avoidance (CSMA/CA) protocol for MAC layer (IEEE Std. 802.11, 1999).

The IEEE 802.11e MAC layer is to enhancing the quality of services in WLAN which provides a contention-based channel access function and a centrally controlled channel access function called the Hybrid Coordination Function (HCF). The HCF combines a distribution contention-based channel access mechanism, referred to as Enhanced Distributed Channel Access (EDCA) and a centralized polling-based channel access mechanism referred to as HCF Controlled Channel Access (HCCA). In this article, we

concentrate on EDCA protocol which defines multiple Access Categories (AC) services for each station. Different levels of services are provided to each AC includes Contention Window (CW) sizes, Arbitration Interframe Space (AIFS) values and Transmit Opportunity (TXOP) limits for providing QoS to users. In this study we concentrate on the performance analysis of EDCA scheme, in the assumption of non ideal conditions and finite number of terminals.

According to the author's knowledge the first analytical model of DCF was proposed by Bianchi (2000). Bianchi proposed a Markov chain based model to evaluate saturation throughput, the mobile stations always have something to transmit (i.e., the saturation condition), assuming a finite number of stations and ideal channel conditions (no errors). While in (Shyang *et al.*, 2005) the authors extended the Bianchi model in order to consider unsaturated traffic conditions by adding another state (idle) to represent the node with empty queue, not present in the original Bianchi's model, in which the station buffer is empty, after a successful completion of a packet transmission. In the modified model, the packet is discarded after m^{th} backoff stages, while in Bianchi's model, the station keeps iterating in the m^{th} backoff stage until the packet

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gets successfully transmitted. There are some works on unsaturated traffic condition and post backoff stage for IEEE 802.11b (Malone *et al.*, 2007; Dhanasekaran senthil kumar and Krishnan, 2010; Daneshgaran *et al.*, 2008). However, these models are not based on simplifying assumptions that the IEEE 802.11 standard defines a Station Short Retry Count (SSRC), which is the maximum number of RTS transmission attempts that will be made before a frame is discarded Typically it is set to 5 or 7 (IEEE Std. 802.11, 1999; Wu *et al.*, 2002; Chatzimisios *et al.*, 2004; Prakash and Thangaraj, 2010). In (Chatzimisios *et al.*, 2004), the performance of IEEE 802.11 assumes that there is a finite transmission and presence of transmission error. In an adhoc network (Priakanth and Thangaraj, 2009), proposed an efficient packets scheduling and queuing algorithm by achieving better fairness in Medium Access Control (MAC) protocol. In (Murugan and Shanmugam, 2010), proposed a solution to identify the malicious node in both routing and MAC layer in the adhoc network using cumulative frequency based detection technique. Both articles referenced performances of MAC layer without markov model.

The majority of analytical work on the performance of 802.11e EDCA assumes that there is a finite retransmission limit (retry limit) and infinite retry limit under saturation and non-saturation condition using markov chain model (Huang *et al.*, 2007; Wei *et al.*, 2007; Kong *et al.*, 2004; Xiao, 2005; Engelstad and Osterbo, 2005; Inan *et al.*, 2009). The EDCF and provided performance studies via simulation. In (Huang *et al.*, 2007), the performance of IEEE 802.11e has investigated in the error prone channel under saturation condition. Based on the Markov chain model for unsaturated condition (Wei *et al.*, 2007), an analytical approach is proposed for throughput and delay of 802.11e EDCA. (Xiao, 2005; Kong *et al.*, 2004) extended the bianchi markov model to analyze the CW and AIFS differentiation under saturation condition. In (Kong *et al.*, 2004) Kong's model considered the difference of AIFS in back-off procedures, but neglected AIFS while the back-off procedure reminded one timeslot. In (Hui and Devsilitios, 2005) the authors proposed a new unified performance model to saturation throughput and delay performance of the network. These models were not provided real network condition. A few studies proposed real network condition which is on non-saturation analysis but not considered channel error. Englestad (2005c) presented an analytical model for IEEE 802.11e with Virtual collision handler (VCH) and post-backoff under non saturation condition. Inan *et al.* (2009) proposed 3-dimensional DTMCs under unsaturated traffic which

provide accurate treatment of AIFS, CW differentiation and EDCA TXOP. In (Pan and Wu, 2009) throughput of the EDCA is investigated under heterogeneous traffic. In this study, we propose a new markov chain model (proposed model) for analyzing EDCA protocol under non-saturation condition with error-prone channel. Due to internal (virtual) collision occurs within the station, the contention window size of the station is need not to be doubled for packet transmission. In case of transmission error due to fading or packet collision from other stations experiences external collision, the contention window size is doubled for every transmission. Based on this previous work of Xiao's model (2005), Senthilkumar and Krishnan (2010), we developed a Markov chain model for the EDCA analysis. The study is organized as follows. In this study, we present the new Markov chain model by extending the model proposed initially by Bianchi. Performance of the proposal scheme is analyzed after markov chain model explanation. We discuss numerical results and then finally we present conclusion of this study.

MATERIALS AND METHODS

Markov model for IEEE 802.11e EDCA: We consider a WLAN in Unsaturated (Nonsaturation) condition, ie., buffer of the transmitting station is empty, after a successful transmission. To analyze an EDCA protocol, we extend the previous works on following assumption: (1) real channel condition; (2) channel is prone to errors due to fading channel; (3) finite and fixed number N of contending stations. Traffics are categorizing into N different Access categories according to their QoS requirements. For simplicity, we summarize all parameters related with the nth AC have a subscript n. Fig.1 shows that the state of the nth AC by {n, i, k}. Here, i, (i = 0, 1, ..., m_n) represents the backoff stage, where m_n denotes the retry limit. k (k = 0,1,2, ..., W_{n,i}-1) represents the value of backoff counter, where W_{n,i} is the contention window size in the backoff stage i for the nth AC. The state (n, i, k) represents the ith backoff stage of nth AC with backoff counter value k and the CW size of backoff stage i of nth AC is expressed as:

$$W_{n,i} = \begin{cases} 2^i W_{n,0}, & 0 \leq i \leq m_n \\ 2^{m_n} W_{n,0}, & m_n < i \leq m'_n \end{cases} \quad (1)$$

where, $W_{n,0} = CW_{n,min} + 1$, m_n is the backoff stage of which CW size is the maximum CW size and m'_n is the frame retry limit. Our main aim in this performance study is the effective modification of the EDCA MAC protocol in order to characterize the behavior of MAC in the event of channel errors. In the basic AC, the contention window is doubled after every unsuccessful transmission.

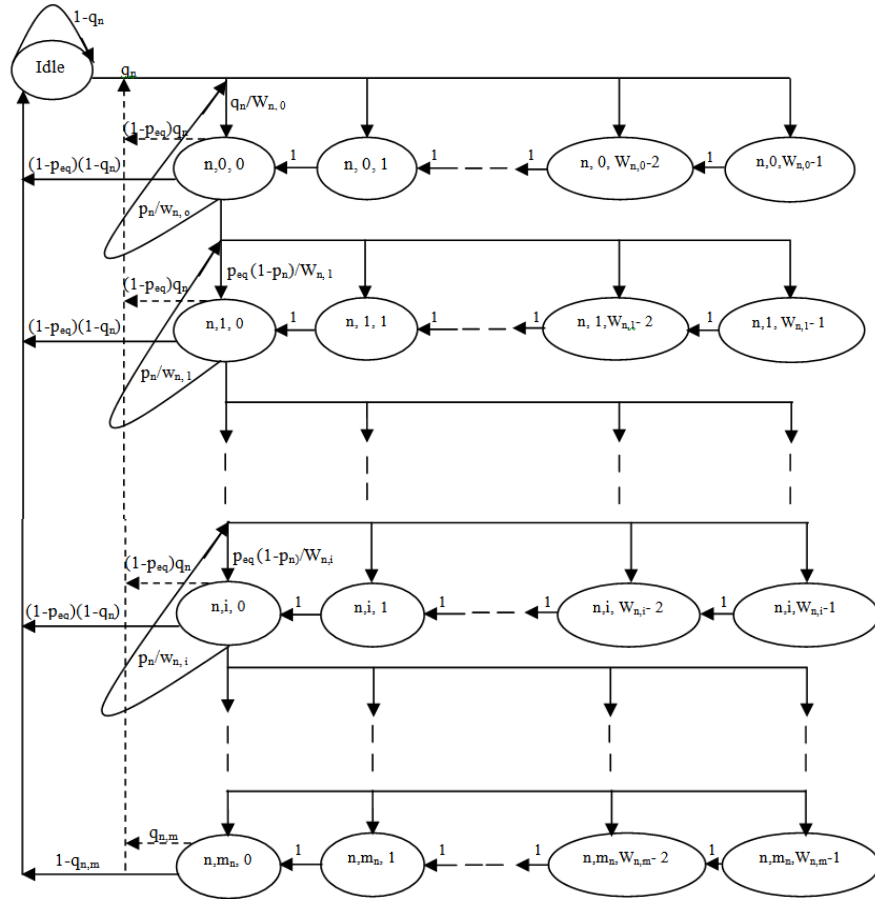


Fig. 1: Proposed Markov Chain Model for EDCA

Unsuccessful transmission happens in two cases: (i) internal collision or virtual collision of a packet with other packets with in a station, (ii) due to error in the channel and packet collision with other station. Let $b(t)$ be the stochastic process that represents the backoff timer for a specific station and $s(t)$ be the stochastic process representing the backoff stage $[0, \dots, m]$ for a given station at time t ; where m is the packet retry limit. Our analysis assumes that the network consists of n Contending stations and that each station has not always a packet available for transmission. The key assumption of our model is that the collision-error probability (p_{col}) and transmission error (p_e) of a transmitted packet is constant and independent of the number of collisions or transmission errors of this packet has suffered in the past. We assume that collisions (internal collision) and transmission error (external collision) events are statistically independent. The three dimensional discrete time Markov chain is depicted in Fig. 1. In this Markov chain, the only non-null one step transition probabilities are as follows:

$$\begin{aligned}
 &P(n, i, k / n, i, k+1) = 1, \\
 &k \in [0, W_{n,i} - 1], i \in [0, m_n] \\
 &P(n, 0, k / n, i, 0) = \frac{q_n(1-p_{eq})}{W_{n,0}}, \\
 &k \in [0, W_{n,0} - 1], i \in [0, m_n] \\
 &P(n, i, k / n, i, 0) = \frac{p_n}{W_{n,i}}, \\
 &k \in [0, W_{n,i} - 1], i \in [0, m_n - 1] \\
 &P(n, i, k / n, i-1, 0) = \frac{p_{eq}(1-p_n)}{W_{n,i}}, \\
 &k \in [0, W_{n,i} - 1], i \in [1, m_n]
 \end{aligned} \tag{2}$$

If there is no packet in a buffer after a successful transmission, the station is waiting in the idle state until a new packet arrives:

$$\begin{aligned}
 &P(\text{Idle} / n, i, 0) = (1 - q_n)(1 - p_{eq}), \\
 &i \in [0, m_n - 1] P(\text{Idle} / n, m_n, 0) = 1 - q_{m_n} \\
 &P(\text{Idle} / \text{Idle}) = 1 - q_n
 \end{aligned} \tag{2a}$$

The first Eq. in (2), beginning of each slot time, backoff time is decremented. The second equation in (2) states that, the initialization of backoff window after successful transmission for a new packet. The new value of the backoff timer is uniformly chosen in the interval $(0, W_{n,0}-2)$. The third equation represent that the probability of unsuccessful transmission due to internal collision (p_n) , but maintenance the same backoff window. The fourth equation accounts that, probability of unsuccessful transmission due to external collision or channel error (p_{eq}) . In Eq. (2) p_{eq} represents the external collision and channel errors, p_n represents that the probability due to internal collision and q represents the probability of atleast one packet awaiting transmission at the start of a counter decrement. The probability of successful transmission is $(1-q_n)(1-p_{eq})$. Let $b_{n,i,k} = \lim_{t \rightarrow \infty} P[s(n, t) = i, b(n, t) = k]$ be the stationary distribution of the Markov chain. In steady state, we can derive the following relations through chain regularities.

Analysis and Throughput Computation:

$$b_{n,i,0} = p_{eq}(1-p_n)b_{n,i-1,0} + p_n b_{n,i,0}, \quad i \in (0, m_n)$$

$$b_{n,i,0} = P^i \cdot b_{n,0,0} \quad i \in (0, m_n)$$

Where

$$P = \frac{p_{eq}(1-p_n)}{p_n}$$

p_{eq} (probability of failed transmission) = $p_c + p_{col} - p_c p_{col}$:

$$b_{idle} = \frac{(1-p_{eq})(1-q_n)}{q_n} \sum_{i=0}^{m_n} b_{n,i,0} + (1-q_n)p_{eq}^{m_n+1} \cdot b_{n,0,0} \quad (3)$$

All the steady state probabilities of the markov chain are expressed as function of $b_{n,0,0}$ and it can be obtained from this normalization equation:

$$1 = \sum_{i=0}^{m_n} \sum_{k=0}^{W_{i,j}-1} b_{n,i,k} + b_{idle} \quad (4)$$

We know that:

$$b_{n,i,0} = p_{eq}^i \cdot b_{n,0,0} \quad (5)$$

$$b_{n,0,0} = \frac{2(1-2P)(1-P)q_n}{W_{n,0}(1-(2P)^{m_n+1})(1-P)q_n + (1-2P)(1-P^{m_n+1})q_n + W_{n,0} \cdot 2^{m_n} \cdot P^{m_n+1}(1-2P)q_n(1-P^{m_n-m_n'}) + (1-q_n)(1-2P)(1-P)(1-P^{m_n-1})m_n > m_n'} \quad (6)$$

$$b_{n,0,0} = \frac{2(1-2P)(1-P)q_n}{1-(2P)^{m_n+1} \cdot W_{n,0}(1-P)q_n + (1-P^{m_n+1})(1-2P)q_n + (1-P^{m_n+1})(1-q_n) + (1-q_n) \cdot P^{m_n+1} \cdot q_n(1-2P)(1-P)m_n \leq m_n'} \quad (7)$$

Let τ_n denote the transmission probability can be written as:

$$\tau_n = \sum_{i=0}^{m_n} b_{n,i,0} = \frac{1-P^{m_n+1}}{1-P} \cdot b_{n,0,0} \quad 1 \leq n \leq N_t \quad (8)$$

A transmitted frame collides when two or more stations transmit during slot time, so the probability p_n that transmitted frame collides and channel busy probability p_b in a slot can be expressed as:

$$p_n = 1 - (1-\tau_n) \prod_{j=0}^{N_t-1} (1-\tau_j)^{n_j} \quad (9)$$

$$p_b = 1 - \prod_{i=0}^{N_t-1} (1-\tau_i)^N \quad (10)$$

The values of P and τ are still unknown in above Eq. 8-9 which can be solved using numerical techniques and represents as nonlinear equations. The probability that no station is transmitting in the slot time is expressed as:

$$P_{idle} = \prod_{i=0}^{N_t-1} (1-\tau_i)^N = 1 - p_b \quad (11)$$

Non-Saturation Throughput: Let $P_{n,s}$ be the probability that a successful transmission occurs in a slot time of the nth AC and P_s denote the probability that successful transmission occurs in a slot time. We have:

$$P_{n,s} = \tau_n (1-\tau_n)^{n-1} \prod_{j=0}^{N_t-1} (1-\tau_j)^{n_j} \quad (12)$$

$$P_s = \sum_{n=0}^{N_t-1} P_{n,s} = \sum_{n=0}^{N_t-1} \frac{n_n \tau_n}{1-\tau_n} (1-p_b) \quad (13)$$

The normalized throughput of nth AC, S_n is:

$$S_n = \frac{[\text{payload information successfully transmitted in slot time}]}{[\text{Average length of a timeslot}]}$$

$$S_n = \frac{P_{n,s}(1-p_e).PACKET}{(1-p_b)\sigma + P_s(1-p_e)T_s + (p_b - P_s)T_c + P_s.p_e.T_e} \quad (14)$$

PACKET includes PHY header, MAC header and data payload length of the nth AC. $T_{n,s}=T_s$ and $T_{n,c}=T_c$ are the successful and unsuccessful transmission time. T_e is the unsuccessful transmission time due to transmission errors. The value of T_s, T_c and T_e can be expressed as:

$$T_{n,s} = \text{PACKET} + \text{ACK} + 2\delta + \text{SIFS} + \text{AIFS}[n]$$

$$T_{n,c} = \text{RTS} + \text{AIFS}[n] + \delta$$

$$T_e = \text{PACKET} + 2\delta + \text{SIFS} + \text{AIFS}[n] + \text{ACK Timeout}$$

ACK is the time to transmit the Acknowledgement (ACK) packet, $\text{AIFS}[n]$ is the time of AIFS of priority n class, RTS is the time to transmit the packet RTS, CTS is the time to transmit the packet CTS and δ is the propagation delay. In our analysis, we consider Poisson process for packet arrival. q_n is the probability that indicates if there is at least one packet to be transmitted in queue during the time slot under the condition that the queue is empty at the beginning of the slot. For unsaturation condition, the probability q can be expressed as:

$$q_n = 1 - e^{-\lambda_n E[\text{slot}]}$$

Where $E[\text{slot}] = (1-p_b).\sigma + P_s(1-p_e).T_s + (p_b - P_s)T_c + P_s.p_e.T_e$ and λ_n is the Poisson arrival rate of traffic to AC[n].

RESULTS AND DISCUSSION

In this study, we present numerical results that show the impact of transmission errors on the system capacity. The network parameters used in these results are shown in Table 1 and we assume every station is able to listen each other and there are no hidden terminals in the systems. The Figure validates our mathematical analysis since an almost exact match is observed between analytical (symbols) and simulation results (lines) from our IEEE 802.11e simulator developed with the NS-2 simulation package. Figure 2 compares number of stations for each AC per station against throughput. In this graph, the highest priority of AC shows that higher throughput for fixed packed length.

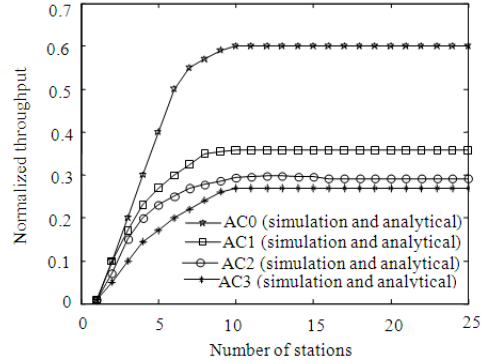


Fig. 2: Numerical and simulation results for normalized throughput

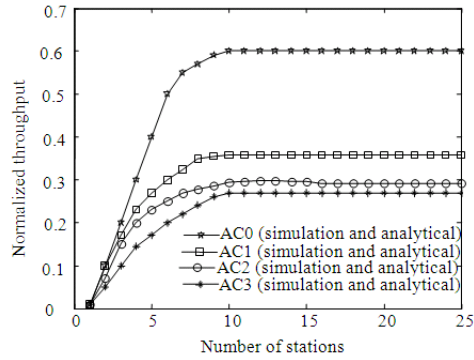


Fig. 3: Throughput versus number of stations for $p_e=0.0001$

Table 1: Calculation and Simulation Parameter

PHY header	192 bits
MAC header	272 bits
RTS frame	PHY header + 160 bits
CTS frame	PHY header + 112 bits
ACK timeout	DIFS+ACK
Date frame	2Mbps
Slot time	20μs
SIFS	10μs
DIFS	SIFS+2.aSlotTime
AIFSN	{2, 2, 3, 7}
Propagation delay	1μs
CW_{min}	{7, 15, 31, 31}
CW_{max}	{15, 31, 1023, 1023}

Figure 3 shows the throughput versus number of station with probability of error. Here, the channel bit rate is increases and the throughput slightly decreases with increased networks. Figure 4 compares the simulation and analytical results of modified model by plotting the throughput against different packet arrival rate for transmission error channel. In this graph, the low traffic of all AC shows that the modified model

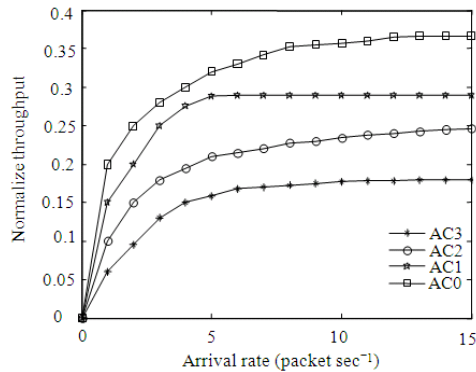


Fig. 4: Throughput versus packet arrival rate

significantly increases the throughput. From above results, the number of higher priority ACs is AC0 gives an acceptable throughput performance for all situation.

CONCLUSION

In this study, we have presented an analytical model that calculates throughput of the IEEE 802.11e EDCA protocol. We have presented an accurate analytical model to evaluate the performance of EDCA under nonsaturation conditions. Simulation and analysis results show that our analytical model can accurately predict the throughput performance of IEEE 802.11e EDCA under nonsaturation conditions in presence of channel errors. Based on this model we derive a novel and generalized expression for the station's transmission probability, which is more realistic, such as traffic load conditions (different ACs) and non ideal channel conditions. Our study shows that an optimally chosen number of contending stations can significantly improves the network throughput.

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