Performance Analysis of IEEE 802.11e EDCA

Ming-Ju Wu
Computer Science Department,
National Chengchi University,
Taipei, Taiwan, ROC
g9107@cs.nccu.edu.tw

Tzu-Chieh Tsai
Computer Science Department,
National Chengchi University,
Taipei, Taiwan, ROC
ttsai@cs.nccu.edu.tw

Abstract*-The main purpose of the IEEE 802.11 group e is to support Quality of Service (QoS) for wireless networks. It uses Enhanced Distributed Channel Access (EDCA) to differentiate service of priorities by means of various Inter-Frame Space (IFS) and Contention Window (CW). In order to further develop efficient QoS management schemes for the IEEE 802.11e networks, we propose an analytical model to evaluate throughput and delay under different multimedia traffic flows, namely, voice, video, and data. The correctness of our analysis has been validated via simulation results. Throughout our model, call admission control (CAC) and resource management can be easily applied, and thus QoS for hybrid requirements is supported.*

Keywords: EDCA, 802.11e, QoS, MAC

1. Introduction

Since the radio frequencies used by the 802.11 wireless families are free, enterprises, companies, families, or individual persons can build their own wireless LAN, and avoid pulling network wires. The prices of IEEE 802.11 b/a/g dropped quickly, and data rates increased. More and more researches and commercial projects focus on 802.11 WLAN dramatically these years.

The major 802.11 [1] MAC has two fundamental mechanisms to access medium. They are all based on the carrier sense multiple access with collision avoidance. One is Distributed Coordination Function (DCF). In DCF, the station has to contend to obtain the opportunity to access the channel. The other is Point Coordination Function (PCF). PCF may be used only when there is at least a Point Coordinator (PC) to control this channel, and it can support limited QoS. The PC is always an Access Point (AP). Time will be divided into repeated periods called super-frames. A super-frame is composed by a Contention Free Period (CFP) that uses PCF and a Contention Period (CP) that uses DCF.

There are two techniques to transmit packets. First is a two-way handshaking technique, called basis access. When the sender obtains the opportunity to access channel, it will send data directly and wait MAC acknowledgement (ACK) sent from receiver. If collision occurs, it will waste much time until large packet transmission finish. Another is a four-way handshaking technique, also known as Request-To-Send / Clear-To-Send (RTS/CTS). When a station obtains the access opportunity of channel, it fist sends a small RTS frame and waits CTS frame from receiver, then starts to transmit packets. Other stations that hear RTS, CTS or DATA frame will defer a period of time to access channel, called Network Allocation Vector (NAV). The NAV value is set according to the length field in RTS, CTS or DATA frame.

Since the higher applications such as video, voice, or data have different QoS requirements for bandwidth, delay, jitter, and packet loss, the legacy IEEE 802.11 is not insufficient because it can not transmit data streams with different QoS requirements. The IEEE 802.11e has been drawn up for supporting QoS further. In order to verify the QoS management for different traffic flows, we propose this model to analyze EDCA, and make policy of CAC by this model.

The remainder of the paper is organized as follows. In Section II, we make a brief introduction about the IEEE 802.11e EDCA MAC. In Section III, some other studies about EDCA performance are investigated. Our Markov chain model is proposed and explained in Section IV. In Section V, we verify the accuracy of our model by comparing throughput and delay with the results in NS-2 simulation. The concluding of this paper is in section VI.

2. The IEEE 802.11e

The members of IEEE 802.11 task group e have been working for supporting and managing QoS in wireless LAN (WLAN) from 2000 March called 802.11e [3]. The QoS services are such as Voice over Internet Protocol (VoIP), Videoconference, and Video on demand (VoD). 802.11e also has CFP and CP with two different MAC mechanisms. One is EDCA. Another is Hybrid Coordination Function (HCF) Controlled Channel Access (HCCA). The 802.11e station is named QSTA (QoS Station).

The EDCA in 802.11e is the basis for the HCCA and is extend from DCF. EDCF can be used only in the CP. Contention-based channel access is referred to as EDCA. Now IEEE 802.11 task group e defines 4 access categories (ACs). The priorities from high to low are Voice (VO), Video (VI), Best Effort (BE), and Back Ground (BK).

HCF is the enhanced version of PCF. The maximum different between HCCA and PCF is HCCA can obtain additional transition opportunity (TXOP) in the CP. To ensure the QoS in HCCA, we must consider the basic of HCCA: EDCA.

In EDCA, MAC Service Data Units (MSDUs) are now delivered through multiple backoff instances within one QSTA. Each AC independently starts a backoff after detecting the channel being idle for an Arbitration Inter-Frame Space (AIFS); the AIFS is at least DIFS, and can be enlarged individually for each AC. AIFS = SIFS + AIFSN*Slot. The AIFSN means AIFS number. After waiting for AIFS, each backoff sets a counter to a random number drawn from the interval between 0 and CW[AC]. The minimum size and the maximum size of the CW (CWmin[AC] and CWmax[AC]) are other parameters dependent on the AC. CW of backoff stage 0 is CWmin[AC]. The backoff stage increases when collision or virtual collision occurs. If the new backoff stage ≦ retry limit in 802.11, the CW will be the maximum value of $2^{(\text{backoff stage})}$(CWmin[AC]+1)-1 and CWmax[AC]. If the backoff stage > retry limit, the backoff stage will become zero, and CW will be reset to CWmin[AC]. The initial backoff stage of a new arrived packet is 0, and the backoff stage can not be greater than retry limit. If a transmission failure occurs when backoff stage equals retry count, it will be set to zero again, and CW will be obtained with this new backoff stage.

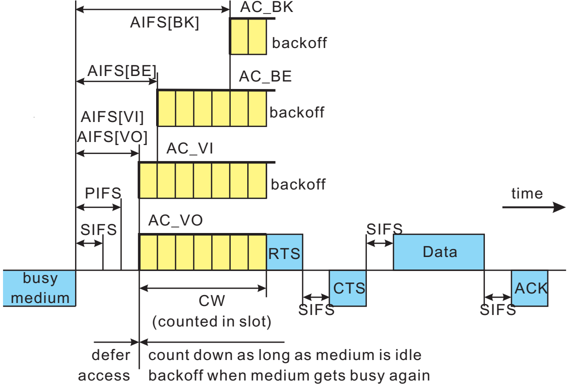

Figure 1. Multiple EDCA Backoff Entities Contention with RTS/CTS

When the medium is sensed busy before the counter reaches zero, the backoff has to wait for the medium being idle for AIFS again, before continuing to count down the counter. If the backoff counter reaches zero, the backoff instance will try to transmit packets like Figure 1. The 802.11e indicates 4 queues in MAC for VO, VI, BE, and BK traffic. If two backoff instances in the same QSTA want to transmit in the same slot, the higher priority traffic will transmit, and the other will act as a collision occurs, called virtual collision, which backoff like a transmission failure. Figure 2 indicates the virtual queue architecture of 802.11e.

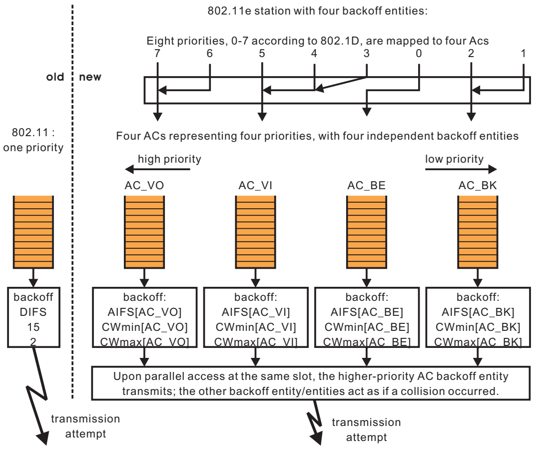

Figure 2. Access Categories in the IEEE 802.11e

3. Performance studies about DCF and EDCA

There are several performance studies about EDCA [7][8] and old DCF [4][5][6]. [5][6][7][8] are all inspired from the same Markov chain in [4]. In [7], the authors used three-dimension discrete-time Markov chain. The paper took into account AIFS and CW for different ACs, and considered different busy probabilities in different time points when the channel is sensed idle at least a DIFS time. Another performance study about EDCA is [8]. The authors also took AIFS and CW for different AC into account, and obtained the performance. The author of [4] provides a bi-dimension discrete-time Markov chain to simulate the action in the 802.11 DCF CP. In [5], the Markov chain goes a step further through considering the retry limit in 802.11. [6] followed Markov chain in [4] and compared different CW for different service. All these studies assumed each station in DCF or QSTA in EDCA has only one flow, and every flow has fully loading and always has a packet. In such saturated network environment, we can not observe QoS-sensitive traffics without greediness precisely, and it was not considered that one QSTA usually has more than one traffic flow either.

We combined model in [5] and [7], and extend the model to support different QoS flows in the same QSTA. Different with [7][8] in our model, we also support VO or VI without greediness, and one QSTA can support up to three different traffics.

4. EDCA Markov Chain Model

Our Markov model is improved from [5] and [7]. We extend this Markov chain up to four-dimensions.

Every QSTA could communicate with each other directly. In order to use this model to guarantee the QoS of VO and VI flows in a strict environment, we assume every QSTA have greedy BE and BK flows. It means every BE or BK has always a packet available for transmission. Each QSTA has at most another CBR flow with VO or VI. All flows with VO use the same Traffic Specification (TSPEC), and all flows with VI also use the same TSPEC. VO is the only one AC whose packet size is different from the other VI, BE, and BK, because the packet of VO is always far smaller than packets of other ACs. Assume that all data are transmitted with RTS/CTS mode. Each Markov chain expresses one flow in a QSTA. Consider the number of QSTA is N. The number of AC flow is defined as N_{AC}. $N_{BE} = N_{BK} = N \geqq N_{VO} + N_{VI}$, because each QSTA has BE and BK flows, but it has at most another VO or VI flow.

There are two channel states for EDCA, one is busy, and another is idle. So we add a dimension for supporting different transmission time, which means the channel state. Other three dimensions are similar to the model in [7], and consider transition probabilities for different condition for collisions and virtual collisions.

There are two Markov chains here. First is for VO traffic and second is for VI, BE and BK. The difference is that VO uses smaller size of packet than other ACs.

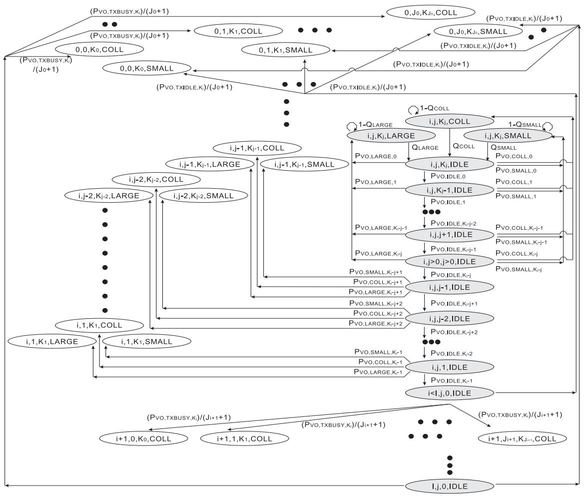

Figure 3. EDCA Markov Chain for VO

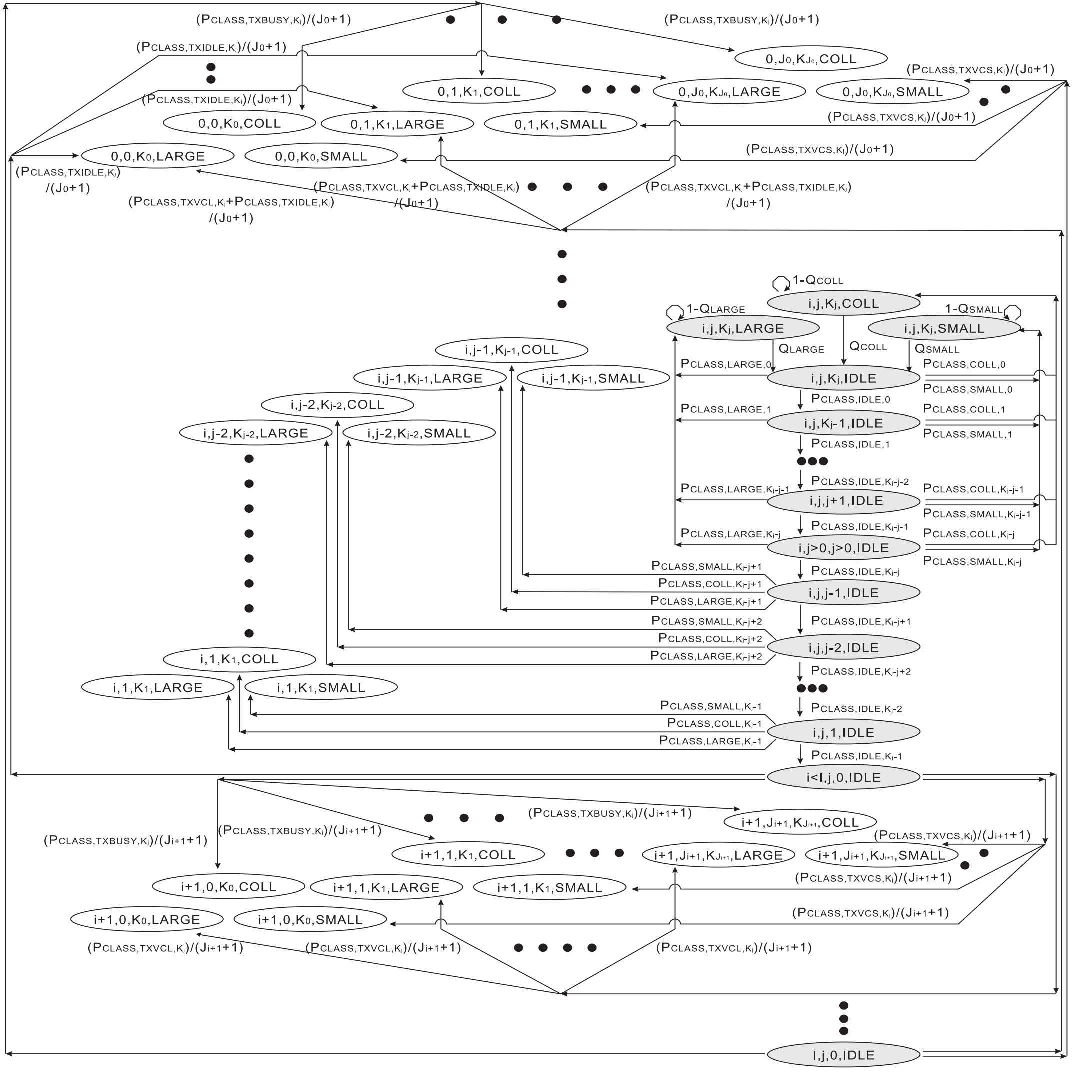

Figure 4. EDCA Markov Chain for VI, BE, and BK

4.1 Markov Chain State

I is the retry limit of 802.11. Let i(t) be the first discrete-time stochastic process representing backoff stage. A discrete and integer time scale is adopted: t and t+1 correspond to the beginning of two consecutive slot times. Here one unit of time means one time slot in 802.11.

The second discrete-time stochastic process is j(t). It represents the backoff number not including AIFS at the last time which the channel is sensed busy. The upper bound of j(t) we defined is j_i which depend on the value of i(t). $J_{AC,i}$ (J_i) is the CW_{AC} of backoff stage i.

The CWO_{AC} means the result of subtracting self AC's AIFSN off the minimum AIFSN of all ACs. Let k(t) be the backoff number including CWO_{AC}. When it counts down to zero, it will try to transmit data. It counts down only when the channel is sensed idle for the minimum AIFS time of all ACs. The k is reset to CWO_V + the minimum value between j and k when the channel is sensed busy because of a successful transmission or a collision. The upper bound of k is $K_{AC,j}$ (K_j).

The last stochastic process s(t) represents the channel state. There are four channel states. One is IDLE, which means the channel is idle at least for a PIFS time. Then, SMALL, LARGE, COLL mean the channel is sensed busy because of VO transmission, other AC transmission, or collision respectively.

We use this four-dimensional process b(t) = { i(t), j(t), k(t), s(t) } with the discrete-time Markov chain described in Figure 3 and Figure 4 to model EDCA. They have a little different when its k(t) count down to zero, and s(t) is IDLE.

4.2 Transition Probability Matrix

In Figure 3 and Figure 4, several transition probabilities are shown as follows:

$$\begin{cases}
P_{AC}(i,j,j+CWO_{AC},IDLE \mid i,j,j+CWO_{AC},LARGE) = Q_{LARGE} & \\
P_{AC}(i,j,j+CWO_{AC},LARGE \mid i,j,j+CWO_{AC},LARGE) = 1-Q_{LARGE} & \\
P_{AC}(i,j,j+CWO_{AC},IDLE \mid i,j,j+CWO_{AC},SMALL) = Q_{SMALL} & \\
P_{AC}(i,j,j+CWO_{AC},SMALL \mid i,j,j+CWO_{AC},SMALL) = 1-Q_{SMALL} & \\
P_{AC}(i,j,j+CWO_{AC},IDLE \mid i,j,j+CWO_{AC},COLL) = Q_{COLL} & \\
P_{AC}(i,j,j+CWO_{AC},COLL \mid i,j,j+CWO_{AC},COLL) = 1-Q_{COLL} & \\
P_{AC}(i,j,k-1,IDLE \mid i,j,k,IDLE) = P_{AC,IDLE,j+CWO_{AC}-k} & k\in[1,j+CWO_{AC}] \\
P_{AC}(i,j,j+CWO_{AC},LARGE \mid i,j,k,IDLE) = P_{AC,LARGE,j+CWO_{AC}-k} & k\in[j+1,j+CWO_{AC}] \\
P_{AC}(i,j,j+CWO_{AC},SMALL \mid i,j,k,IDLE) = P_{AC,SMALL,j+CWO_{AC}-k} & k\in[j+1,j+CWO_{AC}] \\
P_{AC}(i,j,j+CWO_{AC},COLL \mid i,j,k,IDLE) = P_{AC,COLL,j+CWO_{AC}-k} & k\in[j+1,j+CWO_{AC}] \\
P_{AC}(i,k,k+CWO_{AC},LARGE \mid i,j,k,IDLE) = P_{AC,LARGE,j+CWO_{AC}-k} & k\in[1,j] \\
P_{AC}(i,k,k+CWO_{AC},SMALL \mid i,j,k,IDLE) = P_{AC,SMALL,j+CWO_{AC}-k} & k\in[1,j] \\
P_{AC}(i,k,k+CWO_{AC},COLL \mid i,j,k,IDLE) = P_{AC,COLL,j+CWO_{AC}-k} & k\in[1,j] \\
P_{AC}(0,m,m+CWO_{AC},LARGE \mid i,j,0,IDLE) = \dfrac{P_{AC,TXIDLE,j+CWO_{AC}}}{J_{AC,0}+1} & AC\neq VO, m\in[0,J_{AC,0}] \\
P_{VO}(0,m,m+CWO_{VO},SMALL \mid i,j,0,IDLE) = \dfrac{P_{VO,TXIDLE,j+CWO_{AC}}}{J_{AC,0}+1} & m\in[0,J_{VO,0}] \\
P_{AC}((i+1)\%I,m,m+CWO_{AC},SMALL \mid i,j,0,IDLE) = \dfrac{P_{AC,TXVCS,j+CWO_{AC}}}{J_{AC,(i+1)\%I}+1} & m\in[0,J_{AC,(i+1)\%I}] \\
P_{AC}((i+1)\%I,m,m+CWO_{AC},LARGE \mid i,j,0,IDLE) = \dfrac{P_{AC,TXVCL,j+CWO_{AC}}}{J_{AC,(i+1)\%I}+1} & m\in[0,J_{AC,(i+1)\%I}] \\
P_{AC}((i+1)\%I,m,m+CWO_{AC},COLL \mid i,j,0,IDLE) = \dfrac{P_{AC,TXBUSY,j+CWO_{AC}}}{J_{AC,(i+1)\%I}+1} & m\in[0,J_{AC,(i+1)\%I}]
\end{cases}$$

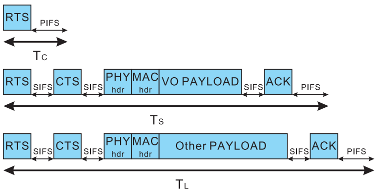

Figure 5. T_C, T_S, and T_L

Figure 5 shows the transmission time for different event. T_L means the transition time of a packet with VI, BE, or BK. T_S means the transition time of a packet with VO. T_C means the collision time of RTS packet. Then we obtain the probability from BUSY state to IDLE state as follows.

$$Q_{LARGE} = 1/T_{LARGE}\ , Q_{SMALL} = 1/T_{SMALL}\ , Q_{COLL} = 1/T_{COLL}$$

We define $Z_{AC,m}$ as the transition probability for an AC flow when the system is sensed idle for the minimum AIFS time of all ACs + m time. $RATIO_{AC}$ is attempting ratio of a slot which equals the minimum of (1, expected throughput / maximum possible throughput). The expected throughput is defined by TSPEC. The maximum possible throughput is obtained from our Markov chain model with fully load AC, explained latter in next sub-section. Because BE and BK are fully load, $RATIO_{BE}$ = $RATIO_{BK}$ = 1. $Z_{AC,m}$ can be derived as follows:

$$\begin{cases}
Z_{AC,m} = 0 & 0 < m < CWO_{AC} \\
Z_{AC,m} = RATIO_{AC} * \dfrac{\sum_i b(i, m-CWO_{AC}, m, IDLE)}{\sum_i \sum_{j=m}^{CW_{AC}+CWO_{AC}} b(i, j-CWO_{AC}, j, IDLE)} & CWO_{AC} \le m \le CW_{AC} + CWO_{AC} \\
Z_{AC,m} = RATIO_{AC} & m > CW_{AC} + CWO_{AC}
\end{cases}$$

Several transition probabilities when the system is sensed idle for the minimum AIFS time of all ACs + m time are defined as follows:

$P_{AC,\ IDLE,\ m}$: the probability that the channel will be sensed idle at next slot.

$P_{AC,\ SMALL,\ m}$: the probability that the channel will be sensed busy at next slot because of a successful transmission with VO.

$P_{AC,\ LARGE,\ m}$: the probability that the channel will be sensed busy at next slot because of a successful transmission with VI, BE, or BK.

$P_{AC,\ COLL,\ m}$: the probability that the channel will be sensed busy at next slot because of a collision.

$P_{AC,\ TXIDLE,\ m}$: the probability that the channel will be sensed idle at next slot when it wants to access the channel, and no other flows want to access.

$P_{AC,\ TXVCS,\ m}$: the probability that there is a virtual collision at next slot when it wants to access the channel because a higher priority VO flow wants to access the channel at the same time.

$P_{AC,\ TXVCL,\ m}$: the probability that there is a virtual collision at next slot when it wants to access the channel because a higher priority VI or BE flows want to access the channel at the same time.

$P_{AC,\ TXBUSY,\ m}$: the probability that the channel will be sensed busy for this AC at next slot when more than one other flow wants to access the channel. It will cause a collision.

IDLE means there are no other flows want to transmit, so the $P_{AC,\,IDLE,\,m}$ can be obtained easily as following:

$$\begin{cases} P_{VO,IDLE,m} = (1-Z_{VO,m})^{N_{VO}-1}(1-Z_{VI,m})^{N_{VI}}(1-Z_{BE,m})^{N}(1-Z_{BK,m})^{N} \\ P_{VI,IDLE,m} = (1-Z_{VO,m})^{N_{VO}}(1-Z_{VI,m})^{N_{VI}-1}(1-Z_{BE,m})^{N}(1-Z_{BK,m})^{N} \\ P_{BE,IDLE,m} = (1-Z_{VO,m})^{N_{VO}}(1-Z_{VI,m})^{N_{VI}}(1-Z_{BE,m})^{N-1}(1-Z_{BK,m})^{N} \\ P_{BK,IDLE,m} = (1-Z_{VO,m})^{N_{VO}}(1-Z_{VI,m})^{N_{VI}}(1-Z_{BE,m})^{N}(1-Z_{BK,m})^{N-1} \end{cases}$$

For exactly considering the probabilities include collision, virtual collision, and successful transmission, there are twelve cases of transmissions shown in Figure 6. Here we observe the whole system from point of view of self QSTA. Succ QSTA means the QSTA with successful transmission. Remaining QSTAs are Other QSTAs. Probability of successful transmission is shown as follows:

$$\sum_{\substack{possible\\case}} \begin{pmatrix} probability \\ of \\ case \end{pmatrix} * \begin{pmatrix} transmission \\ probability \\ of \quad case \end{pmatrix} * \begin{pmatrix} combination \quad of \\ Succ \quad QSTA \\ transmissions \end{pmatrix}$$

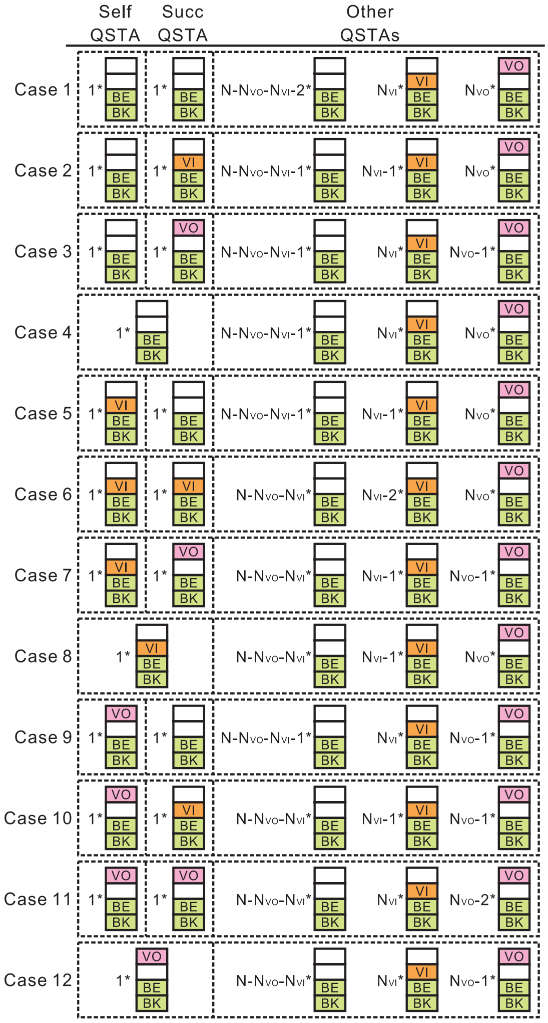

Figure 6. Possible Cases of Transmissions

To calculate $P_{VO,\,SMALL,\,m}$, only case 11 is involved. In case 11, we know a successful VO transmission in Succ QSTA and other QSTAs have totally (N_{VO}-2) VO flows, N_{VI} VO flows, (N-1) BE flows and (N-1) BK flows but they are not allowed to transmit. Since VO has higher priority than BE and BK, BE and BK flows in the Succ QSTA can be ignored Thus,

$$P_{VO,SMALL,m} = 1 * \begin{bmatrix} (1-Z_{VO,m})^{N_{VO}-2}(1-Z_{VI,m})^{N_{VI}} \\ (1-Z_{BE,m})^{N-1}(1-Z_{BK,m})^{N-1} \\ Z_{VO,m} \end{bmatrix} * (N_{VO}-1)$$

Similarly, to calculate $P_{BE,\,SMALL,\,m}$, case 3, 7, 11, and 12, are involved, and can be listed as follows:

$$\begin{aligned} P_{BE,SMALL,m} &= \frac{N-N_{VO}-N_{VI}}{N} * \begin{bmatrix} (1-Z_{VO,m})^{N_{VO}-1}(1-Z_{VI,m})^{N_{VI}} \\ (1-Z_{BE,m})^{N-2}(1-Z_{BK,m})^{N-1} \\ Z_{VO,m} \end{bmatrix} * N_{VO} \\ &+ \frac{N_{VI}}{N} * \begin{bmatrix} (1-Z_{VO,m})^{N_{VO}-1}(1-Z_{VI,m})^{N_{VI}} \\ (1-Z_{BE,m})^{N-2}(1-Z_{BK,m})^{N-1} \\ Z_{VO,m} \end{bmatrix} * N_{VO} \\ &+ \frac{N_{VO}}{N} * \begin{bmatrix} (1-Z_{VO,m})^{N_{VO}-1}(1-Z_{VI,m})^{N_{VI}} \\ (1-Z_{BE,m})^{N-2}(1-Z_{BK,m})^{N-1} \\ Z_{VO,m} \end{bmatrix} * (N_{VO}-1) \\ &+ \frac{N_{VO}}{N} * \begin{bmatrix} (1-Z_{VO,m})^{N_{VO}-1}(1-Z_{VI,m})^{N_{VI}} \\ (1-Z_{BE,m})^{N-1}(1-Z_{BK,m})^{N-1} \\ Z_{VO,m} \end{bmatrix} * 1 \end{aligned}$$

Other transition probabilities can be calculated similarly.

4.3 Throughput and Delay Calculation

The throughput and delay can be derived from the above equations as follows:

$$\begin{cases} TH_{VO} = \min\left(expected \quad TH_{VO}, \dfrac{SIZE_{VO}\sum_{i,j} b_{VO}(i,j,0,IDLE) * P_{VO,TXIDLE,j}}{SLOT} \right) kbps \\ TH_{VI} = \min\left(expected \quad TH_{VI}, \dfrac{SIZE_{VI}\sum_{i,j} b_{VI}(i,j,0,IDLE) * P_{VI,TXIDLE,j}}{SLOT} \right) kbps \\ TH_{BE} = \dfrac{SIZE_{BE}\sum_{i,j} b_{BE}(i,j,0,IDLE) * P_{BE,TXIDLE,j}}{SLOT} kbps \\ TH_{BK} = \dfrac{SIZE_{BK}\sum_{i,j} b_{BK}(i,j,0,IDLE) * P_{BK,TXIDLE,j}}{SLOT} kbps \end{cases}$$

$$Delay_{AC} = \frac{SLOT * 1000}{\sum_{i,j} b_{AC}(i,j,0,IDLE) * P_{AC,TXIDLE,j}} ms$$

Because the equations are not linear, we solved them by iterative method. Our Markov model is with finite spaces, and they form a closed set. The initial states are distributed in [$b_{AC}(0,j,K_j,LARGE)$, $b_{AC}(0,j,K_j,IDLE)$]. We compute the transition probabilities and state distribution in Markov Chain iteratively until all values are almost unchanged.

5. Model Validation

Table 1. TSPEC for VO and VI

TSPEC	VoIP(G.729A)	Video
Mean rate	13.02kbps	384kbps
Packet size	800bits	16384bits
Inter-arrival	60ms	41.667ms
Delay bound	10ms	20ms

In this section, we validate our analytical model through comparing with NS-2 results. The EDCA module in NS-2 was provided by Qiang Ni in [9]. The TSPEC we used are in Table 1, and the MAC and PHY parameters are listed in Table 2. In order to reduce the transmitting frequency of VO flows, we use six VO frames as a packet. Each VO frame length is 80 bit. IP/UDP/RTP header is 320 bits. Coding rate is 8 kbps. So the mean data rate without silence-compression is about 13.02 kbps. About the VI, we use 384 kbps which is the same as 3G. We assume that delay bounds of VO and VI are 10ms and 20ms respectively.

Table 2. System Parameters

RTS	160bytes + PLDP	VO CWmax/ CWmin/AIFSN	15/ 7/2
CTS	112bytes +PLDP	VI CWmax/ CWmin/AIFSN	31/ 15/2
ACK	112bytes + PLDP	BE CWmax/ CWmin/AIFSN	1023/ 31/3
Bit rate	11Mbps	BK CWmax/ CWmin/AIFSN	1023/ 31/7
SLOT	20us	Minim. bit rate	1Mbps
PLDP	24bits	MAChdr	272bits
SIFS	10us	Retry Limit	4
PIFS	30us	Prop. Delay	1us

In NS-2, we assume that all QSTAs transmit data to the AP, and each VO or VI starts at a random time fallen between 0 and 40 ms. Figure 7 shows total throughput of different ACs. The solid lines represent the results obtained from our model, and the dotted lines represent the outcomes from NS-2.

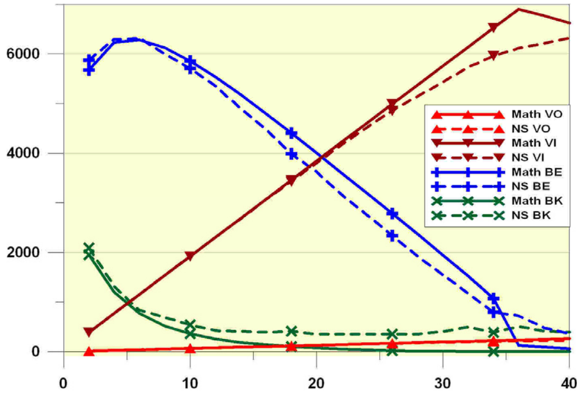

Figure 7. Throughput (N : N_{VO} : N_{VI} = 2:1:1)

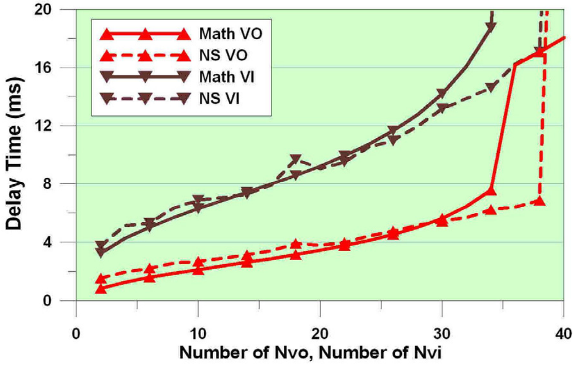

Figure 8. Delay Time (N : N_{VO} : N_{VI} = 2:1:1)

Figure 8 shows the delay time of VO and VI. Since BE and BK are fully load, delay time is the reciprocal of throughput. The differences between our analytical model and simulation are less than 10% in most situations

6. Conclusions and Future Work

Here we propose a Markov Chain model to analyze throughput and delay in the IEEE 802.11e EDCA for supporting QoS. Our model assumes an ideal channel state, and each QSTA can support up to three traffic classes. We consider (virtual) collision, AIFSN, CW. Through the results, the mean delay and throughput are calculated very accurately for different ACs.

Future, we will use the statistics obtained from this model to do connection admission control (CAC).

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