An Analytical Model for the IEEE 802.11e Enhanced Distributed Coordination Function

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Abstract— **The IEEE 802.11e protocol is designed to enhance the QoS capability of wireless local area networks (WLAN). In this paper, we propose a three dimensional Markov chain model for the 802.11e enhanced distributed coordination function (EDCF)[1] mode and compute the maximum sustainable throughput and service delay distribution for each priority class when under heavy load. This provides an analytical approach to pick the parameter values associated with EDCF to meet the QoS requirements of each priority. This is accomplished by modeling the performance impact of *all* the major QoS-specific features (i.e. CWMin, CWMax, AIFS, internal collision resolution) of the 802.11e EDCF mode.**

I. INTRODUCTION

The last few years have witnessed an explosive growth of 802.11 [1] wireless local area network (WLAN) deployment. As Wi-Fi hotspots mushroom, the upper layer applications running over it are no longer confined to best-effort data (e.g. email and web browsing). QoS-sensitive services, such as VoIP and video streaming, are also expected to be delivered via WLAN. However, bandwidth is a scarce resource in a wireless environment. Therefore, an efficient medium access control (MAC) protocol is indispensable for a WLAN to effectively manage the channel access and provide differentiated QoS to different applications.

Unfortunately, the current 802.11 MAC does not possess any effective service differentiation capability, because it treats all the upper layer traffic in the same fashion. Hence, a special working group, IEEE 802.11e [2], was established to enhance the 802.11 MAC to meet QoS requirements for a wide variety of applications. Although IEEE 802.11e [3] is yet to be finalized, the proposed basic QoS enhancements are deemed mature and much work has been done to study its performance. It has been shown, using simulation models [4] [5], that the new protocol has a significant improvement over the current 802.11 MAC, with regard to the capability of supporting QoS. [6] analyzes the impact of backoff window size on the throughput for each traffic class, but neglects the effect of different values of the distributed interframe spacing (DIFS). [7] and [8] modified the Markov chain in [9] to model resource sharing by different classes in 802.11e. However, various approximation techniques (e.g., Markov chain decomposition) have been used, either explicitly or implicitly in the previous work.

In this paper, we propose a three dimensional Markov chain model for the 802.11e protocol, which takes *all* the new QoS mechanisms into consideration. Based upon this Markov model, we compute the throughput that different traffic classes can sustain and the distribution of the service delay that each head of line (HOL) packet experiences, when the network is heavily loaded. This model is also an extension of the Markov chain proposed by Bianchi in [9] for the 802.11 distributed coordination function (DCF) mode. However, to the best of our knowledge, our analytical model is the first to capture all the major QoS-specific features for the EDCF mode as described in [3]. This is important, since these features interact with each other in a non-trivial way.

The rest of the paper is organized as follows. In section II, we briefly introduce the new QoS scheme defined in the 802.11e draft [3]. In section III, the proposed analytical model is elaborated and a simple example is used to illustrate the application of our model. The saturation throughput and service delay distribution are also computed in this section. The corresponding model validation and simulation results are presented in section IV. Section V ends the paper with conclusions and future research directions.

II. PROTOCOL DESCRIPTION

The 802.11e EDCF is an extension of the basic DCF mechanism of current 802.11. Unlike DCF, EDCF is not a separate coordination function, but a part of a single coordination function of 802.11e called the hybrid coordination function (HCF). The HCF combines both DCF and PCF from the current 802.11 specification with new QoS specific enhancements. It uses EDCF and a polling mechanism for contention-based and contention-free channel access, respectively. Since the polling mechanism of HCF is beyond the scope of this paper, it is not discussed hereafter.

In EDCF, each station can have multiple queues that buffer packets of different priorities. Each frame from the upper layers bears a priority value which is passed down to the MAC layer. Up to eight priorities are supported in a 802.11e station and they are mapped into four different access categories (*AC*) at the MAC layer [3]. A set of EDCF parameters, namely the arbitration interframe space *(AIFS[AC])*, minimum contention window size *(CWMin[AC])* and maximum contention window

[1] In the latest IEEE 802.11e draft, enhanced distributed channel access (EDCA) replaces EDCF. However, since the major QoS schemes remain the same in EDCA, we will still call it EDCF throughout this paper.

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size *(CWMax[AC])*, is associated with each access category to differentiate the channel access. $AIFS[AC]$ is the number of time slots a packet of a given AC has to wait after the end of a time interval equal to a short interframe spacing (SIFS) duration before it can start the backoff process or transmit. After i ($i \geq 0$) collisions, the *backoff counter* in 802.11e is selected uniformly from $[1,\ 2^i \times CWMin[AC]]$, until it reaches the *backoff stage i* such that $2^i \times CWMin[AC] = CWMax[AC]$. At that point, the packet will still be retransmitted, if a collision occurs, until the total number of retransmissions equals the maximum number of allowable retransmissions ($RetryLimit[AC]$) specified in [3], with the backoff counters always chosen from the range $[1,\ CWMax[AC]]$. Since multiple priorities exist within a single station, it is likely for them to collide with each other when their backoff counters decrement to zero simultaneously. This phenomenon is called an *internal collision* in 802.11e and is resolved by letting the highest priority involved in the collision win the contention. Of course, it is still possible for this winning priority to collide with packets from other station(s).

III. THROUGHPUT AND DELAY ANALYSIS

In our analysis, we assume that the 802.11e network under investigation is heavily loaded. This implies that there is always at least one packet awaiting transmission at each AC queue within a station. We also assume that all nodes have chosen the same EDCF parameters (i.e. $AIFS[AC]$, $CWMin[AC]$ and $CWMax[AC]$) and are thus identical. The WLAN operates in an ideal physical environment, meaning that frame errors, the hidden terminal effect or the capture effect will not be modeled in our Markov model.

For our purpose, the concept of "access category" is equivalent to the idea of "priority". Therefore, we will from now on use the term "priority" throughout our analysis. For the sake of simplicity, we will adopt the less cumbersome notation $W_{min}[c]$, $W_{max}[c]$ and $D[c]$, to represent $CWMin[AC]$, $CWMax[AC]$ and $AIFS[AC]$, respectively. Here, $0 \leq c \leq C-1$, where $c = 0$ corresponds to the highest priority. $m[c]$, defined as $log_2(\frac{W_{max}[c]}{W_{min}[c]})$, is the maximum backoff stage for priority c, for which the backoff window size can still double. We further introduce two auxiliary variables in Equation 1 to facilitate the mathematical derivation:

$$\begin{aligned} W_c^i &\triangleq 2^i \times W_{min}[c] \qquad && i \in [0, m[c]],\ c \in [0, C-1] \\ D_{j,i} &\triangleq D[j] - D[i] \qquad && i, j \in [0, C-1],\ j \geq i \end{aligned} \tag{1}$$

The following presentation of the analysis is divided into five parts. In section III-A, we define the three dimensional embedded Markov chain. An example of an 802.11e network with relatively small QoS parameters is discussed in section III-B to further demonstrate how the embedded Markov chain is constructed. Section III-C provides a set of equations that corresponds to the Markov chain with general parameters. In section III-D, we compute the saturation throughput for each priority, under the heavy load condition. The service delay distribution for the HOL packet of each priority will be discussed in section III-E.

A. Markov Chain Model

As depicted in Figure 1, the temporal evolution of the wireless channel under heavy load is cyclic. We study the activity on the wireless channel from the perspective of the highest priority. Every operation cycle starts with a busy period (e.g. either a successful transmission or a collision on the wireless medium by packets of any priority), followed by a $D[0]$ interval and then one or more backoff time slots. Once another busy period starts, the system enters the next operation cycle.

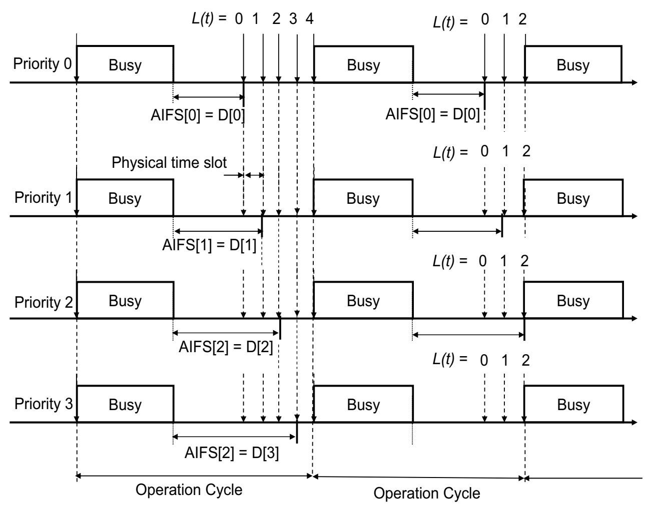

Fig. 1: Observation time instances and operation cycle.

Three state variables $[S^c(t), B^c(t), L(t)]$ ($c \in [0,\ C-1]$), the first two of which are the values of the backoff stage and backoff time counter, respectively, can represent the state of the packet at the head of the priority c queue at a station. The third state variable, denoted as $L(t)$, helps us locate the physical time slot (see Figure 1) in an operation cycle. In other words, $L(t) = k$ means that the observation time instance is k ($k \in [0,\ WMax]$) time slot(s) after the end of last $D[0]$ period. $WMax$, defined as $\min_{c \in [0,\ C-1]} \{D[c] - D[0] + W_{max}[c]\}$, is the largest number of backoff slots that any priority can continuously count down within an operation cycle, under the *heavy load condition*. This upper limit exists, because under heavy load, there will always be a transmission attempt before $WMax$. This also causes the *trimming effect* in the Markov chain, as we shall explain later. Also, note that $L(t)$ only has significance within one operation cycle and its value renews when each new cycle begins. The observation points that we use to construct the embedded Markov Chain are those at which state variables $[S^0(t), B^0(t), L(t)]$ change value. In Figure 1, the time instances when the state changes are illustrated by arrows. We will use $[c, i, j, k]$ and $p(c, i, j, k)$ to denote the state $[S^c(t) = i, B^c(t) = j, L(t) = k]$ and its corresponding steady state probability.

B. An Example

We use an 802.11e network with relatively small QoS parameters to facilitate an illustration on how the embedded Markov chain model is constructed. In the example WLAN, each station supports two priorities. The parameters of these two priorities are listed in Table I. The Markov chains models for the high and low priority queues are shown in Figures 2 and 3, respectively.

TABLE I: Parameters of the example system.

	High Priority (c = 0)	Low Priority (c = 1)
$D[c]$ (in physical time slots)	2	3
$W_{min}[c]$	2	3
$W_{max}[c]$	4	6

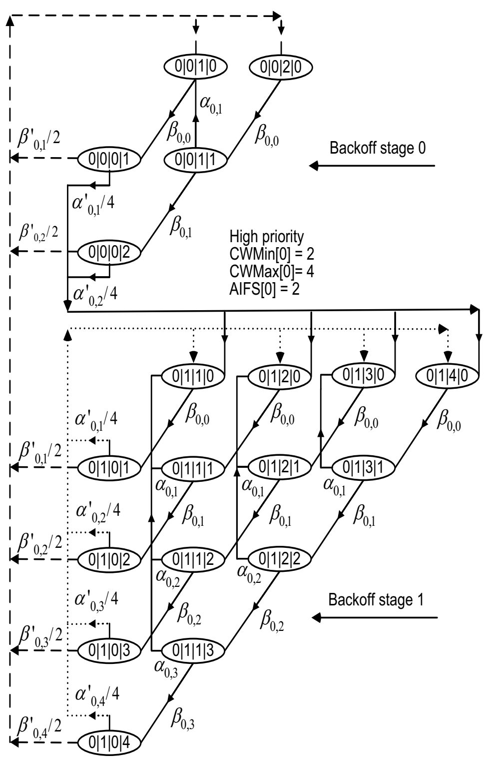

Fig. 2: Example Markov chain for a high priority queue.

In the state transition diagrams, the four numbers within each state $(c|i|j|k)$ correspond to the c, i, j and k in the state $[c, i, j, k]$ introduced in section III-A. The state transition probabilities $\alpha_{c,k}$, $\beta_{c,k}$, $\alpha^{'}_{c,k}$ and $\beta^{'}_{c,k}$ are defined in Equation 2.

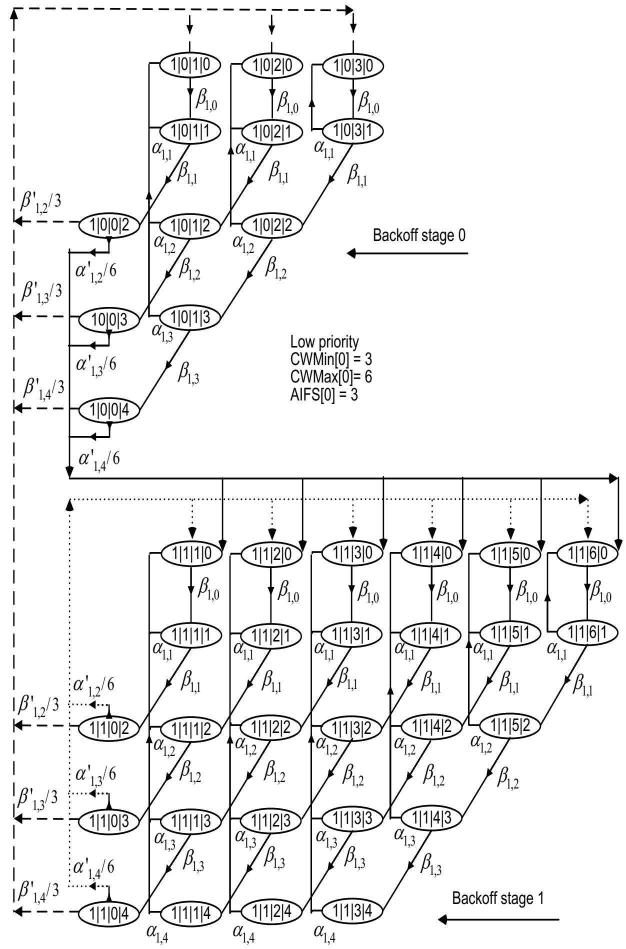

Fig. 3: Example Markov chain for a low priority queue.

$$\begin{cases} \beta_{c,k} = & P\{\text{A priority } c \text{ packet finds channel idle} \\ & \qquad \mid L(t) = k \text{ and } j > 0\} \\ \alpha_{c,k} = & P\{\text{A priority } c \text{ packet finds channel busy} \\ & \qquad \mid L(t) = k \text{ and } j > 0\} \\ \beta^{'}_{c,k} = & P\{\text{A priority } c \text{ packet transmits successfully} \\ & \qquad \mid L(t) = k \text{ and } j = 0\} \\ \alpha^{'}_{c,k} = & P\{\text{A priority } c \text{ packet has a collision} \\ & \qquad \mid L(t) = k \text{ and } j = 0\} \end{cases} \tag{2}$$

Under the heavy load condition, when the HOL packet of priority c is successfully transmitted or dropped, the next priority c packet becomes the HOL packet and selects an initial backoff counter value. This corresponds to the fact that the Markov chain is initially entered from state $[c, 0, j, 0]$ for each new packet. The transition from $[c, i, j, k]$ to $[c, i, j-1, k+1]$ represents the case where the channel is sensed idle and backoff counter gets decremented with probability $\beta_{c,k}$. If the channel becomes busy with probability $\alpha_{c,k}$, the current operation cycle terminates and the backoff process at the local station is frozen until the end of ongoing transmission(s). This event is modeled by the transition from $[c, i, j, k]$ to

$[c, i, j, 0]$. When backoff counter counts down to zero, a transmission is attempted. Then for $i \in [0, m[c]-1]$, the transition corresponding to a packet transmission starts from $[c, i, 0, k]$ and either ends at $[c, 0, j, 0]$ with probability $\frac{\beta'_{c,k}}{W_{min}[c]}$ for a successful transmission, or ends at $[c, i+1, j, 0]$ with probability $\frac{\alpha'_{c,k}}{W_c^{i+1}}$ for a collision. Both $m[0]$ and $m[1]$ in this example happen to be 1.

A special transition for the lower priority is from state $[1, i, j, 1]$ to $[1, i, j, 0]$. This corresponds to the scenario where low priority packets are still deferring in the $D[1]$ period, while high priority packets have already finished their $D[0]$ period and have started to decrement their backoff counters.

The backoff algorithm specified in 802.11e has set a limit on the maximum number of retransmissions a packet can experience before it is dropped. Therefore, the Markov chain model should have as many stages as a packet can go through. However, this will increase the number of states in our Markov model considerably. Therefore, to simplify the throughput computation, we assume that once a packet reaches its maximum window size, it stays at that stage, until it transmits successfully. This simplification implies that we do not model packet drops due to excessive retransmissions and the state variable i is limited to the range of $[1,\ m[c]]$. However, for the delay analysis, we will take the packet drops into consideration.

One interesting phenomenon to note is that the example Markov chain for backoff stage 1 for the low priority is truncated at the bottom (Figure 3), due to the *trimming effect* that we discussed in section III-A. As shown in Figure 3, the transmission of the HOL high priority packet makes it impossible for the low priority to consecutively decrement the backoff counter for more than $W_{max}[0]$ times.

C. The Markov Chain for the General Case

Suppose there are N stations in a general 802.11e network. Assume that $\forall i, j \in [0,\ C-1]$ and $j > i$, $W_{max}[i] > D_{j,i}$. In this case, contention for channel access exists between any two priorities in the 802.11e network. For all $c \in [0,\ C-1]$, and $i \in [0,\ m[c]]$, the Markov chain for priority c can be represented by Equation 3. The variables $q_{c,i}$ in the equation will be defined later in Equation 4.

$$\begin{cases} p(c,i,j,0) = q_{c,i} + \sum_{v=1}^{min\{W_c^i + D_{c,0} - j, WMax\}} \alpha_{c,v} p(c,i,j,v) \\ \qquad \text{when } j \in [1,\ W_c^i]; \\ p(c,i,j,k) = \beta_{c,k-1} p(c,i,j,k-1) \\ \qquad \text{when } j \in [1,\ W_c^i],\ k \in [1,\ D_{c,0}]; \\ p(c,i,j,k) = \beta_{c,k-1} p(c,i,j+1,k-1) \\ \qquad \text{when } j \in [0,\ W_c^i - 1], \\ \qquad\qquad k + j \le W_c^i + D_{c,0}, \\ \qquad\qquad k \in [D_{c,0}+1, \\ \qquad\qquad\qquad min\{W_c^i + D_{c,0}, WMax\}]; \end{cases} \tag{3}$$

The first case in Equation 3 describes the transitions into the state $[c, i, j, 0]$, which is the starting point of an operation cycle for all priorities. The second case describes the situation where the priority c queue is still in its $AIFS$ period, while higher priority queues have started counting down. The third range represents the scenario when priority c can decrement its counter.

The auxiliary variables $q_{c,i}$ in Equation 3 are used to model the transitions leaving those states, when a transmission is attempted at priority c. Equation 4 relates $q_{c,i}$ with state probabilities $p(c,i,j,k)$ and transition probabilities $\alpha'_{c,k}$ and $\beta'_{c,k}$ as follows:

$$\begin{cases} q_{c,0} = \sum_{v=0}^{m[c]} \sum_{k=D_{c,0}+1}^{min\{WMax,\ W_c^v + D_{c,0}\}} \frac{\beta'_{c,k} p(c,v,0,k)}{W_{min}[c]} \\ q_{c,i} = \sum_{k=D_{c,0}+1}^{min\{WMax,\ W_c^{i-1} + D_{c,0}\}} \frac{\alpha'_{c,k} p(c,i-1,0,k)}{W_c^i} \\ \qquad\qquad 1 \le i \le m[c]-1; \\ q_{c,m[c]} = \sum_{k=D_{c,0}+1}^{min\{WMax,\ \frac{W_{max}[c]}{2} + D_{c,0}\}} \frac{\alpha'_{c,k} p(c,m[c]-1,0,k)}{W_{max}[c]} \\ \qquad + \sum_{k=D_{c,0}+1}^{min\{WMax,\ W_{max}[c] + D_{c,0}\}} \frac{\alpha'_{c,k} p(c,m[c],0,k)}{W_{max}[c]} \end{cases} \tag{4}$$

The first case in Equation 4 (i.e., $i = 0$) corresponds to the $0th$ backoff stage. The second case, where $1 \le i \le m[c]-1$, represents any intermediate backoff stages. For the last stage (i.e., $i = m[c]$), a collision always leads to a loopback to stage $m[c]$, since we assume that an unsuccessful station will keep retransmitting with backoff window set to $W_{max}[c]$.

$\alpha_{c,k}$ and $\beta_{c,k}$ are the probabilities that the wireless channel is observed to be busy/idle at the kth slot during an operation cycle by a priority c HOL packet, whose backoff counter value j has not reached zero yet. Similarly, $\alpha'_{c,k}$ and $\beta'_{c,k}$ represent the probability that the channel is found to be busy/idle which leads to a collision or success, respectively, during the kth slot in an operation cycle by a priority c packet, whose backoff counter value j reaches zero. To relate $\alpha_{c,k}$, $\beta_{c,k}$, $\alpha'_{c,k}$ and $\beta'_{c,k}$ with the steady state probability $p(c,i,j,k)$, we introduce another set of variables $\tau_{c,k}$, where:

$$\tau_{c,k} = P\{\text{A packet of priority } c \text{ transmits} \mid L(t) = k\}. \tag{5}$$

We further make an assumption that $\tau_{c,k}$ only depends on the relative interval in which a state transition occurs and thus ignore its dependence on the exact backoff stage i. Define $H[c]$ as the largest integer for each priority that satisfies $W_c^{H[c]} + D_{c,0} \le WMax$. Also, let $W_c^{-1} = 0$. Then, $\tau_{c,k}$ can be written as Equation 6.

The first case in Equation 6 corresponds to the scenario when the priority c queue is still in its $AIFS$ period and thus its conditional transmission probability is always 0. The second case represents the interval during which priority c queue has completed its $AIFS$ period but hasn't counted down for more than $min\{WMax, W_{min}[c] + D_{c,0}\}$ time slots.

The last case accounts for the trimming effect, if applicable. Though we can handle it, for simplicity, we do not consider the case where $W_{min}[c] + D_{c,0} \geq WMax$, which represents an unlikely choice of the QoS parameters.

$$\tau_{c,k} = \begin{cases} 0 \quad k \in [0,\ D_{c,0}]; \\ \frac{\sum_{i=v}^{m[c]} p(c,i,0,k)}{\sum_{i=v}^{m[c]} [\sum_{j=0}^{W_c^i+D_{c,0}-k} p(c,i,j,k)]} \\ \quad v \in [0,\ H[c]],\ H[c] \geq 0, \\ \quad k \in [W_c^{v-1} + D_{c,0} + 1, \\ \qquad min\{WMax, W_c^v + D_{c,0}\}]; \\ \frac{\sum_{i=H[c]+1}^{m[c]} p(c,i,0,k)}{\sum_{i=H[c]+1}^{m[c]} [\sum_{j=0}^{W_c^i+D_{c,0}-k} p(c,i,j,k)]}, \\ \quad k \in [W_c^{H[c]} + D_{c,0} + 1, WMax],\ H[c] \geq 0; \end{cases} \tag{6}$$

For any $k \in [0,\ WMax]$, we express $\alpha_{c,k}$, $\beta_{c,k}$, $\alpha'_{c,k}$, $\alpha'_{c,k}$ and $\beta'_{c,k}$ in terms of $\tau_{c,k}$ in Equation 7.

$$\begin{cases} \beta_{c,k} = (1-\tau_{c,k})^{N-1} \times \\ \qquad \prod_{u=0}^{c-1} (1-\tau_{u,k})^N \prod_{u=c+1}^{C-1} (1-\tau_{u,k})^N \\ \beta'_{c,k} = \prod_{u=0}^{c-1} (1-\tau_{u,k})^N \prod_{u=c}^{C-1} (1-\tau_{u,k})^{N-1} \\ \alpha_{c,k} = (1-\beta_{c,k}) \\ \alpha'_{c,k} = (1-\beta'_{c,k}) \end{cases} \tag{7}$$

The impact of *internal collision resolution* is reflected in the expressions for $\alpha_{c,k}$, $\beta_{c,k}$, $\alpha'_{c,k}$ and $\beta'_{c,k}$. Note that all the transition probabilities have been expressed as functions of the steady state probabilities. Equation 3 then can be solved as follows. Combine equations for each Markov chain together with the C normalization conditions (i.e., $\sum_{i,j,k} p(c,i,j,k) = 1$, for all priorities). After removing the redundant equation for each Markov chain, Equations 3, 4, 6 and 7 form a nonlinear system, which can be solved numerically by using commercial off-the-shelf software (e.g., the $FSOLVE$ function in the Optimization Toolbox of $MATLAB$).

D. Throughput

From the perspective of priority c, four events can take place on the wireless channel at any randomly chosen time slot. The channel may be idle for a backoff, or busy either due to a successful priority c transmission or one collision. It is also possible that priority c in all the stations are *frozen*, in which case no priority c in any station is transmitting, or decrementing the backoff counter, because at least one transmission of another priority is ongoing on the wireless channel.

We use Pb_c, Ps_c, Pc_c and Pf_c to denote the probabilities that priority c is in backoff, successful transmission, collision and freeze period, respectively. Tb, Ts_c, Tc_c and Tf_c are the corresponding average length of a backoff time slot, successful transmission, collision and freeze period. Define S_c as the fraction of time the network transmits the packet payload bits of priority c successfully. S_c then can be expressed as:

$$\begin{aligned} S_c &= \frac{E\{\text{Payload information transmitted in a slot time}\}}{E\{\text{Average length of a slot time}\}} \\ &= \frac{Ps_c \cdot Payload}{Pb_c \cdot Tb + Ps_c \cdot Ts_c + Pc_c \cdot Tc_c + Pf_c \cdot Tf_c} \\ &\approx \frac{Ps_c \cdot Payload}{Pb_c \cdot Tb + (Ps_c + Pc_c + Pf_c) \cdot Ts_c} \\ &= \frac{Ps_c \cdot Payload}{Pb_c \cdot Tb + (1 - Pb_c) \cdot Ts_c} \end{aligned} \tag{8}$$

The probability of having a success and a backoff can be written as:

$$\begin{cases} Ps_c &= \sum_{k_0=1}^{WMax-1} [P\{k=k_0\} \\ &\qquad \times P\{\text{A success for priority } c \mid L(t)=k_0\}] \\ &= \sum_{k_0=1}^{WMax-1} [P\{k=k_0\} \cdot N\tau_{c,k_0}(1-\tau_{c,k_0})^{N-1} \\ &\qquad \times \prod_{u=0}^{c-1} (1-\tau_{u,k_0})^N \times \prod_{u=c+1}^{C-1} (1-\tau_{u,k_0})^{N-1}] \\ Pb_c &= \sum_{k_0=0}^{WMax-1} [P\{k=k_0\} \\ &\qquad \times P\{\text{A backoff slot for priority } c \mid L(t)=k_0\}] \\ &= \sum_{k_0=0}^{WMax-1} [P\{k=k_0\} \times \prod_{u=0}^{C-1} (1-\tau_{u,k_0})^N] \end{cases} \tag{9}$$

In Equation 9, $P\{k=k_0\}$ is the probability that a priority is in the state of $[c,i,j,k_0]$. Since $P\{k=k_0\}$ only depends on k_0 and is independent of the priority c, we derive $P\{k=k_0\}$ for the high priority $c=0$.

$$P\{k=k_0\} = \begin{cases} \sum_{i=0}^{m[c]} [\sum_{j=1}^{W_c^i} p(c,i,j,k_0)] \\ \qquad k \in [0,\ D_{c,0}]; \\ \sum_{i=v}^{m[c]} [\sum_{j=0}^{W_c^i+D_{c,0}-k} p(c,i,j,k_0)] \\ \qquad v \in [0,\ H[c]],\ H[c] \geq 0; \\ \qquad k \in [W_c^{v-1} + D_{c,0} + 1, \\ \qquad min\{WMax,\ W_c^v + D_{c,0}]\}; \\ \sum_{i=H[c]+1}^{m[c]} [\sum_{j=0}^{W_c^i+D_{c,0}-k} p(c,i,j,k_0)] \\ \qquad H[c] \geq 0; \\ \qquad k \in [W_c^{H[c]} + D_{c,0} + 1, WMax]; \end{cases} \tag{10}$$

Finally, by substituting Equation 9 and 10 into Equation 8, we can obtain the throughput for each priority.

E. Service Delay Distribution

The service delay of a successfully delivered HOL packet is the time duration from its first backoff till it leaves the system. While studying service delay, we incorporated the possibility of a packet drop into our Markov model. As explained in section III-B, our Markov model defined in section III-A can easily accommodate packet drops, by duplicating the last stage in our chain for $RetryLimit[c] - m[c]$ times. A similar modification was made in [11].

Once we solve the modified Markov model, the service delay distribution can be obtained as follows. For an HOL packet of priority c, start from state $[c,0,j,0]$ with backoff counter values $j \in [1, W_{min}[c]]$ picked with equal probability. This corresponds to the initial state probability vector $[\underbrace{\frac{1}{CWMin[c]}, ..., \frac{1}{CWMin[c]}}_{CWMin[c]}, 0, 0, ...0]$. We keep multiplying this vector with the transition matrix of the Markov chain, until the resulting state probability vector converges. By counting the number of iterations and the corresponding probability that the packet is successfully transmitted, we can derive the delay distribution.

IV. MODEL VALIDATION AND SIMULATION

To validate the analytical model, we have developed an event-driven custom simulator for the 802.11e EDCF using the C programming language. The basic parameters used in both simulator and analysis are shown in Table II. The QoS parameters, i.e., $CWMin[AC]$, $CWMax[AC]$ and $AIFS[AC]$, used in the following discussion are similar to the values specified by IEEE 802.11e Working Group for voice and video traffic [12].

TABLE II: Basic parameters for DSSS system.

Packet payload size	8184 bits at 11Mbps
MAC header	272 bits at 11Mbps
PHY header	192 bits at 1Mbps
ACK	112 bits + PHY header
Propagation delay	1μs
Slot time	20μs
SIFS	10μs

In Figure 4, each station contains two priorities, which are only differentiated by the internal collision resolution algorithm discussed before. As expected, internal collision resolution by itself can provide some differentiation for channel access between different priorities.

The two priorities in each station are further differentiated by $AIFS$ and $CWMin/CWMax$ in Figure 5 and Figure 6, respectively. It can be seen that $AIFS$ may have a more marked effect on service differentiation than $CWMin/CWMax$ alone.

When we enable all QoS mechanisms in 802.11e EDCF, the resulting throughput is shown in Figure 7. Comparing Figure 7 with Figure 5, we find that the QoS differentiation effect of $AIFS$ is almost identical to the aggregate impact of $AIFS$ plus $CWMin/CWMax$.

All the figures reveal that as the number of stations in the network grows, the throughput for each priority as well as the total throughput drop fairly fast, especially when the QoS-specific parameters are small. Under our heavy load assumption, the throughput for low priority often decreases down to almost zero before the number of stations gets to 10. For this region, the high priority traffic dominates.

Figures 8 and 9 show the cumulative delay distribution for high and low priority packets, respectively, for the case of a 3-node network. In Figure 8, relative to the backoff time, the delay caused by an unsuccessful transmission or being frozen due to a transmission dominates. Therefore, the delay for high priority are centered around several discrete points corresponding to transmission events. In Figure 9, it can be seen that the service delay of low priority packet is substantially higher than that of high priority. Note that the analysis and simulation points are almost on the same in all cases.

Note that this analysis gives the *worst case* maximum throughput and delay distribution for low priority traffic class. Under light or moderate high priority traffic load, we expect the throughput(delay) of low priority traffic to be above(below) these values.

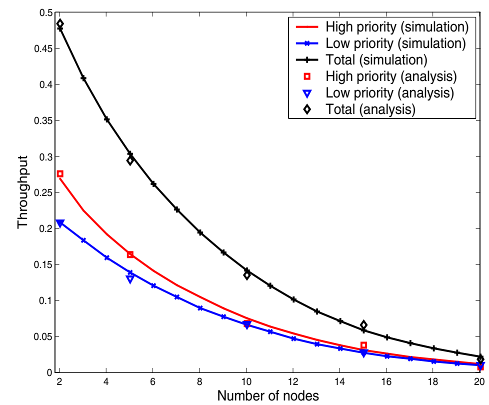

Fig. 4: Two priorities differentiated only by internal collision resolution: $CWMin/Max[0] = 8/16$, $CWMin/Max[1] = 8/16$, $AIFS[0] = 2$, $AIFS[1] = 2$

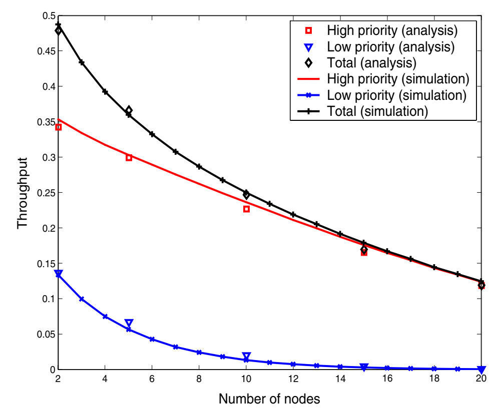

Fig. 5: Two priorities with different AIFS values: $CWMin/Max[0] = 8/16$, $CWMin/Max[1] = 8/16$, $AIFS[0] = 2$, $AIFS[1] = 3$

V. CONCLUSIONS

In this paper, we develop a multi-dimensional Markov chain model to analyze the saturation throughput and service delay distribution of the 802.11e protocol draft. The analytical results show that different values of QoS-specific parameters can differentiate the channel access for packets of different priorities. The simulation results validate our analytical model.

As for future research, we will study the impact of each QoS parameter (e.g. $AIFS[AC]$, $CWMin[AC]$ and

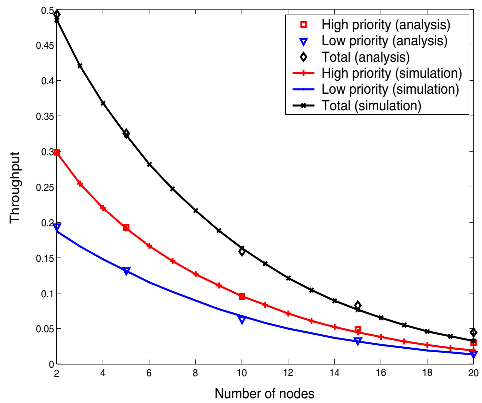

Fig. 6: Two priorities with different CWMin and CWMax. $AIFS[0] = 2$, $AIFS[1] = 2$, $CWMin/Max[0] = 8/16$, $CWMin/Max[1] = 10/20$

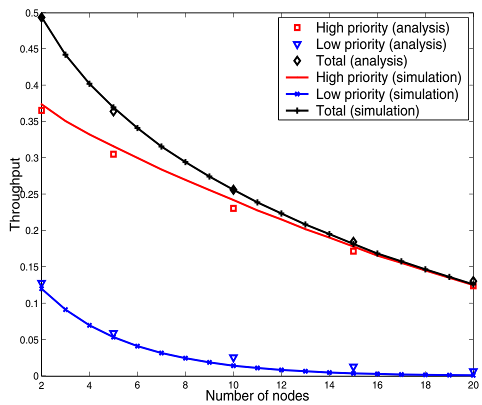

Fig. 7: Two priorities with different CWMin, CWMax and AIFS: $AIFS[0] = 2$, $AIFS[1] = 3$, $CWMin/Max[0] = 8/16$, $CWMin/Max[1] = 10/20$

$CWMax[AC]$) on service differentiation more thoroughly. Furthermore, we will design an algorithm to determine these QoS parameters (i.e. $AIFS[AC]$, $CWMin[AC]$ and $CWMax[AC]$) so as to maximize the network throughput while meeting requirements for bandwidth partitioning and the QoS requirements for different priorities.

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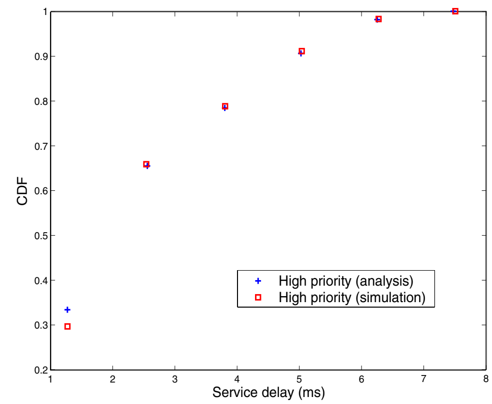

Fig. 8: Cumulative distribution for high priority's service delay: $AIFS[0] = 2$, $AIFS[1] = 3$, $CWMin/Max[0] = 2/4$, $CWMin/Max[1] = 3/6$

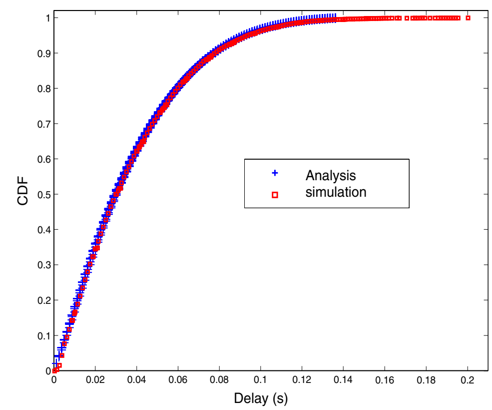

Fig. 9: Cumulative distribution for low priority's service delay: $AIFS[0] = 2$, $AIFS[1] = 3$, $CWMin/Max[0] = 2/4$, $CWMin/Max[1] = 3/6$

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