

A Contribution to Performance Analysis Approach of the IEEE 802.11 EDCA in Wireless Multi-hop Networks

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Abstract

The IEEE 802.11e standard has been introduced to support service differentiation for wireless local area networks. In wireless multi-hop networks, the performance of IEEE 802.11e EDCA has to confront with some practical problems such as unsaturation traffic and hidden node problem. Hence, this problem has attracted numerous studies in recent years, in which several investigations use analytic model to evaluate the performance due to its accuracy aspect. However, the accuracy and complexity of analytical model depends on a range of assumed parameters. The complexity caused by the introduction of realistic conditions in wireless multi-hop networks is the major challenge of current studies in this field. To overcome this challenge, this paper proposes an analytical model which covers full specification of IEEE 802.11e EDCA. To reduce the complexity, the model is simplified by decomposing the problem in two models based on Markov chain that can be easily solved by numerical method. The proposed model is presented in the theoretical aspect as well as numerical results to clarify its accuracy.

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1. Introduction

The IEEE 802.11 has become ubiquitous and gained widespread popularity for wireless multi-hop networks. To adapt the quality of service requirements of multi-media applications, the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) has been standardized [1]. EDCA provides differentiated, distributed access to the wireless medium for node based on eight user priorities which are mapped into four Access categories in MAC layer. Three characteristic parameters of access categories are Contention Window (CW), Arbitrary Inter-Frame Space (AIFS) and

Transmission Opportunity (TXOP).

In the recent years, a large body of work has appeared in the literature to investigate performance of IEEE 802.11e EDCA through analytical models. Most of them focused on the impacts of the parameter differences on network performance. However, due to very high complexity of presenting an analytical model which addresses all the features and details of the standard, the models are limited or ignore some important specifications to simplify the modeling. Many analytical models of IEEE 802.11e are extended from Bianchi model for IEEE 802.11 Distributed

Coordination Function (DCF) [2]. They fall into two cases: Saturations and unsaturation conditions. Under saturated condition the authors in [3, 4] proposed analytical models to capture AIFS and contention window differentiation to analyze the throughput and delay of the IEEE 802.11e. However, the impact of AIFS differentiation is not covered. The proposed analytical model in [5] use the AC-specific EDCA cycle time for predicting the EDCA saturation performance but it can not clarify the impact of the contention window.

Under unsaturated condition, the authors in [6] used frame transmission cycle approach to consider the difference of AIFS. The model analyzes WLAN based on IEEE 802.11e EDCA in detail; however it is not applicable to multi-hop networks. The proposed analytical models used renewal reward approach to extend a saturation model of single cell IEEE 802.11e to comfort with both unsaturated and saturated conditions [7, 8]. In [9], internal collisions in each node, concurrent transmission collisions among nodes, differences of CWs among ACs, and effects of contention zone are considered. However, these models in [7, 8] do not count to the hidden node problem, and the model in [9] focus only on throughput analysis in multi-hop string topology. It is clear that, the lack of input factors in analytical model can lead to its inaccuracy in the performance analysis problem [10].

To our best knowledge, there isn't any analytical model considering fully of parameters of IEEE 802.11e EDCA with realistic conditions including contention window, AIFS, virtual collision, hidden nodes and unsaturated condition in multi-hop networks. Hence, in this paper, a novel

analytical model enhanced from our previous work is proposed to overcome these previous limitations to analyze throughput and access delay multi-hop network performances [11]. The remains of this paper is structured as follows: In Section 2, the proposed analytical model is presented in full details. Main numerical results and our discussions are adopted in Section 3. The conclusion is drawn in Section V with the indication of our future work.

2. Analytical Model

To capture quality of service and priority characteristics of IEEE 802.11e EDCA, we used our previous analytical model with some modifications [11]. We specialized the node state model to AC sub-node state model which different between ACs by EDCA parameters. We also propose the channel state model and transmission probabilities to take AIFS, CW values difference and virtual collision into account. In the following subsections, we describe our assumptions and the analytical model in detail.

2.1. Assumptions and Notations

Considering an IEEE 802.11e EDCA based network containing n nodes distributed as a two-dimensional Poisson process with density γ . The network works on single radio single channel mode with error-prone condition. Every node has four ACs defined in the standard and homogeneous physical characteristics. Assume M is the average number of nodes in the area A , the probability of finding n node in area A is

$$p(n, M) = \frac{M^n}{n!} e^{-M}, M = \gamma.A$$

The problem of hidden nodes is illustrated in Figure 1. In which, node i transmits to node j with the present of hidden node k in the same time. The hidden area A_H depends on distance between transmitter and receiver (x), and then the average number of nodes in hidden area is $M_H = \gamma A_H(x)$. Some main notations in this paper are represented in Table 1.

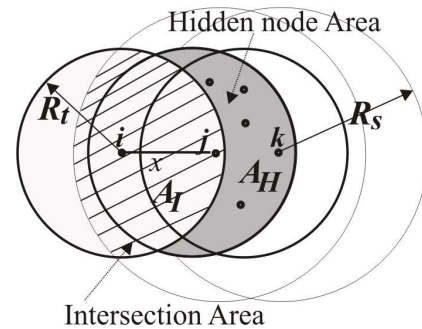


Figure 1. A hidden node scenario.

Table 1. Notation of parameters in our model

Index	Parameters	Notation
1	Radius of transmission range	R_t
2	Radius of sensing range	R_s
3	Density of node's distribution function	γ
4	Average number of nodes in node' sensing range	M
5	Average number of nodes in node' transmission range	N
6	The average number of node in the hidden area	M_H
7	Network throughput	Th
8	Duration of a PHY slot	σ
9	Arrival rate (lambda)	λ
10	Maximum retry limits (short:4, long:7)	m
11	Prob.{ a node (4 ACs) transmits a packet in a time slot}	p_t
12	Prob.{ successful transmission in a time slot}	p_s
13	Bit error rate (BER)	p_b

According to the principle of CSMA/CA mechanism, all ACs follow an exponential back-off scheme that a discrete back-off value which is chosen uniformly from *zero* to *CW* and reduced by one when the medium is free for a slot time. When back-off counter of an AC reduces to *zero*, the first packet in the AC's queue is transmitted. These transmitting probabilities will be explored using two simple Markov chains to model criteria of IEEE 802.11e operation. In which, a node is considered as four individual sub-nodes interplaying under internal virtual collision handler called AC sub-node. For convenience, we denote four access categories in IEEE 802.11e standard as $AC^j, j = (1, 2, 3, 4)$; from

lowest to highest priority. The packet transmission of each AC sub-node depends on actions of other ACs in the same node and other node in the same carrier sense area at the same time. We define the probability of AC^j sub-node transmitting a packet in a time slot by $p_t^{(j)}$, which becomes $p_t^{(j)}$ when count to virtual collision, and completing transmission with probability $p_s^{(j)}$. In a similar way, p_t and p_s are probabilities of a node which transmits and successfully transmits a packet in any AC, respectively. Also define a virtual slot $E^{(j)}[T]$ whose duration depends on what event belong to any AC happens during the slot.

2.2. AC Sub-node State Model

An AC sub-node is modeled by Markov chain as shows in Figure 2. Steady states of an AC sub-node state model includes four states: idle, defer, failure and success, which are denoted as $\pi_i^{(j)}$, $\pi_d^{(j)}$, $\pi_f^{(j)}$, $\pi_s^{(j)}$ respectively.

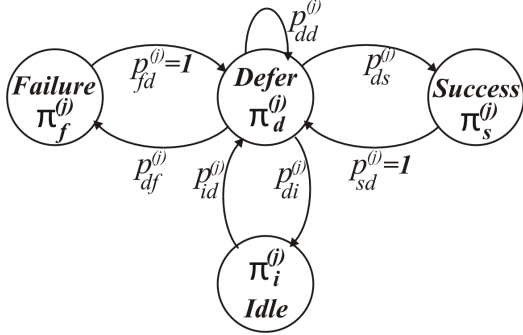


Figure 2. Markov chain for AC sub-node state model.

The transition probability from *defer* to *success* state for an AC sub-node depends on three factors: successful sending ($p_1^{(j)}$), successful receiving ($p_2^{(j)}$) and no error occurs during transmission time. We consider a network with imperfect channel which has packet error probability p_e^{packet} , $p_e^{packet} = 1 - (1 - p_e^{bit})^{L_{packet}}$ for both control and data packets (notation as $p_e^{RTS/CTS}$, p_e^{Data}). We have

$$p_1^{(j)}(M, p_t^{(j)}) = p_t'^{(j)} \sum_{n=2}^{\infty} (1 - p_t)^{n-1} \times p(n, M) \quad (2)$$

$$p_2^{(j)}(M_H, p_t, T^{(j)}) = \left(\sum_{n=0}^{\infty} (1 - p_t)^n \times p(n, M_H) \right) \frac{T^{(j)}}{\sigma} \quad (3)$$

where $T^{(j)}$ is vulnerable time, M_H is average number of nodes in the hidden area as shown on Figure 1.

The duration times of two types of IEEE 802.11e access mechanisms are

$$T_{Basic} = AIFS^{(j)} + T_{DATA} + \delta + SIFS, \quad (4)$$

$$T_{RTS/CTS} = AIFS^{(j)} + T_{RTS} + \delta + SIFS. \quad (5)$$

The transition probability of a node changes from *defer* state to *success* state with Basis access scheme is

$$p_{ds}^{(j)}(x) = p_1^{(j)}(N_t, p_t^{(j)}) (1 - p_e^{Data}) \times p_2^{(j)}(M_H, p_t, T_{Basic}^{(j)}) (1 - p_e^{Ack}) \quad (6)$$

And with RTS/CTS scheme is

$$p_{ds}^{(j)}(x) = p_1^{(j)}(N_t, p_t^{(j)}) (1 - p_e^{RTS}) (1 - p_e^{Data}) \times p_2^{(j)}(M_h, p_t, T_{RTS/CTS}^{(j)}) (1 - p_e^{CTS}) (1 - p_e^{Ack}) \quad (7)$$

Finally, we have

$$p_{ds}^{(j)} = \int_0^{R_t} f(x) p_{ds}^{(j)}(x) dx = \int_0^{R_t} 2xp_{ds}^{(j)}(x) dx \quad (8)$$

with the assumption each node transmits to a random receiver in its transmission area with equal probability of density function $f(x)$ depends on distance x , $f(x) = 2x, 0 < x < R_t$.

The transition probability of AC sub-node changes from *defer* state to *idle* state is

$$p_{di}^{(j)} = \begin{cases} 1 - \frac{\lambda^{(j)}}{\mu^{(j)}} & \text{if } \lambda^{(j)} < \mu^{(j)} \\ 0 & \text{else} \end{cases} \quad (9)$$

where $\mu^{(j)}$ is service rate at an AC sub-node; its value is calculated in Section 3.

The transition probabilities of AC sub-node changes from *defer* to *failure* and from *defer* to *defer* state are $p_{df}^{(j)} = p_t^{(j)} - p_{ds}^{(j)}$ and $p_{dd}^{(j)} = 1 - p_t^{(j)} - p_{di}^{(j)}$.

From Figure 2, we have some constraints to calculate the stable probabilities of AC sub-node state:

$$\begin{aligned} \pi_s^{(j)} &= \pi_d^{(j)} p_{ds}^{(j)}, \pi_f^{(j)} = \pi_d^{(j)} p_{df}^{(j)}; \\ \pi_i^{(j)} &= \pi_d^{(j)} p_{di}^{(j)} + \pi_i^{(j)} p_{ii}^{(j)}; \\ \pi_d^{(j)} &= \pi_d^{(j)} p_{dd}^{(j)} + \pi_i^{(j)} p_{id}^{(j)} + \pi_f^{(j)} + \pi_s^{(j)}; \\ p_{ii}^{(j)} + p_{id}^{(j)} &= 1, p_{di}^{(j)} + p_{dd}^{(j)} + p_{df}^{(j)} + p_{ds}^{(j)} = 1. \end{aligned} \quad (10)$$

With some basic calculus, we have the

steady states probabilities of the node state model are:

$$\begin{aligned} \pi_i^{(j)} &= \frac{P_{di}^{(j)}}{P_{id}^{(j)} \left(2 - p_{dd}^{(j)} - p_{di}^{(j)} + \frac{p_{di}^{(j)}}{P_{id}^{(j)}} \right)}; \\ \pi_d^{(j)} &= \frac{1}{\left(2 - p_{dd}^{(j)} - p_{di}^{(j)} + \frac{p_{di}^{(j)}}{P_{id}^{(j)}} \right)}; \\ \pi_s^{(j)} &= \frac{P_{ds}^{(j)}}{\left(2 - p_{dd}^{(j)} - p_{di}^{(j)} + \frac{p_{di}^{(j)}}{P_{id}^{(j)}} \right)}; \\ \pi_f^{(j)} &= \frac{P_{df}^{(j)}}{\left(2 - p_{dd}^{(j)} - p_{di}^{(j)} + \frac{p_{di}^{(j)}}{P_{id}^{(j)}} \right)}. \end{aligned} \quad (11)$$

2.3. Channel State Model

The channel around node (*i*) is modeled by using four-state Markov chain as in Figure 3.

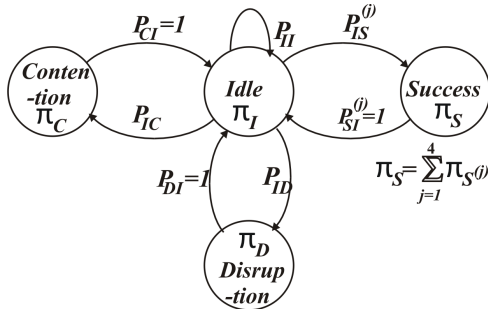


Figure 3. Markov chain for channel state model.

We denote steady states and their durations by $\pi_I, \pi_C, \pi_S, \pi_D$, and T_I, T_C, T_S, T_D , respectively. Furthermore, the *success* state is derived from 4 sub-states denoted as $S^{(j)}, j = (1, 2, 3, 4)$ corresponding to four ACs.

The transition probabilities between channel states in channel state model is illustrated in the figure and there are some transition probabilities equal to 1, $P_{CI} = P_{DI} = P_{SI}^{(j)} = 1$.

The transition probabilities P_{II}, P_{IC} and P_{ID} of channel around node are acquired by similar arguments as in [11]:

$$P_{II} = \sum_{n=1}^{\infty} (1 - p_t)^n p(n, M); \quad (12)$$

$$P_{IC} = \sum_{n=2}^{\infty} \left(1 - np_t (1 - p_t)^{n-1} - (1 - p_t)^n \right) p(n, M); \quad (13)$$

$$P_{ID} = 1 - P_{IC} - P_{IS} - \sum_{j=1}^4 P_{IS}^{(j)}. \quad (14)$$

The transition probability from *idle* state to each *success* state comprises two probabilities: successful transmitting ($P_{IS1}^{(j)}$) and successful receiving ($P_{IS2}^{(j)}$) for the given AC^j :

$$P_{IS1}^{(j)} = \sum_{n=1}^{\infty} np_s^{(j)} (1 - p_t)^{n-1} P(n, M) \quad (15)$$

$$P_{IS2}^{(j)} = \sum_{n=1}^{\infty} np_t^{(j)} (1 - p_t)^{n-1} P(n, M_A) \quad (16)$$

in which, $p_t^{(j)}$ is the successful transmission probability from node *k* in annulus A_A to a node in the intersection area A_I (Figure 1), $p_s^{(j)}$ is $\pi_s^{(j)}$ examined in AC sub-node state model as

$$P_{IS}^{(j)} = P_{IS1}^{(j)} + P_{IS2}^{(j)} \quad (17)$$

From these probabilities and the relationship on Figure 3, the idle steady state probability is

$$\begin{aligned} \pi_I &= \pi_I P_{II} + \pi_C P_{CI} + \pi_D P_{DI} + \sum_{j=1}^4 \pi_{S^{(j)}} P_{SI}^{(j)} \\ &= \pi_I P_{II} + 1 - \pi_I \end{aligned} \quad (18)$$

Thus, stable state probabilities of channel model are

$$\begin{aligned} \pi_I &= \frac{1}{2 - P_{II}}; \quad \pi_C = \frac{P_{IC}}{2 - P_{II}}; \quad \pi_D = \frac{P_{ID}}{2 - P_{II}}; \\ \pi_S &= \sum_{j=1}^4 \pi_{S^{(j)}}; \quad \pi_{S^{(j)}} = \frac{P_{IS}^{(j)}}{2 - P_{II}}. \end{aligned} \quad (19)$$

2.4. Derivation of Analytical Problem

Contrast to Bianchi's approach that based on the non-linear equations for unknown

probabilities called collision probability and transmission one, we propose relationship between probability of transmission and their successful probability from our two models as described in previous sections.

The event a packet of AC^j is sent from the AC's queue to virtual collision handler happens when node i changes from idle state to defer state (P_{id}^j) and channel around a node is idle ($P_{\Phi}^{(i)}$) and back-off process is finished ($P_{BO}^{(j)}$). We have

$$p_t^{(j)} = p_{id}^{(j)} \times P_{\Phi}^{(j)} \times P_{BO}^{(j)} \quad (20)$$

The probability that channel around a node is idle is different between ACs due to the disparity in the AIFS value and can be obtained from steady state probabilities of channel model in (19):

$$\begin{aligned} P_{\Phi}^{(j)} &= \frac{\pi_i T_i^{(j)}}{\pi_i T_i^{(j)} + \pi_c T_c^{(j)} + \pi_d T_d^{(j)} + \sum_{s=1}^4 \pi_{s(i)} T_s^{(j)}} \\ &= \frac{T_i^{(j)}}{T_i^{(j)} + P_{ic} T_c^{(j)} + P_{id} T_d^{(j)} + \sum_{s=1}^4 P_{is} T_s^{(j)}} \end{aligned} \quad (21)$$

The probability of back-off counter reduced to Zero in a given time slot ($P_{BO}^{(j)}$) depends on the average contention window at i^{th} attempt and *failure* steady state probability of AC sub-node as formula

$$P_{BO}^{(j)} = \frac{1}{\overline{CW}_{avr}^{(j)}}, \quad \overline{CW}_{avr}^{(j)} = \frac{\sum_{i=0}^m \overline{CW}_i^{(j)} (\pi_f^{(j)})^i}{\sum_{i=0}^m (\pi_f^{(j)})^i} \quad (22)$$

in which, $\overline{CW}_i^{(j)} = CW_i/2; i = 0, m$, the retry limits m and contention windows $CW_i^{(j)}$ is specified for a given AC^j .

From $p_t^{(j)}$, we can derive probability of the given AC in a node transmitting a packet to the channel in a times lot with virtual contention condition $p_t^{(j)}$:

$$p_t'^{(j)} = p_t^{(j)} \prod_{k>j}^4 (1 - p_t^{(k)}). \quad (23)$$

Thus, the probability of a node containing four ACs transmits a packet of any $AC^j, j = (1, 2, 3, 4)$ to the channel around it in a time slot is

$$p_t = \sum_{j=1}^4 p_t'^{(j)}. \quad (24)$$

2.5. Remarks

As described in the previous subsections, the analytical model is decomposed by two state models namely AC-node sub state model and channel state model respectively. By the decomposition, the main IEEE 802.11e EDCA features is exactly captured under realistic conditions. To evaluate its accuracy, the network performance such as throughput and access delay is examined by numerical simulation as bellows.

3. Numeric Results and Discussions

We use MATLAB to calculate throughput and delay performance from our proposed model. Analytical results will be examined under standard parameters of IEEE 802.11e EDCA as shown in Table 2.

The average virtual time slot $E^j[T]$ from the channel model can be estimated by

$$E^j[T] = \pi_i T_i^{(j)} + \pi_c T_c^{(j)} + \pi_d T_d^{(j)} + \sum_{s=1}^4 \pi_s T_s^{(j)}. \quad (25)$$

Table 2: Calculation parameters (IEEE 802.11 EDCA)

Parameter	Value	Parameter	Value
Payload (P)	1024 byte	ACK	256 bits
AIFSN[1,2,3,4]	[2,3,5,7]	RTS	288 bits
CW_{min} [1,2,3,4]	[7,15,31,63]	CTS	256 bits
PHY header	128 bits	Slot time	20 μ s
MAC header	160 bits	SIFS	10 μ s
Basic rate	1 Mbps	Data rate	11 Mbps
Propagation delay (δ)	1 μ s		

Thus, throughput Th is defined as the number of payload bits successfully transmitted in a virtual time slot

$$Th = \sum_{j=1}^4 Th^j, \text{ with } Th^j = \frac{\pi_s^j \times E[P]}{E^j[T]} \quad (26)$$

in which, $E[P]$ is average payload of DATA packets. We denote the length of RTS, CTS, and ACK packets as $L_{RTS}, L_{CTS}, L_{ACK}$, respectively. The transmission durations of RTS, CTS, ACK and DATA packets are

$$\begin{aligned} T_{RTS} &= \frac{L_{RTS}}{R_{basic}}; T_{CTS} = \frac{L_{CTS}}{R_{basic}}; \\ T_{ACK} &= \frac{L_{ACK}}{R_{basic}}; T_{DATA} = \frac{L_{DATA}}{R_{data}}. \end{aligned} \quad (27)$$

The time durations T_I, T_C, T_D, T_S are different with access categories and access scheme applied. With the basic mechanism, we have

$$\begin{aligned} T_S^{(j)} &= AIFS^{(j)} + T_{Data} + \delta + SIFS + T_{Ack} + \delta; \\ T_D^{(j)} &= T_S^{(j)}; T_I^{(j)} = \sigma; \\ T_C^{(j)} &= AIFS^{(j)} + T_{Data} + \delta + SIFS + T_{Ack}. \end{aligned} \quad (28)$$

And with the RTS/CTS mechanism

$$\begin{aligned} T_S^{(j)} &= AIFS^{(j)} + T_{RTS} + \delta + SIFS + T_{DATA} + \delta \\ &\quad + SIFS + T_{CTS} + \delta + SIFS + T_{ACK} + \delta; \\ T_D^{(j)} &= T_S^{(j)}; T_I^{(j)} = \sigma; \\ T_C^{(j)} &= AIFS^{(j)} + T_{RTS} + \delta + SIFS + T_{CTS}. \end{aligned} \quad (29)$$

The average access delay for any packet belong to AC^j is calculated as

$$\begin{aligned} D^{(j)} &= \sum_{i=1}^m (1 - p_s^{(j)})^i p_s^{(j)} \\ &\quad \times \left(\sum_{k=1}^i \overline{CW}_k^{(j)} E^j[T] + T_S^{(j)} + (i-1)T_C^{(j)} \right) \\ &\quad + (1 - p_s^j)^m \times \left(\sum_{k=1}^m \overline{CW}_k^{(j)} E^j[T] + mT_C^{(j)} \right). \end{aligned} \quad (30)$$

From access delay D^j , we have service rate μ^j of AC^j can be calculate from $\mu^j = 1/D^j$.

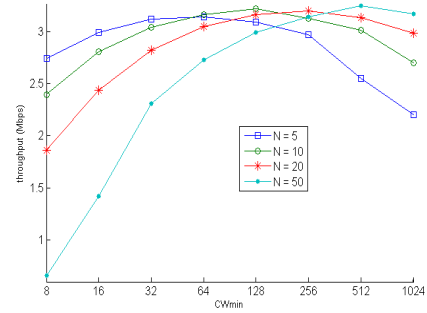


Figure 4. Saturation throughput vs CW_{min} and number of nodes varying.

Firstly, we verify our proposed model on saturation throughput with the value of CW_{min} and number of nodes in transmission range varying (5, 10, 20 and 50). Our scenario uses basic access mechanism to evaluate throughput for a node composing all ACs. Although our approach is different from Bianchi's one, its accuracy is confirmed by the same results as shown in Fig 4 comparing with those in [2] in case of the same input pattern (only AC^2 has arriving packet)

Figure 5 illustrates the influence of packet arrival rate on throughput performance of each AC. The average number of nodes is set equal to 4 to achieve highest throughput. The significant difference in throughput represents a priority of traffic affected by AC parameters such as the CW size, the AIFS value, and the virtual collision in IEEE 802.11e EDCA.

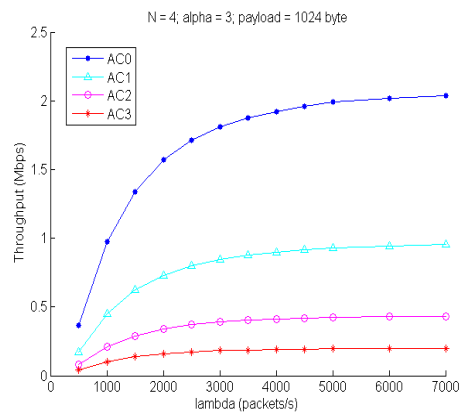


Figure 5. Normalized throughput of ACs against packet arrival rate.

Figure 6 shows the normalized through-put of ACs depends on number of nodes in transmission area (N). When node density increases, not only the throughput of each AC decreases significantly but the difference in throughput also decreases due to more number of nodes contending for bandwidth. Moreover, from figure 5 and figure 6 we can observe the serious impact of hidden nodes in throughput of network, especially in multi-hop network environments, which was investigated in [12] and inadequately examined in [13].

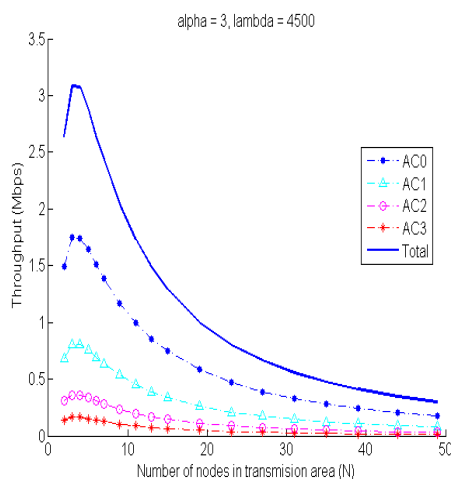


Figure 6. Normalized throughput of ACs vs number of nodes.

To investigate the influence of access mechanisms on throughput, we verify the basic mechanism and RTS/CTS mechanism by varying number of nodes and payload size in Figure 7 and Figure 8. From the figures, we can see that basic access mechanism can provide better performance in condition of small payload, which is more suitable with live voice and video streams. Otherwise, RTS/CTS can assure performance of EDCA networks much better when number of node increases or with larger packet's payload size as ftp flows.

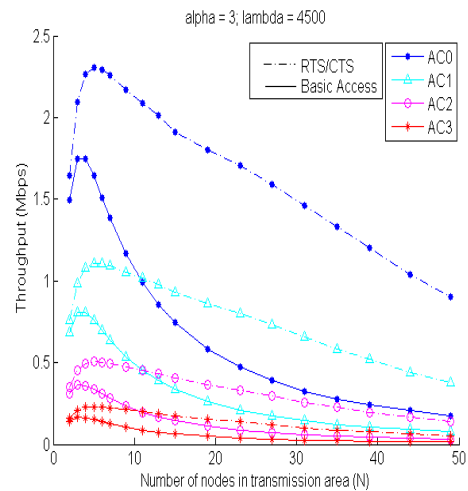


Figure 7. Throughput of ACs vs number of nodes.

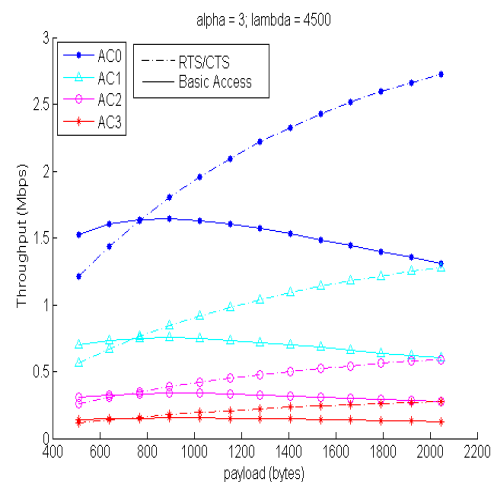


Figure 8. Throughput of ACs vs payload size.

Finally, in Fig 9 and Fig 10, we investigate the differentiation between saturated and unsaturated incoming traffic in multi-hop networks based on IEEE 802.11e EDCA through throughput and access delay of ACs against number of nodes, respectively. We observed that throughput and access delay performance in unsaturated traffic case is decreased much slower than saturated traffic case when N increases. Otherwise, when number of nodes is relatively small, saturated traffic case can achieve significant higher throughput.

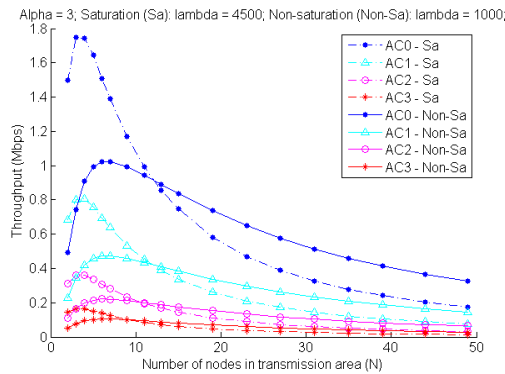


Figure 9. Unsaturated and saturated throughput vs N

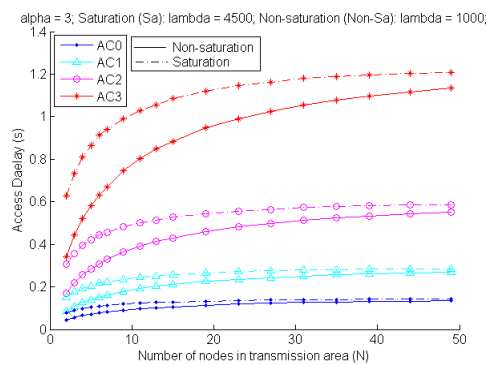


Figure 10. Unsaturated and saturated access delay vs N

4. Conclusion

This paper presented the analytical model which is enhanced from the model of 802.11 DCF based on Markov chains to analyze the performance of IEEE 802.11e EDCA in multi-hop networks. By dividing it into two joint state models, the analytical model captures all main characteristic parameters of IEEE 802.11e EDCA such as CW, AIFS and virtual collision in a simple way. Moreover, realistic conditions of wireless multi hop networks based on 802.11e EDCA such as hidden node problem and unsaturated condition are introduced into the model. The numerical results have been provided to verify the accuracy of the proposed model; it can be used to arrange contention factors of EDCA to optimize QoS differentiation and network performance.

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