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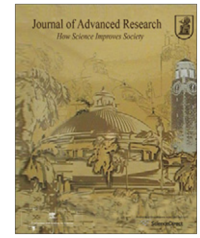

ORIGINAL ARTICLE

IEEE 802.11e (EDCA) analysis in the presence of hidden stations

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Abstract The key contribution of this paper is the combined analytical analysis of both saturated and non-saturated throughput of IEEE 802.11e networks in the presence of hidden stations. This approach is an extension to earlier works by other authors which provided Markov chain analysis to the IEEE 802.11 family under various assumptions. Our approach also modifies earlier expressions for the probability that a station transmits a packet in a vulnerable period. The numerical results provide the impact of the access categories on the channel throughput. Various throughput results under different mechanisms are presented.

Introduction

Recently, there has been an increased interest in understanding the behavior of IEEE 802.11 [1] and IEEE 802.11e Enhanced Distributed Channel Access (EDCA) [2]. IEEE 802.11e (EDCA) is a complex access protocol that attempts to provide quality of service (QoS) for the various expected types of traffic. Innovative analysis appears in Refs. [3–6] which address IEEE 802.11e (EDCA) using a detailed bi-dimensional Markov chain, each with different assumptions and approaches. These analyses cover both the basic access as well as RTS/CTS. Different from the original analysis of IEEE 802.11 in Ref. [3], Huang [4] and Engelstad [5] provide the analysis for MAC enhanced standard IEEE 802.11e (EDCA). Generally the results show that the two parameters, minimum contention windows and the number of stations strongly affect the performance of the basic access mode in wireless network, while these parameters marginally affect the RTS/CTS access performance.

The Bianchi model [3] provides analysis for IEEE 802.11 under the assumption of saturation conditions. Huang and Liao [4] extend the Bianchi model to the IEEE 802.11e (EDCA), including the different AIFSN of Access Categories (ACs) parameter set and virtual collision. The analysis has been performed under the assumption of saturation conditions. Engelstad and Østerbø [5] provide a non-saturation mode analysis, using Markov chain which also includes the saturation mode performance. Hung and Marsic [6] provide analysis for the hidden station effect for the IEEE 802.11.

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Clearly IEEE 802.11 performance suffers tremendously from the effect of the hidden station, See for example Xu and Saadawi [7].

The proposed work relaxes many of the assumptions stated in previous work, and provides analysis of IEEE 802.11e considering both the hidden stations effect as well as the non-saturation condition (which includes the saturation mode as well). Table 1 summarizes the difference of the previous works and highlights our contribution.

The rest of the paper is organized as follows. The next section provides the analytical analysis for IEEE 802.11e under non-saturation. Section 'Non-saturation Markov chain for IEEE 802.11e (EDCA)' is the non-saturation Markov chain model, while in Section 'The presence of hidden stations'; the analysis is extended to include the effect of the hidden station environment. Section 'Numerical analysis' provides the numerical analysis results. Finally, last section provides the conclusion.

Analytical model for IEEE 802.11e (EDCA) with non-saturation

EDCA mechanism defines four Access Categories (ACs) services. Each AC contends for channel using a set of AIFS parameters and is associated with one transmission queue. Considering virtual collisions within the QSTA, the data frames from the higher priority AC receive the TXOP, and the data frames from the lower priority collision AC(s) behave as if there were an external collision.

Non-saturation Markov chain for IEEE 802.11e (EDCA)

In the analysis performance, we assume as previously reported [3–6]: (a) the wireless networks operate in an ideal physical environment, i.e., no frame error and the capture effect (b) each packet collides with constant and independent probability, regardless of the number of collisions already suffered; and (c) fixed number of stations which transmit a packet under non-saturation and saturation conditions.

We denote four ACs as AC_i. For convenience, AC_i provides support for the delivery of traffic from the highest priority to the lowest priority by subscripts 0, 1, 2 and 3 in the analysis.

In the discrete-time Markov chain, s(t) is defined as the backoff stage, at time t;$b(t)$ is the backoff counter at time t. Let state parameters $b_{i,j,k} = \lim_{t\to\infty} Prob\{AC = i, stage(t) = j, backoff(t) = k\}$, be the stationary distribution probability of the chain, where i is type of AC_i and $i \in \{0,1,2,3\}, j \in [0,L_i]$, is called backoff stage. After each unsuccessful transmission attempt,j will increase one in order to let the contention window double until a retry limit or the maximum contention window is reached. $k \in [0, w_{i,j} - 1]$ is the backoff time counter. k is decremented when the channel is sensed idle, "frozen" when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS. The station can transmit one packet when the backoff time reaches zero. $w_{i,j}$ is the contention window size at backoff stage $j(w_{i,j}) = 2^j w_{i,0}$ for AC_i, where $i \in \{0,1,2,3\}$ and $j \in [0,L_i]$. $w_{i,0}$ is the minimum contention window size for AC_i,L_i is AC_i's frame retry limit. Sometimes we use $L_i = m_i + f_i$, where f_i is the amount of time the contention window will not double for AC_i after it is greater than is the maximum number of times that the contention window may be doubled for AC_i, (maximum backoff stage).

We now show how to obtain a closed-form solution for this Markov chain. In the Fig. 1, $b_{i,j,k}$ is simplified as $\{i,j,k\}$. In the state $\{i,0,0,e\}$, the backoff has completed and is only waiting for a packet to arrive in the queue. If assuming the queue receives a packet during a timeslot at a probability q_i and senses the channel busy at a probability p_i, it moves to a new state in the second row at a probability $p_i q_i$. Otherwise, it moves to state $\{i,0,0\}$, to do a transmission attempt at a probability $(1 - p_i)q_i$, since a packet is now ready to be sent. The packet waiting in a AC_i queue is sent whenever the backoff counter becomes zero regardless of the backoff stage. The transmission starting in state $\{i,0,0\}$ succeeds at a probability $1 - p_i$. It will stay in the same state $\{i,0,0,e\}$ at a probability $1 - q_i$ if it does not receive a packet during a timeslot.

When the state has received a packet it moves to a corresponding state in the second row with a packet at probability q_i^*. The state remains in the first row with no packets waiting for transmission.

One-step transition state will stay in its previous state at a probability p_i^* during a timeslot when the channel is busy and the station is not able to count down backoff slots because of different AC priority.

When the channel idles, the station is counting down the backoff slots from its previous state $\{i,j,k+1\}$ to $\{i,j,k\}$. If the transmission does not succeed, queue doubles the contention window and goes into the next row backoff.

If the transmission is successful and a new received packet is waiting in the transmission queue at the time when a transmission is completed, the queue resets its contention window and goes into second row backoff. If the transmission succeeds and no packet is waiting in the transmission queue at the time a transmission is completed, the queue reset its contention window and goes into the first row backoff.

If the transmission fails after the L_i-th backoff stage, the packet will be dropped and the state will start another backoff procedure with probability one.

We let ρ_i be the probability that there is a packet waiting in the transmission queue of the backoff of AC_i at the time a transmission is completed. In the Markov chain, the states of $\{i,0,k,e\}$ the top row represent the channel is not fully saturated and AC_i queue of a backoff is empty at a probability

Table 1 Summary of IEEE 802.11 analyses.

	802.11 Saturation	802.11 Non-saturation	802.11e Saturation	802.11e Non-saturation	Hidden stations
Bianchi [3]	×				
Huang and Liao [4]	×		×		
Engelstad and Østerbø [5]	×	×	×	×	
Hung and Marsic [6]	×				×
Proposed work	×	×	×	×	×

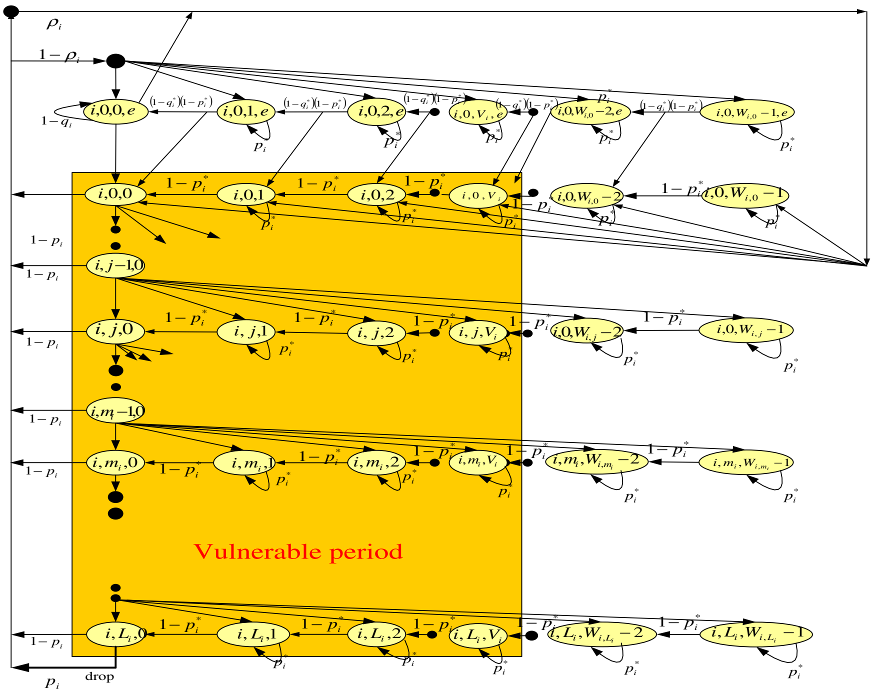

Fig. 1 Markov Chain model for a single AC inside the EDCA station and a vulnerable period in the presence of hidden station (both saturation and non-saturation).

$1 - \rho_i$ when the time of a transmission is completed. If the queue on the other hand is non-empty, the backoff is started by entering the state $\{i,0,k\}$ at probability ρ_i.

p_i is the collision probability at each transmission attempt for AC_i. $p - i^*$ is the probability that the backoff of AC_i is sensing the channel is busy and is thus unable to count down the backoff slot from one timeslot to the other. $1 - p_i^*$ is the probability that the backoff counter for AC_i can be successfully decreased by one in a given time slot and moves to another state, i.e., when there are no transmissions initiated by other stations or other higher priority ACs inside the same station in the period between minimum of AIFS (i.e., DIFS) and AIFSN.

q_i is a probability while a station receives a packet during a timeslot in the state $\{i,0,0,e\}$.q_i^* is a probability that states $\{i,0,k,e\}$ have received a packet while in the previous state $\{i,0,k+1,e\}$.

The presence of hidden stations

The basic access mechanism in IEEE 802.11 is a two-way handshaking method. The hidden stations do not sense the transmission from the source until they receive an ACK. Until then, the channel is considered as idle. If any one of these hidden stations completes its backoff procedure before sensing the ACK, it will send another data frame to the destination, which will collide with the data frame from the existing source. The vulnerable period in hidden stations equals the length of a data frame of AC_i, Fig. 2.

The RTS/CTS mechanism (four-way handshaking method) reserves the medium before transmitting a data frame by transmitting a RTS frame as the first frame of any frame exchange sequence and replying a CTS frame after a SIFS period. The hidden station effect on the RTS/CTS access method is shown in Fig. 3. The vulnerable period V_i for the hidden stations

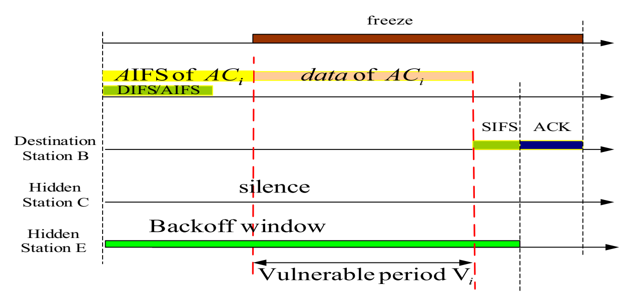

Fig. 2 Basic access method.

equals the length of the RTS frame plus a SIFS period. Unlike the basic access method, the vulnerable period V_i for hidden stations in RTS/CTS access method is a fixed length period and is not related to the length of the data frame of AC_i from the source.

Analysis the performance in the presence of hidden stations

Let $a = \sum_{j=0}^{L_i-1}(1-p_i)b_{i,j,0} + b_{i,L_i,0}$ and let $b = a\rho_i + p_i q_i b_{i,0,0,e}$. The kernel rule of Markov chain is that the birth rate of a state

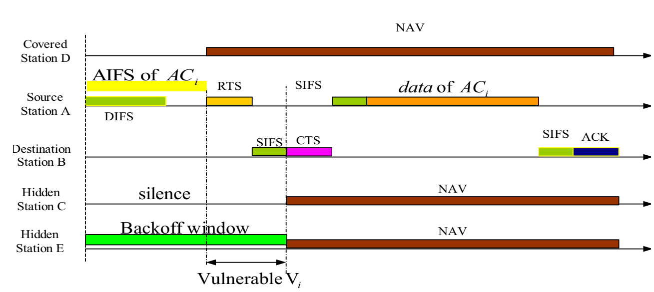

Fig. 3 RTS/CTS access method.

will be equal to its death rate when the Markov chain becomes a stationary distribution of the chain. With this, by writing all the birth-death equations recursively through the chain from right to left, from the top row to the bottom row, we have the distribution probability

$$b_{i,0,k,e} = \frac{a(1-\rho_i)}{w_{i,0}(1-p_i^*)} \frac{1-\left(1-q_i^*\right)^{w_{i,0}-k}}{q_i^*} \quad \text{where } k \in [1, w_{i,j}-1] \tag{1}$$

$$b_{i,0,0,e} = \frac{a(1-\rho_i)}{w_{i,0}q_i} \frac{1-\left(1-q_i^*\right)^{w_{i,0}}}{q_i^*} \tag{2}$$

$$b_{i,0,k} = \frac{b(w_{i,0}-k)}{w_{i,0}(1-p_i^*)} + q_i^* \sum_{s=k+1}^{w_{i,0}-1} b_{i,0,s,e} \quad \text{where } k \in [1, w_{i,j}-1] \tag{3}$$

$$b_{i,0,0} = b + q_i(1-p_i)b_{i,0,0,e} + q_i^*\left(1-p_i^*\right) \sum_{s=1}^{w_{i,0}-1} b_{i,0,s,e} \tag{4}$$

$$b_{i,j,k} = \frac{(w_{i,j}-k)p_i^j b_{i,0,0}}{w_{i,j}(1-p_i^*)} \quad \text{where } k \in [1, w_{i,j}-1], j \in [1, ,L_i] \tag{5}$$

$$b_{i,j,0} = p_i b_{i,j-1,0} \tag{6}$$

From Eq. (6), we obtain

$$b_{i,j,0} = p_i^j b_{i,0,0} \tag{7}$$

Finally, as [3–6], the normalization requires that:

$$1 = \sum_{k=0}^{w_{i,0}-1} b_{i,0,k,e} + \sum_{j=0}^{L_i} \sum_{k=0}^{w_{i,j}-1} b_{i,j,k} \tag{8}$$

we get

$$\frac{1}{b_{i,0,0}} = \sum_{j=0}^{L_i} p_i^j \left(1 + \sum_{k=1}^{w_{i,j}-1} \frac{(w_{i,j}-k)}{w_{i,j}(1-p_i^*)}\right) + \frac{(1-\rho_i)}{w_{i,0}} \left[\frac{1-\left(1-q_i^*\right)^{w_{i,0}}}{q_i^*}\right] \left[\frac{(w_{i,0}-1)p_i}{2(1-p_i^*)} + \frac{1}{q_i}\right] \tag{9}$$

We know ρ_i represents the probability that there is a packet waiting in the transmission queue at the time a transmission is completed or a packet is dropped. When $\rho_i \to 1$, the second part $\frac{(1-\rho_i)}{w_{i,0}}\left[\frac{1-\left(1-q_i^*\right)^{w_{i,0}}}{q_i^*}\right]\left[\frac{(w_{i,0}-1)p_i}{2(1-p_i^*)} + \frac{1}{q_i}\right]$ in Eq. (9) will disappear, so that the second part is the dominant term under non-saturation. We can rewrite (11) using $w_{i,j} = \begin{cases} 2^j w_{i,0} & j \leqslant m_i \\ 2^m w_{i,0} & m_i < j \leqslant L_i \end{cases}$ where $i \in \{0,1,2,3\}$ and $j \in [0,L_i]$.

Since a transmission occurs whenever the backoff counter becomes zero, the transmission probability in a randomly chosen slot time (no matter whether the transmission results in a collision or not) for an AC can be expressed by τ_i

$$\tau_i = \sum_{j=0}^{L_i} b_{i,j,0} = \frac{1-p_i^{L_i+1}}{1-p_i} b_{i,0,0} \quad \text{where } i \in \{0,1,2,3\} \tag{10}$$

Hence substituting Eq. (9) for Eq. (10), we obtain the stationary probability that the station transmits a packet in a randomly chosen slot time.

We notice that collisions may occur among different AC_i in the same EDCA station (this is called virtual collisions), and collisions may also take place among different EDCA stations (this is called external collisions). Let $Prob_i^{virt}$ denote the probability of virtual collisions for AC_i, and $Prob^{ext}$ be the probability of external collisions in the system.

The probability of virtual collisions $Prob_i^{virt}$ can be expressed as follows, considering that each AC will collide only with higher priority AC_i in the same station.

$$\begin{cases} Prob_0^{virt} = 0 \\ Prob_1^{virt} = \tau_0 \\ Prob_2^{virt} = 1-(1-\tau_0)(1-\tau_1) \\ Prob_3^{virt} = 1-(1-\tau_0)(1-\tau_1)(1-\tau_2) \end{cases} \tag{11}$$

Because the data frames from the higher priority AC receive the TXOP when there are collisions within a QSTA and the data frames from the lower priority colliding AC(s) behave as if there were an external collision. So we should modify τ_i, the transmission probability of AC_i, for an EDCA station in a randomly chosen slot time.

Let the modified τ_i be denoted as τ_i^{virt}, $i \in \{0,1,2,3\}$, denoting the transmission probability of AC_i for an EDCA station. Thus,

$$\begin{cases} \tau_0^{virt} = \tau_0 \\ \tau_1^{virt} = \tau_1(1-\tau_0) \\ \tau_2^{virt} = \tau_2(1-\tau_0)(1-\tau_1) \\ \tau_3^{virt} = \tau_3(1-\tau_0)(1-\tau_1)(1-\tau_2) \end{cases} \tag{12}$$

And the total transmission probability for all AC inside a single EDCA enable station is

$$\tau_{total}^{virt} = \sum_{i=0}^{3} \tau_i^{virt} \tag{13}$$

With τ_{total}^{virt}, the probability of external collisions in the coverage area can be expressed by

$$Prob_{coverage}^{ext} = 1 - \left(1-\tau_{total}^{virt}\right)^{N_c-1} \tag{14}$$

where N_C is the number of stations in the coverage area. Each station is an EDCA enabled station. N_C is also the number of each AC.

In order to calculate S_i, the average throughput of AC_i in a hidden system, we need to derive the stationary probability $\tilde{\tau}_i$ that a station transmit AC_i packets in its vulnerable period as defined above. We know, after k slots counter down,b_{i,j,V_i} transmission probability is $\left(1-p_i^*\right)^k b_{i,j,k}$. All states whose counter is less than V_i, will count down one by one. They will become in the period of V_i slots, and then become the state which can transmit with some probability. So we get $\tilde{\tau}_i = \sum_{j=0}^{L_i}\sum_{k=0}^{V_i-1}\left(1-p_i^*\right)^k b_{i,j,k}$, shown in Fig. 2. Calculating $\tilde{\tau}_i$, we have

$$\tilde{\tau}_i = \frac{1-p_i^{L_i+1}}{1-p_i} b_{i,0,0}\left[1 + \frac{\left(1-p_i^*\right)-\left(1-p_i^*\right)^{V_i}}{(1-p_i^*)p_i^*}\right] + \left[\frac{\left(1-p_i^*\right)-\left(1-p_i^*\right)^{V_i}}{p_i^*} - (V_i-1)\left(1-p_i^*\right)^{V_i}\right]\frac{b_{i,0,0}}{(1-p_i^*)p_i^*} \times \sum_{j=0}^{L_i} \frac{p_i^j}{w_{i,j}} \tag{15}$$

Considering the virtual collision factor in hidden stations, let $\tilde{\tau}_i^{virt}$ be a modification of $\tilde{\tau}_i, i \in \{0, 1, 2, 3\}$. We have,

$$\begin{cases} \tilde{\tau}_0^{virt} = \tilde{\tau}_0 \\ \tilde{\tau}_1^{virt} = \tilde{\tau}_1(1 - \tilde{\tau}_0) \\ \tilde{\tau}_2^{virt} = \tilde{\tau}_2(1 - \tilde{\tau}_0)(1 - \tilde{\tau}_1) \\ \tilde{\tau}_3^{virt} = \tilde{\tau}_3(1 - \tilde{\tau}_0)(1 - \tilde{\tau}_1)(1 - \tilde{\tau}_2) \end{cases} \tag{16}$$

Considering virtual collision factor, the total transmission probability of a hidden EDCA station in its vulnerable period for all AC inside one EDCA station is $\tilde{\tau}_{total}^{virt} = \sum_{i=0}^{3} \tilde{\tau}_i^{virt}$. So the probability that at least a hidden station transmits packets during the vulnerable period is $Prob_{hidden}^{ext} = 1 - (1 - \tilde{\tau}_{total}^{virt})^{N_h}$. N_h is the number of hidden stations.

In the stationary state, the collision probability p_i, in the presence of hidden stations, can be expressed as:

$$p_i = Prob_i^{virt} + \left(1 - Prob_i^{virt}\right) Prob^{ext} \tag{17}$$

But the $Prob^{ext}$ is

$$\begin{aligned} Prob^{ext} &= Prob_{coverage}^{ext} + \left(1 - Prob_{coverage}^{ext}\right) Prob_{hidden}^{ext} \\ &= 1 - \left(1 - \tau_{total}^{virt}\right)^{N_c - 1} \left(1 - \tilde{\tau}_{total}^{virt}\right)^{N_h} \end{aligned} \tag{18}$$

where τ_{total}^{virt} and $\tilde{\tau}_{total}^{virt}$ can be found from previous equations. We are now ready to derive the throughput for each AC_i with hidden stations in the system. Let $Prob_{busy}$ denote the probability that at least one station transmits AC_i data frame in the considered time slot, and $Prob_i^{hidden}$ be the probability that exactly one station transmits on the channel. In the chosen time slot, this probability can also be considered as the probability that n stations transmit and none of its covered station transmits in the slot and none of the hidden station transmits in the vulnerable period.

$$Prob_{busy} = 1 - \left(1 - \tau_{total}^{virt}\right)^{N} \tag{19}$$

The total number of contending stations, N, is equal to $N_c + N_h$.

$$Probs_i^{hidden} = \frac{N_c \tau_i^{virt} \left(1 - \tau_{total}^{virt}\right)^{N_c - 1} \left(1 - \tilde{\tau}_{total}^{virt}\right)^{N_h}}{Prob_{busy}} \tag{20}$$

and PFC denotes the probability that a transmission attempt fails due to a collision given that there is at least one station transmitting in the considered time slot. By definition,

$$PFC = \frac{1 - \left(1 - \tau_{total}^{virt}\right)^{N} - N_c \tau_{total}^{virt} \left(1 - \tau_{total}^{virt}\right)^{N_c - 1} \left(1 - \tilde{\tau}_{total}^{virt}\right)^{N_h}}{Prob_{busy}} \tag{21}$$

Let S_i^{hidden} denote the average throughput of AC[i] in the system. Thus,

$$\begin{aligned} S_i^{hidden} &= \frac{Prob_i^{hidden} Prob_{busy} E[Length]}{(1 - Prob_{busy}) \times slotTime + \sum_{i=0}^{3} Prob_{busy} Probs_i^{hidden} t_{S_i} + Prob_{busy} PFC \times t_c} \\ &\quad \frac{E[Length]}{\frac{\left(1 - \tau_{total}^{virt}\right)^{N - N_c + 1}}{N_c \tau_i^{virt} \left(1 - \tilde{\tau}_{total}^{virt}\right)^{N_h}} \times slotTime + \sum_{j=0}^{3} \frac{\tau_j^{virt}}{\tau_i^{virt}} t_{S_j} + \frac{PFC \times t_c}{Probs_i^{hidden}}} \end{aligned} \tag{22}$$

Where $\frac{PFC}{Probs_i^{hidden}} = \frac{1 - \left(1 - \tau_{total}^{virt}\right)^{N} - N_c \tau_{total}^{virt} \left(1 - \tau_{total}^{virt}\right)^{N_c - 1} \left(1 - \tilde{\tau}_{total}^{virt}\right)^{N_h}}{N_c \tau_i^{virt} \left(1 - \tau_{total}^{virt}\right)^{N_c - 1} \left(1 - \tilde{\tau}_{total}^{virt}\right)^{N_h}}$. The expressions t_c is the average time the channel is sensed busy by each station during a collision and t_{s_i} is the average time the channel is sensed busy (i.e., the slot time lasts) because of a successful transmission, The t_c and t_{si} can be derived based on basic and RTS/CTS access modes.

The backoff countdown with AIFS differentiation

Without AIFS differentiation, the probability that a backoff senses a slot as idle in the Markov chain equals the probability that all other stations do not transmit (by setting $p_i^* = p_i$). We know there are AIFS differentiations among AC_i. The countdown blocking probability p_i^* will not be equal to p_i again.

Let dif_i denote the differences in the number of time slots between minimum AIFS and AIFSN, i.e.,

$$dif_i = \frac{AIF_i - AIF_{min}}{aslotTime} \approx \frac{AIF_i - DIFs}{aslotTime} \tag{23}$$

p_i^* will be one until the channel has been idle. After the wireless medium becomes idle during AIFSi, AC_i will start to count down counter value, with $1 - p_i^*$ probability. But during its countdown, if the higher priority AC_i of its inside station is transmitting, those lower priority countdown will freeze. The lower priority queue must wait until the higher priority finishes transmission. With dif_i, p_i^* can be expressed by

$$\begin{cases} p_0^* = 1 & before\ AIFS[AC\_VI] \\ p_0^* = 0 & after\ AIFS[AC\_VI] \end{cases} \tag{24a}$$

$$\begin{cases} p_1^* = 1 & before\ AIFS[AC\_VO] \\ p_1^* = 1 - \left[\left(1 - \tau_0^{virt}\right)\left(1 - \tau_0^{virt}\right)^{N-1}\right]^{dif_1 - dif_0} & after\ AIFS[AC\_VO] \end{cases} \tag{24b}$$

Table 2 System default parameters/configuration.

MAC header	272 bits
PHY header	128 bits
ACK	112 bit + PHY header
RTS	160 bit + PHY header
CTS	112 bit + PHY header
Channel bit rate	1, 2, 11 Mbit/s
Slot time	50 μs
SIFS	28 μs
DIFS	128 μs
Stations	From 3 to 100
Data payload length	216 octets

Table 3 System default parameters/configuration.

	Setting one			
	AC[0]	AC[1]	AC[2]	AC[3]
AIFSN	4	6	7	8
M_i	5	6	6	7
L_i	7	8	8	9
CWmin	3	4	5	6
CWmax	15	31	1023	1023
Retry limit (long/short)	7/4	8/4	8/4	9/4

$$
\begin{cases}
p_2^* = 1 & before\ AIFS[AC\_BE] \\
p_2^* = 1 - \left[\left(1-\tau_0^{virt}\right)\left(1-\tau_0^{virt}\right)^{N-1}\right]^{dif_1-dif_0} & \\
\times \left[\prod_{i=0}^{1}\left(1-\tau_i^{virt}\right)\left(1-\tau_i^{virt}\right)^{N-1}\right]^{dif_2-dif_1} & after\ AIFS[AC\_BE]
\end{cases}
\tag{24c}
$$

$$
\begin{cases}
p_3^* = 1 & before\ AIFS[AC\_BK] \\
p_3^* = 1 - \left[\left(1-\tau_0^{virt}\right)\left(1-\tau_0^{virt}\right)^{N-1}\right]^{dif_1-dif_0} & \left[\prod_{i=0}^{1}\left(1-\tau_i^{virt}\right)\left(1-\tau_i^{virt}\right)^{N-1}\right]^{dif_2-dif_1} \\
\left[\prod_{i=0}^{2}\left(1-\tau_i^{virt}\right)\left(1-\tau_i^{virt}\right)^{N-1}\right]^{dif_3-dif_2} & after\ AIFS[AC\_BK]
\end{cases}
\tag{24d}
$$

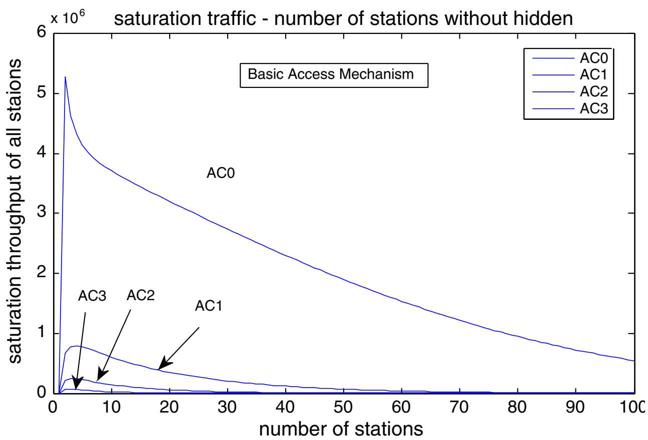

Fig. 4 Basic access mechanism-saturation throughput-vs-number of stations without the hidden station effect.

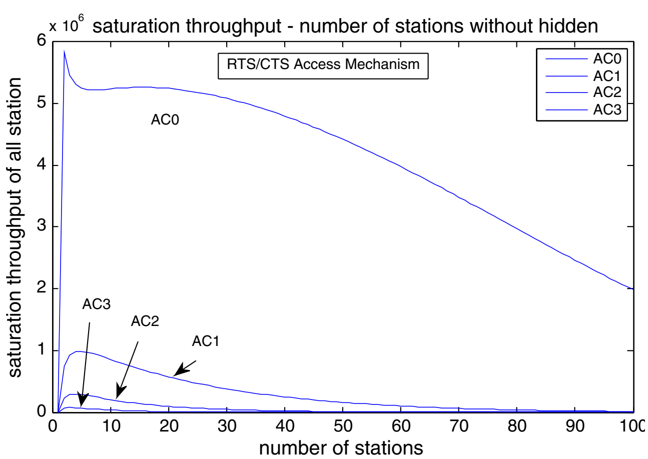

Fig. 5 RTS/CTS access mechanism-saturation throughput-vs-number of stations without hidden stations.

Numerical analysis

Parameters for numerical calculations

For simplicity and to keep focus on the most important issues, we have assumed that all traffic classes send packets of equal lengths (i.e., of 216 bytes) so that each packet fits perfectly into one TXOP and we simply used the default 802.11e values summarized in Tables 2 and 3. The channel bit rate has been assumed equal to 11 Mbit/s.

Maximum throughput

The analytical model given above allows us to determine the maximum achievable saturation throughput when $\rho_i = 1$.

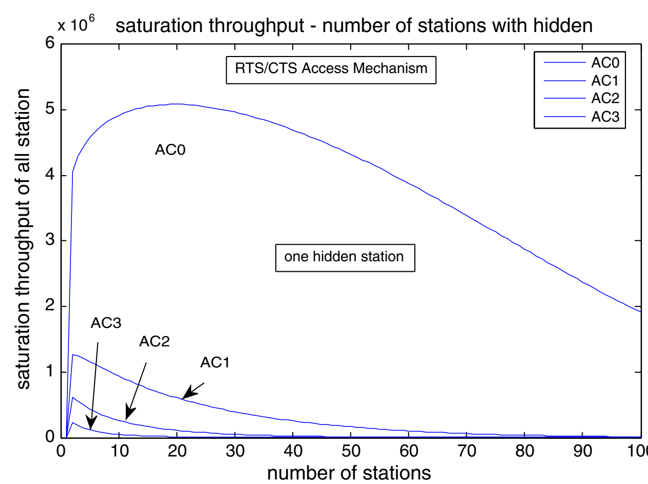

Fig. 7 RTS/CTS access mechanism-saturation throughput in the presence of hidden station.

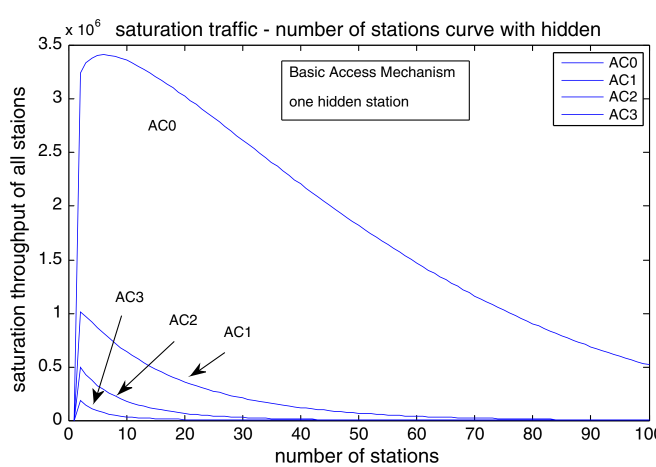

Fig. 6 Basic access mechanism-saturation throughput-vs-number of stations in the presence of hidden station.

We show the throughput results without the hidden station effect in Fig. 4 (basic access) and Fig. 5 (RTS/CTS access). As expected, we notice here that the throughput varies depending on the access categories, AC_i, with AC0 providing the highest throughput.

We present the throughput results in the presence of hidden stations in Fig. 6(basic access) and Fig. 7 (RTS/CTS access). Again we notice the same throughput results patterns. Also comparing Figs. 6 and 7 with their counterparts Figs. 4 and 5, we notice that the throughput degrades for the RTS/CTS case when compared with the Basic Access.

Conclusion

In this paper, we have extended earlier works by other authors dealing with IEEE 802.11e and applied the Markov chain model for IEEE 802.11e under non-saturation conditions and effects of the hidden stations. Our initial results show the saturation throughput versus the number of stations for different access categories. We intend to continue further our analysis and to simulate such environments to help in the understanding of IEEE 802.11e behavior.

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