An Analytical Model for the IEEE 802.11e EDCF

Extended Abstract

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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 multidimensional Markov 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. Since the QoS mechanisms and their associated parameters in IEEE 802.11e interact with each other in a complex way, it is important to model the aggregate effect of all the mechanisms. The approach we present does so and therefore provides an analytical approach to pick the parameter values associated with EDCF to meet the QoS requirements of each priority.

I. INTRODUCTION

The IEEE 802.11 protocol for wireless local area network (WLAN) has enjoyed tremendous commercial success since it was first introduced in 1999. As the raw data rate at the physical (PHY) layer of 802.11a/g is now up to 54Mbps, applications such as voice over IP over WLAN (VoIPoWLAN) and video streaming become feasible. However, the medium access control (MAC) protocol in the original 802.11 standard was designed with best-effort applications (e.g., email, web browsing) in mind and thus cannot meet the basic quality of service (QoS) requirements for these emerging applications. To address this issue, the IEEE 802.11e working group [2] was established to strengthen QoS support at the MAC layer.

Although the IEEE 802.11e has not been finally ratified, it has already received much attention from the research community. [3][4] explains the new features introduced in 802.11e draft in detail. Among others, [5][6][7][8] have simulated the new protocol and shown a significant improvement over the current 802.11 MAC, with regard to the capability of supporting QoS. [9] presents an analytic model for *p-DCF*, which uses a different backoff algorithm (i.e. *p-persistent*) from the 802.11e draft. [10] analyzes the impact of backoff window size on the throughput for each traffic class, but neglects the effect of different values of DIFS. There has been an effort to study the aggregate effect of all new QoS features. For example, [11] [12] [13] modify a two dimensional Markov chain that was initially proposed by Bianchi in [14] for IEEE 802.11 DCF to model the resource sharing by different classes in 802.11e. However, various approximations (e.g. Markov chain decomposition) have been made either explicitly or implicitly.

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 Bianchi's Markov chain. The major contribution of our analytic model is that it is able to capture all the major QoS-specific features for the EDCF mode by incorporating the interaction between traffic classes.

The rest of the extended abstract is organized as follows. In section II, we summarize the new QoS scheme defined in the 802.11e draft [15]. In section III, the proposed analytical model is explained. Due to the limit on space, the approach to solving the Markov chain and computing the throughput and the service delay distribution is only outlined here. The interested reader can refer to [16] for more details.

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[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.

Sample model validation and simulation are briefly discussed in section IV. Section V ends the paper with conclusions and future research directions.

II. PROTOCOL DESCRIPTION

As an extension of the basic distributed coordination function (DCF) mechanism defined in the current 802.11 standard, the 802.11e enhanced distributed coordination function (EDCF) enhances the DCF function and incorporates it into a single coordination function called the hybrid coordination function (HCF). 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 an 802.11e station and they are mapped into four different access categories (*AC*) at the MAC layer.

A set of EDCF parameters, namely the arbitration interframe space *(AIFS[AC])*, minimum contention window size *(CWMin[AC])* and maximum contention window 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 [15], 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 packet involved in the collision win the contention. Of course, it is still possible for this winning priority packet to collide with packets from other station(s). Interested readers can refer to [5] [6] [7] for a more thorough explanation on how the EDCF mode operates.

The 802.11e draft has also defined a transmission opportunity ($TXOP$), during which a particular station has the right to transmit. The limit of TXOP (i.e. $TXOPLimit[AC]$) is another QoS specific parameter for each AC. Multiple frames from the same AC can be transmitted continuously during a single EDCF TXOP, which is referred to as a contention-free burst (CFB) in 802.11e. Since this feature is optional, we will not embed it into our model. No packet fragmentation will be considered either in our analysis.

III. MARKOV MODEL

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.

As depicted in Figure 1, the temporal evolution of wireless channel under heavy load can be considered as cyclic. Assume a station has C priorities. For priority c, "$c = 0$" corresponds to the highest priority, "$c = 1$" to the next highest priority, and so on. We study the activity on the wireless channel from the perspective of the highest priority. $AIFS[0]$ corresponds to the smallest $AIFS$ value among all priorities. 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 an $AIFS[0]$ interval and then one or multiple backoff time slots. Once another busy period starts, the system enters the next operation cycle.

The behavior of a priority at a particular station can be characterized by three state variables $[S^c(t), B^c(t), L(t)]$ $(c \in [0,\ C-1])$, the first two of which represent the values of the backoff stages and backoff time counter, respectively, for the packet at the head of the priority c queue. The third state variable, $L(t)$, helps

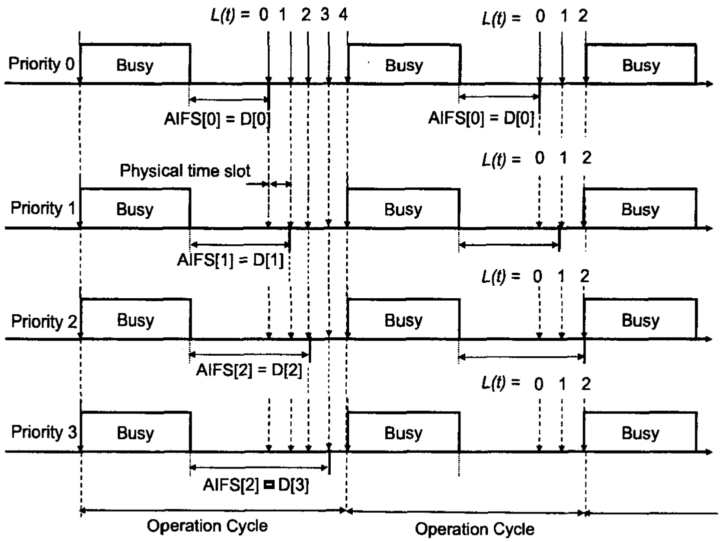

Fig. 1: Observation time instances and operation cycle.

us locate the physical time slot (relative to the end of the last $AIFS[0]$ period) in an operation cycle. In other words, $L(t) = k$ means that the observation time instance is k ($k \in [0,\ WMax]$) physical time slot(s) away from the end of last $AIFS[0]$ period. $WMax$, defined as $\min_{c\in[0,\ C-1]}\{AIFS[c] - AIFS[0] + W_{max}[c]\}$, 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 $WMax$. Note that $L(t)$ only has significance within one operation cycle and its value renews when a 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. We will use $p(c, i, j, k)$ to denote the steady state probability for the state $[S^c(t) = i, B^c(t) = j, L(t) = k]$ of priority c. Since each priority has one Markov chain, we have a total of C Markov chains to model a IEEE 802.11e EDCF network with C priorities.

Within the Markov chain for each priority, all the transition probabilities can be expressed as functions of the steady state probabilities $p(c, i, j, k)$. We then relate these probabilities to the probability of successful transmission and collision, using the assumption that the probability of success or collision does not depend on the backoff stage each packet is in. Note that this is a generalization of the assumption used in [14]. Combine all the equations for each Markov chain with C normalization conditions, we eventually can obtain a set of independent nonlinear equations. This system can be solved numerically by using off-the-shelf software (e.g. the $FSOLVE$ function in the Optimization Toolbox of $MATLAB$). Based upon the Markov chains, throughput and the service delay distribution for each class of traffic can be determined by using standard techniques.

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 I. The QoS parameters, i.e., $CWMin[AC]$, $CWMax[AC]$ and $AIFS[AC]$, used in our study are similar to the values specified by IEEE 802.11e Working Group for voice and video traffic [17].

When we enable all QoS mechanisms in 802.11e EDCF, the resulting throughput and service delay

TABLE I: 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

distribution obtained by our analytic model agree with the the simulation results. This validates the assumptions underlying our analysis.

Note that the results we obtain give the *worst case* maximum throughput for the low priority traffic class. When traffic load for high priority is light or moderate, we expect the throughput of low priority traffic to exceed these values.

V. CONCLUSIONS

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 $CWMax[AC]$) on service differentiation more thoroughly. Furthermore, we will design an algorithm to determine these QoS parameters so as to meet the throughput, delay and delay jitter requirements of different priority traffic sources.

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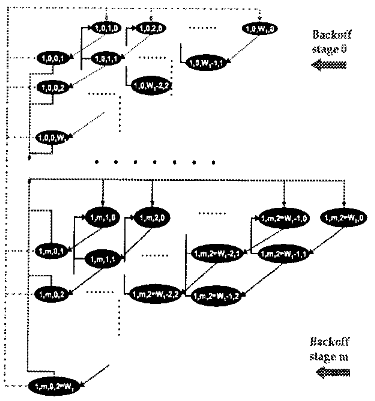
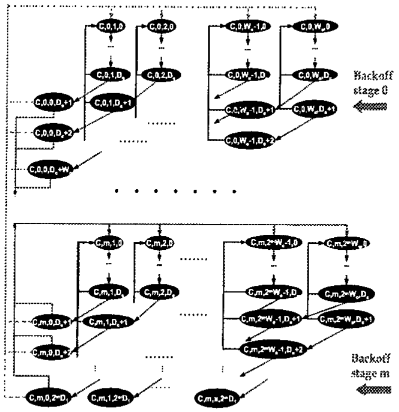
Markov Model: High Priority



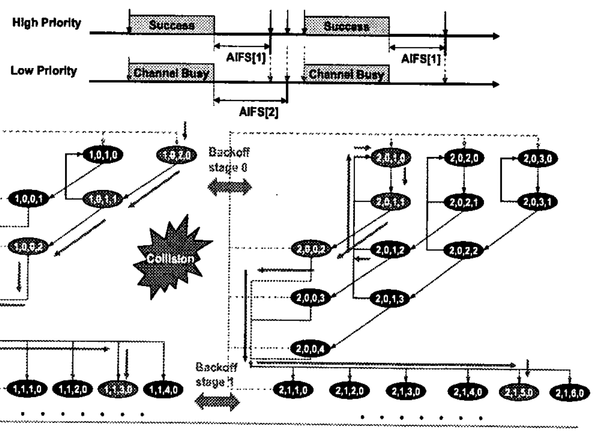
- An embedded Markov chain model
- EDCF mode
- Heavy traffic
- i, j, k
  {S[c], B[c], L[c]}
  - current backoff stage
  - backoff counter value
  - number of physical time slot(s) away from the end of last AIFS[0] period.

Markov Model: Low Priority



- Does not model the maximum number of retransmissions.
- Does not model the packet drop due to excessive retransmissions.
- The trimming effect on the Markov chain for lower priority queue: No queue can count down consecutively for more than $\min\{W_{max}[AC]\}$.

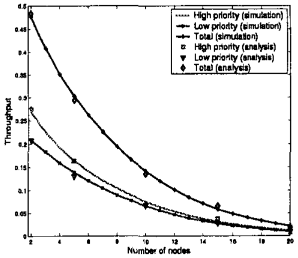
Markov Model: Illustration



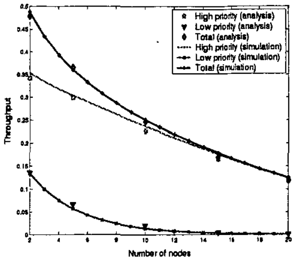
Saturation Throughput

- **Saturation throughput:** The fraction of time the network transmits the packet payload bits of priority c successfully.

CWMin[1] = 8, CWMax[1] = 16, AIFS[1] = 2
CWMin[2] = 8, CWMax[2] = 16, AIFS[1] = 2
Effect of internal collision resolution



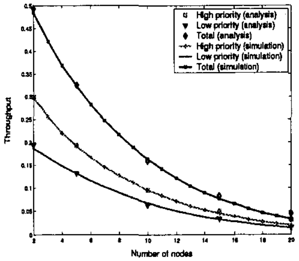
CWMin[1] = 8, CWMax[1] = 16, AIFS[1] = 2
CWMin[2] = 8, CWMax[2] = 16, AIFS[1] = 3



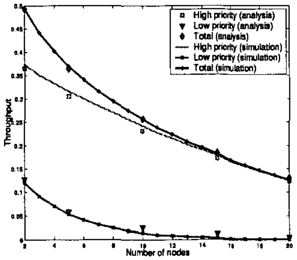
Saturation Throughput

- The QoS impact of AIFS[AC] is more obvious than that of CWMin[AC]/CWMax[AC]
- This analysis gives the worse case maximum throughput for low priority traffic class.

CWMin[1] = 8, CWMax[1] = 16, AIFS[1] = 2
CWMin[2] = 10, CWMax[2] = 20, AIFS[1] = 2



CWMin[1] = 8, CWMax[1] = 16, AIFS[1] = 2
CWMin[2] = 10, CWMax[2] = 20, AIFS[1] = 3

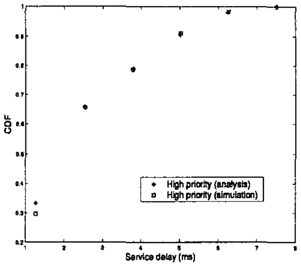


Service Delay Distribution

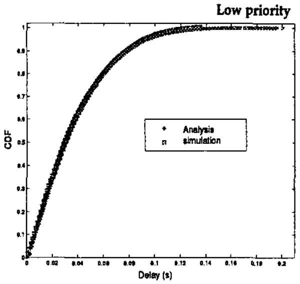
- ***Service delay:*** *The time duration between the time that the HOL starts to* contend for the wireless channel and the time that it is successfully delivered.

CWMin[1] = 2, CWMax[1] = 4, AIFS[1] = 2
CWMin[2] = 3, CWMax[2] = 6, AIFS[1] = 3

High priority



Low priority



Discussion and Future Work

Discussion

- The Markov chain is able to model the QoS effect of CWMin[AC], CWMax[AC], AIFS[AC], internal collision resolution, persistence factor.
- It is easy to incorporate a channel error model into this Markov chain.
- The current model assumes that the network is heavily loaded, therefore it is the worst case maximum throughput/delay for low priority traffic class
- Homogeneous traffic sources only

Future work

- Design an algorithm to dynamically determine the QoS parameters so as to maximize the network throughput as well as meet requirements for bandwidth partitioning among different priorities.
- Evaluate the capability of EDCF to support upper layer QoS-sensitive applications.