Throughput Modeling of Differentiation Schemes for IEEE 802.11e MAC Protocol

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***Abstract*—Most recent analyses on IEEE802.11e quality of service (QoS)-aware enhanced distributed coordination function (EDCA) require a large degree of complexity, making it difficult to apply them to a wide range of parameter settings for the evaluation of service differentiation mechanisms supported in EDCA, including the Contention Window (CW) and Arbitration Inter-Frame Space (AIFS) mechanisms. In this paper, we propose an improved analytical model to analyze the throughput of EDCA with AIFS and CW differentiation schemes. The model is simplified by decomposing the problem into two easily solved Markov chains that can jointly be solved by numerical method. We present simulation and analytical results over a broad range of system parameters to demonstrate the accuracy of the proposed model. The model is simple to implement and can be applied to general configuration circumstances for the evaluation of EDCA. The results are valuable to facilitate proper design of parameters in 802.11e enhanced distributed channel access for the QoS support required by specific applications.**

Keywords-Wireless LAN, 802.11e, protocols, performance evaluation

I. INTRODUCTION

To address the quality of service (QoS) requirements of multimedia traffic over wireless local area networks (WLANs), which have been widely deployed as integral parts of the multi-service global communication network, the IEEE 802.11 Task Group E recently published the IEEE 802.11e standard [1] that specifies QoS enhancements to the current IEEE 802.11 medium access control (MAC). The existing IEEE 802.11 Distributed Coordination Function (DCF) is extended by IEEE 802.11e through Enhanced Distributed Channel Access (EDCA), which incorporates a number of mechanisms to provide differentiated QoS by giving different access priority levels to different access categories (ACs). These include the contention window (CW) differentiation mechanism, the arbitration interframe space (AIFS) differentiation mechanism and transmit opportunity (TXOP) limits. In this paper, we focus on modeling the CW and AIFS-based priority schemes.

In contrast to DCF in IEEE 802.11[1], backoff counters in EDCA in IEEE 802.11e [2] are selected from the interval [0, $CW[AC]$], where $CW[AC]$ is a function of AC; specifically $CW[AC] \in [CWmin[AC], CWmax[AC]]$. With EDCF, after each successful transmission, the corresponding $CW[AC]$ is set to $CWmin[AC]$. A source station determines that its transmission has failed if a time-out occurs and an acknowledgment (ACK) has not been received from the destination station; in this case the station calculates CW as $CW[AC] = min\{CWmax, CW[AC]\times 2\}$ as defined in [1].

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In EDCA, AIFS periods are used in place of DCF Inter-frame Space (DIFS) in DCF, where AIFS ≥ DIFS. Each AC is assigned a different AIFS[AC] value to differentiate the QoS received by different ACs. By using a smaller AIFS[AC] value for a higher priority AC, stations in a higher priority AC would encounter fewer access failures and their backoff counters would count down faster than stations in a lower priority AC. AIFS[AC] is determined by AIFS[AC] = SIFS + $AIFSN_{AC} \times$ Tslot. AIFSN is a system parameter set for each AC, with a minimum value of 1for access point (AP) stations and 2 for non-AP stations. SIFS is the short interframe space.

II. RELATED WORK

The introduction of the IEEE 802.11e standard requires for the analytical models to evaluate its performance. Since IEEE 802.11e EDCA is an extension of IEEE 802.11 DCF, most of the recently introduced analytical models for EDCA are built upon the existing DCF models, in which a simple and fairly accurate model proposed by Bianchi [3] that is used to calculate saturation throughput in DCF is widely used. Since Bianchi's model addresses backoff-timing process, it is straightforward to extend his model to evaluate backoff-based CW differentiation, such as Xiao's model for CW priority scheme in [4]. However, when applying [3] to evaluate AIFS differentiation mechanism in EDCA, the results were not satisfactory. Current models used to analyze AIFS differentiation among ACs can be classified into three categories. Models in the first category are developed to investigate AIFS performance by extending Bianchi's two dimensional Markov chain to tri-dimensional or even higher dimensionality. For example, [5][6][7] extend Bianchi's original bi-dimensional Markov chain to tri-dimensional, which significantly increases the model complexity. Based on tri-dimensional methods, virtual collision handling (VCH) is included in the model in [8] to simplify the model to some extent. VCH under unsaturated conditions is considered in [9].

However, VCH and unsaturated situation are not the focus of this paper. The second category employs methods that are not based on Markov chain to account for different AIFS priorities while keeping the bi-dimensional Bianchi backoff process unchanged. However, it is generally difficult for non-Markov chain based approaches to fully capture the details of EDCA including the effect of AIFS without a high complexity unless significant simplification is made. Based on Bianchi's model and two other existing models used for DCF analysis, Hui *et al.* [10] construct a p-persistent carrier-sensed multiple access with collision avoidance (CSMA/CA) model for the analysis of EDCA performance, but the model has a high complexity due to the complicated modifications applied for AIFS analysis without using Markov chain. Compare to [10], methods in [11][12][15] made rather rough approximation for AIFS differentiation with simplified assumptions to avoid complexity by using non-Markov chain approach. Yan and Pan in [13] try to consider correctly the AIFS and backoff cooperation process in EDCA, but unfortunately, their analysis includes some strong assumptions and also some approximations. Firstly, they consider only the case in which the channel is busy due to a transmission by an AC in the same station and neglect the presence of other stations in the network. Secondly, they did not differentiate between channel busy probability and collision probability. An analytical model to develop a mechanism for configuring the parameters of EDCA is proposed in [14]. The restriction imposed on the sources is that they are ergodic; otherwise, the analysis could not rely on the stations' average sending rate. Considering a well designed Markov chain has the advantages of capturing EDCA complexity easily, a third category of methods [16][17] construct separate Markov chains to divide the contention period into different contention zones to account for AIFS differentiation. This method does not expand the dimension of the Markov chain in [5][6][7], nor does it involve complicated changes in [10] or significant simplification in [11][12][15][13][14], in that the original contention window-based backoff process is kept unchanged to solve slot transmission probability. The Discrete-Time Markov Chain (DTMC) model proposed in [18] incorporates the main QoS features of 802.11e, namely, CW, AIFS, and TXOP differentiation. They use a Markov chain similar to [16] to find the long term occupancy of contention zones. the number of states is limited by the maximum idle time between two successive transmissions which is Wmin = min(CWi, max) for a saturated scenario. [19] study the joint setting of CWmin and CWmax (minimum and maximum contention window), AIFS (arbitration interframe space) and TXOP (transmit opportunity) to maximize capacity and optimize performance under QoS constraints. The AIFS analysis are based on [17] considering two classes of wireless stations with higher and lower QoS demands. As far as we know, only two AC has been analyzed for the modeling method based on [16][17] and only simple situations with limited parameter setting were investigated.

Among the above modeling methods, [16][17] in category 3 are the simplest. Therefore, in section 3, we specially focus on the model in the third category and improve it to evaluate collision probability and slot transmission probability in a wide range of parameter settings among a generalized number of ACs. We then derive the saturation throughput performance of IEEE 802.11e EDCA in Section 4. In Section 5, we present an evaluation of the effects of AIFS and CW differentiation on the performance of collision probability and throughput. Finally, conclusions are given in Section 6.

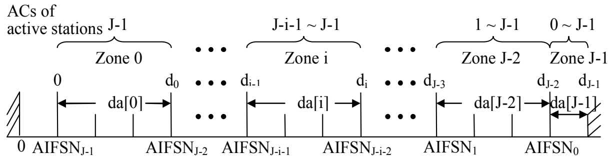

Fig. 1. Relation of contention zones, ACs, and number of time slots

III. ANALYTICAL MODELS

In this section, we derive a mathematical model to analyze the effect of different AIFS and/or CW priorities on collision probability and throughput performance. As in [16][17], we separate the derivations of the average collision probability and the slot transmission probability for each AC using two different Markov chains. The average collision probability for each AC is derived by using a much simplified version of Robinson's contention zone model [16][17], which can cope with any AIFS differences among any number of ACs; and the slot transmission probability by using the basic Bianchi's model [3] applied to each AC taking into account of CW differentiation. We adopt the decoupling assumption initially used by Bianchi's model where the slot transmission of each AC is assumed independent of that of others. This assumption has been widely used by researchers leading to tight approximation of performance, although its validity has never been addressed theoretically.

A. Derivation of Average Collision Probability of Each AC

As shown in Fig. 1, each slot is located in a contention zone, in which the system can be either in the state of transmission with the probability $p_{zone=i}^{tr}$ or non-transmission with the probability $1-p_{zone=i}^{tr}$. Assuming $p_{zone=i}^{tr}$ is constant, we developed a Markov chain as shown in Fig. 2 with each slot representing a state in the chain and the occupancy of slot equals to the state probability. Define $da[i]$ = AIFSN_{J-i-2} − AIFSN_{J-i-1} for $i\in [0, J-2]$ as the period time between AIFSN_{J-i-2} and AIFSN_{J-i-1}, $d_i=\sum_{k=0}^{i} da[k]$ so that $d_i=d_{i-1}+da[i]$. The state k_i of Markov chain ($k_i\in [d_{i-1}, d_i-1]$) denotes that the amount of time equal to k_i slots has elapsed since the end of the AIFS for the classes of AC[J-i-1, J-1]. These states correspond to the slots in the contention zone i, which is the *AIFS* period for Classes of AC[J-i-1, J-1] nodes to attempt to use the channel. In the *next* slots, when the state is $k_{i+1}\in [d_i, d_{i+1}-1]$, the nodes in AC[$J$-$i$-2, J-1] can attempt. Finally when $k_{J-1} = d_{J-1}$ in the last slot, all nodes can attempt. When i = 0, it means the first contention zone 0, in the case, we define d_{-1} = 0, so $k_0\in [0, d_0-1]$. The transmission probability $p_{zone=i}^{tr}$ in any slot of the

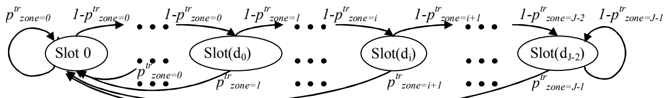

Fig. 2. Markov chain of time slots in a contention period

contention zone i is the probability that at least one transmission from the stations with priorities $[J\text{-}i\text{-}1, J\text{-}1]$ happened. Since $p^{tr}_{zone=i}$ is determined by the priorities of the active nodes in the slot and different contention zones have different priorities of active nodes, $p^{tr}_{zone=i}$ can be formulated as,

$$p^{tr}_{zone=i} = 1 - \prod_{j=J-i-1}^{J-1} (1-\tau_j)^{n_j} \tag{1}$$

In (1), τ_j is the probability that a station in AC j transmit in a randomly chosen slot time and n_j is the number of stations with priority j, both are related to the backoff process of AC j. Since we define the last contention zone include $da[J\text{-}1] = 1$ slot, the maximum slots in the chain which is counted as $d_i = \sum_{k=0}^{i} da[k]$ is equal to d_{J-1}=AIFSN$_0$+1–AIFSN$_{J-1}$. This avoids the necessities to investigate the system smallest maximum number of backoff slots in Robinson's model [12]. Since the slot is reached when the preceding slots have no transmission happened in the system, we denote the occupancy of slot in the Markov chain as $pslot[k_{i-1}]$ ($i \in [1, J]$), the relation between adjacent slot states within contention zone i period can be expressed as,

$$\begin{aligned} &pslot[k_i+1] = (1-p^{tr}_{zone=i}) \cdot pslot[k_i], \\ &k_i \in [d_{i-1}, d_i - 1], i \in [0, J-2], d_{-1} = 0. \end{aligned} \tag{2}$$

Eqn. (2) also shows the relation of time slots between adjacent contention zone. The probability transferring from the last slot in contention zone i-1 to the first slot in contention zone i is $1-p^{tr}_{zone=i-1}$. The occupancy of last slot d_{J-1} in zone J-1 is different from preceding slot. Instead of switching to the next slot, it remains at the last slot until a transmission occurred and turns it back to the initial state. Its occupancy probability is given by,

$$pslot[d_{J-1}] = \frac{1-p^{tr}_{zone=J-2}}{p^{tr}_{zone=J-1}} \times pslot[d_{J-1}-1] \tag{3}$$

Choosing i from 0 to J-2 in (2) together with (3), we can have all the values $pslot[k]$ expressed by $pslot[0]$. And $pslot[0]$ can be derived by imposing the normalized condition: the sum of all the states equals to 1,

$$\begin{aligned} pslot[0] = &\sum_{i=0}^{J-2} \frac{1-(1-p^{tr}_{zone=i})^{da[i]}}{p^{tr}_{zone=i}} \cdot \prod_{j=0}^{i-1} (1-p^{tr}_{zone=j})^{da[j]} \\ &+ \frac{\prod_{o}^{J-2} (1-p^{tr}_{zone=i})^{da[i]}}{p^{tr}_{zone=J-1}} \end{aligned} \tag{4}$$

The occupancy probability of contention zone z_i ($i \in [0, J\text{-}1]$) is derived by the sum of the slot occupancy probability given as below,

$$z_i = \sum_{k_i=d_{i-1}}^{d_i-1} pslot[k_i] \tag{5}$$

The collision probability is defined as at least one more stations transmit besides itself. It is zone-dependent priority stations available on transmit, therefore we have c_{ji} expressed as below,

$$c_{ji} = 1 - \frac{\prod_{k=J-i-1}^{J-1} (1-\tau_k)^{n_k}}{1-\tau_j} \tag{6}$$

In (6), c_{ji} is associated with stations of priority j active in contention zone i. $j \in [0, J-1]$ and $i \in [J-j-1, J-1]$. In each slot k_i of contention zone i, c_{ji} is kept the same. Combining (5), the average collision probability $\bar{c}_j$ conditioned on per slot occupancy of Markov chain in Fig. 2 is,

$$\bar{c}_j = \sum_{i=J-j-1}^{J-1} (c_{ji} \cdot \sum_{k_i=d_{i-1}}^{d_i-1} pslot[k_i]) = \sum_{i=J-j-1}^{J-1} (c_{ji} \cdot z_i) \tag{7}$$

B. Derivation of Slot Transmission Probability of Each

Denote the stationary distribution as $a_j(i,k)$, the backoff counter k found in the backoff stage i. k depends on the contention window that is tracked by i. Define $W_{j,i}$ as the largest backoff window drawn in stage i, we have $W_{j,i} = 2^i \times W_{j,min}$, where $W_{j,min}$ represents CW parameters of CWmin. Similarly, representing CWmax as $W_{j,max}$, we have $m_j = \log_2(W_{j,\max}/W_{j,\min})$, where m_j is the final backoff stage so that i is ranged from 0 to m_j. We note the following relationship between backoff states:

$$a_j(i,0) = (\bar{c}_j)^i \cdot a_j(0,0), \quad i \in (0, m_j] \tag{8}$$

$$a_j(i,k) = \frac{W_{j,i}-k+1}{W_{j,i}+1} \cdot (\bar{c}_j)^i \cdot a_j(0,0), i \in [0, m_j], k \in [0, W_{j,i}] \tag{9}$$

where $\bar{c}_j$ is the averaged conditional collision probability describe in (7). A solution for $a_j(0,0)$ in terms of $\bar{c}_j$ is found by imposing the normalization condition on the Markov process,

$$1 = \sum_{i=0}^{m_j} \sum_{k=0}^{W_{j,i}} a_j(i,k) \tag{10}$$

Recalling our definition that transmissions occur whenever the backoff counter k reaches 0, we find the slot transmission probability τ_j as below,

$$\tau_j = \sum_{i=0}^{m_j} a_j(i,0) \tag{11}$$

Noticing that τ_j is a function of $\bar{c}_j$ and $\bar{c}_j$ is a function of τ_j, we can solve τ_j and $\bar{c}_j$ by numerical method. After found τ_j, we can calculate throughput in the next section.

IV. SATURATION THROUGHPUT ANALYSIS

Denote $p^{s}_{j:zone=i}$ as the probability that a channel access is successful from any backoff instance of class j in any time slot of a contention zone i. It is the probability that only a station in AC j transmits and no other station transmits in the slot. Therefore, we can express $p^{s}_{j:zone=i}$ as follows,

$$p^s_{j:zone=i} = n_j \tau_j \frac{1-p^{tr}_{zone=i}}{1-\tau_j}, \quad j \in [J-i-1, J-1], i \in [0, J-1] \quad (12)$$

Let s_j be the throughput obtained by AC j, s_j is defined as the fraction of time the channel is used to successfully transmit the payload of data frames, then

$$s_j = \frac{E[\mathit{payload\ transmitted\ in\ a\ transmission\ period}]}{\mathrm{E}[\mathit{length\ of\ a\ transmission\ period}]} \quad (13)$$

Denoting σ, T^s and T^c as the duration of a single time slot with no transmission, successful transmission and unsuccessful transmission due to collision, the expected length of transmission period and the payload in the period are then obtained by averaging the length period over the steady-state occupancy of the time slots classified by the contention zone for a specific AC j in a node, as obtained below,

$$E[\mathit{length\ of\ transmission\ period}] =$$
$$\sum_{i=0}^{J-1}\left(\sum_{k_i=d_{i-1}}^{d_i-1} pslot[k_i]\left(\sigma + \sum_{j=J-i-1}^{J-1} p^s_{j:zone=i}T^s_j + \left(1-P^s_{zone=i}\right)T^c\right)\right) \quad (14)$$

$$E[\mathit{payload\ transmitted\ in\ a\ transmission\ period}] =$$
$$\sum_{i=0}^{J-1}\sum_{k_i=d_{i-1}}^{d_i-1} pslot[k_i]\cdot(p^s_{j:zone=i}\cdot E[P_j]) \quad (15)$$

in above, $E[P_j]$ is the payload transmission time of AC j during each cycle to access the channel. T^s_j is the timeslot for successful transmission for AC = j. Except the successful tr ansmission probability, $E[P_j]$, T^s_j and T^c are independent of the contention zones. We express T^s_j and T^c in basic access modes as follows,

$$T^s_{bas:j} = H + E[P_j] + ACK + 2\delta + SIFS + AIFS_{\min} \quad (16)$$

$$T^c_{bas} = H + E[P^*] + ACK + 2\delta + SIFS + AIFS_{\min} \quad (17)$$

H is the time required for transmitting the physical layer header (H_{phy}) and MAC layer header (H_{mac}) of a frame. *ACK*, *RTS* and *CTS* are the transmission time of the corresponding frame and the physical overhead; δ is the propagation delay. $E[P^*]$ is the transmission time of the longest payload involved in collision. In a system where data frames transmitted are of the same fixed size, $E[P_j] = E[P^*] = P$, and $T^s_{bas:j} = T^c_{bas}$. In this paper, we assume basic access mode, however, the results can be easily applied to RTS/CTS mode with modifications on T^s_j and T^c

V. Simulation Results

To evaluate the accuracy of our enhanced analytical model, we conduct simulations in NS-2.26 [20] and compare the results with numerical results computed using the analytical model presented in Sections 3 and 4. Table I lists the IEEE 802.11 MAC and PHY parameters used in both analytical computations and simulations. Saturation conditions are maintained in simulations by generating constant bit rate traffic at a rate higher than the link capacity. The simulator conforms as closely as possible to the 802.11e standard as specified in [2]. The performance is measured by repeating simulation 20 times with each lasting for 3 minutes. The final results are obtained by averaging the 20 simulation results. Following the standard for EDCA, Figs. 3-5 show the results for four ACs differentiated by AIFS and/or CW mechanisms with increasing number of stations per AC.

Table I
802.11e MAC/PHY Parameters in Simulation and Analsysis

Frame payload	8000 bits
MAC header	224 bits
PHY header	192 bits
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
Channel bit rate	1 Mbit/s
Payload bit rate	11 Mbit/s
Propagation delay	1 μs
Slot time	20 μs
SIFS	10 μs

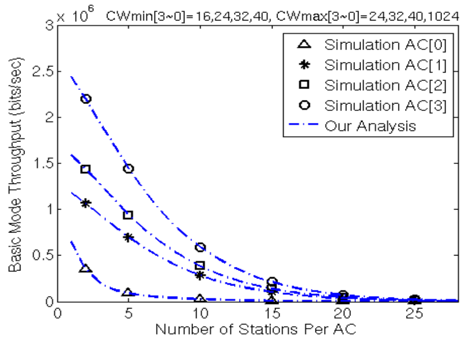

Fig. 3. Pefromance using constant AIFSN and different CW.

Comparing Fig. 3 and Fig. 4, we observe that AIFS differentiation is more effective than CW differentiation. It is clear from (6) that when only CW differentiation is used, the collision probability for each AC would converge to 1 with the increase of traffic load. Correspondingly, in Fig. 4, stations of AC[3-1] are starved of bandwidth simultaneously when the

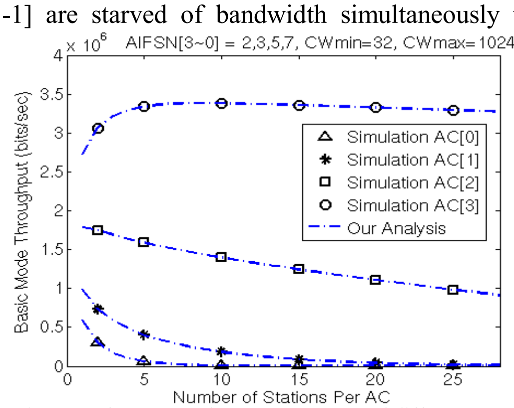

Fig. 4. Performance using constant CW and different AIFSN

number of stations reaches 20. This means that high priority stations could suffer performance degradation due to heavy traffic loads offered by lower priority stations. The only exception where stations in AC[0] starve earlier than those in AC[3-1] is when AC[0] have a maximum window size (CWmax = 1024) that is much larger than those of AC[3-1]. In contrast, the collision probabilities of stations in different ACs employing AIFS differentiation do not converge to 1 simultaneously since stations in a higher priority AC are allowed to transmit not only in a contention zone that is not accessible to stations in a lower priority AC, but also in contention zones that are accessible to stations in all lower priority ACs. This is confirmed by results in Fig. 4, where the throughput of a high priority AC (AC[3]) decreases at a much slower rate than those of lower priority ACs (AC[2-0]) when the number of stations increase. In Fig. 4, AC[0] runs out of bandwidth when the number of stations reaches 10 and AC[1] runs out of bandwidth when the number of stations reaches 15. AC[0] starves earlier than AC[1] since it has the lowest AIFS priority. In comparison with the results in Fig. 4, Fig. 5 provides us another insight that EDCA performance shows increasing degradation with the increase of traffic load especially when a small CWmax is used. Correspondingly for each AC, the throughput reduces faster in Fig. 5 compared to Fig. 4 when the traffic load is increased.

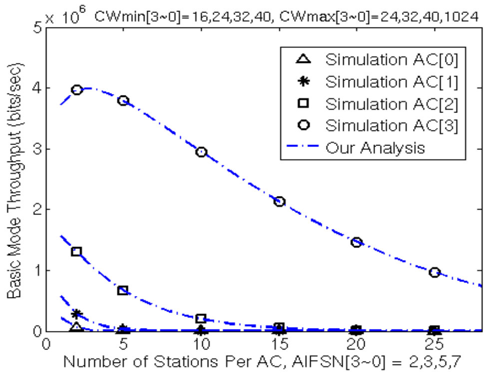

Fig. 5. Performance using different CW and AIFSN

VI. CONCLUSIONS

In this paper, we have presented an improved analytical model to study the performance of EDCA service differentiation schemes, employing AIFS and CW. The model significantly reduces the computation complexity and therefore can be applied to general 802.11 WLAN operation environments that include several ACs and a wide traffic load conditions. We have verified the general effectiveness of EDCA service differentiation through analytical and simulation results. The simulation results agree our analytical models with over 95% high accuracy that gives confidence to the validity of the model. The results are useful to learn how to choose parameters in EDCA for the required QoS performance specified by different applications.

REFERENCES

[1] IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements Part II: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications [S], 2007.

[2] IEEE 802.11e, Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Medium Access Control (MAC) Quality of Service Enhancements, IEEE Std. 802.11e-2005, 2005.

[3] G. Bianchi, “Performance analysis of the IEEE 802.11 DCF”, IEEE J. Select. Areas Commun., vol. 18, pp. 535-547, Mar. 2000.

[4] Y. Xiao. “Performance Analysis of Priority Schemes for IEEE 802.11 and IEEE 802.11e Wireless LANs”, IEEE Transaction on Wireless Communications, Vol. 4, pp. 1506 – 1515, July 2005.

[5] T. Tsai and M.We, “An analytical model for IEEE 802.11e EDCA,” in Proc. IEEE ICC, Seoul, Korea, 2005, pp. 3474–3478.

[6] Z. Tao and S. Panwar, “Throughput and Delay Analysis for the IEEE 802.11e Enhanced Distributed Channel Access”, IEEE Transactions on Communications, Vol. 54, pp. 596 - 603 April 2006.

[7] J.Y. Lee, and H.S. Lee. "A Performance Analysis Model for IEEE 802.11e EDCA Under Saturation Condition", IEEE Trans. Communications, vol. 57, pp. 56 – 63, Jan. 2009.

[8] Ye Yan, Ce Pan. “An improved Analytical Model for IEEE 802.11e Enhanced Distributed Channel Access”, International Symposium on Information Technology Convergence (ISITC), 23-24 Nov. 2007.

[9] J. Wen, M. Wu, Y. Zhen. "A novel delay analysis model for EDCA with virtual collision handler", IEEE International Conference on Communications Technology and Application s ICCTA '09, On page(s): 317 – 321, Beijing, 16-18 Oct. 2009.

[10] J. Hui and M. Devetsikiotis, “Performance analysis of IEEE 802.11e EDCA by a unified model”, IEEE Transaction on Communications, Vol.53, pp. 1498 – 1510, Sep.2005.

[11] A. Banchs, L. Vollero. “Throughput Analysis and Optimal Configuration of 802.11e EDCA”, Computer Networks, vol. 50, pp. 1749 – 1768, 2006.

[12] H. Zhu and I. Chlamtac. “Performance Analysis for IEEE 802.11e EDCF Service Differentiation”, IEEE Transactions on Wireless Communications, Vol. 4, pp. 1779 – 1788, July 2005.

[13] Y. Yan and C. Pan, “An improved analytical model for IEEE802.11e enhanced distributed channel access,” in Proceedings of the International Symposium on Information Technology Convergence (ISITC '07), pp. 135–139, Jeonju, Korea, November 2007.

[14] P. Serrano, A. Banchs, P. Patras and A. Azcorra, “Optimal Configuration of 802.11e EDCA for Real-Time and Data Traffic”, IEEE Transactions on Vehicular Technology, Volume: 59, pp. 2511 - 2528, Jun 2010.

[15] P. E. Engelstad, Olav N. Østerbø, “The Delay Distribution of IEEE 802.11e EDCA and 802.11 DCF”, Proc. IEEE International Performance Computing and Communications Conference (IPCC), pp. 87-96, 2006.

[16] J. W. Robinson, T. S. Randhawa, “Saturation Throughput Analysis of IEEE 802.11e Enhanced Distributed Coordination Function”, IEEE J. Select. Areas Commun., Vol. 22, No. 5, June 2004.

[17] V. Ramaiyan, A. Kumar, and E. Altman, “Fixed Point Analysis of Single Cell IEEE 802.11e WLANs: Uniqueness, Multistability and Throughput Differentiation,” in ACM SIGMETRICS, 2005.

[18] I. Inan, F. Keceli and E. Ayanoglu, “Analysis of the 802.11e Enhanced Distributed Channel Access Function”, IEEE Trans. Communications, vol. 57, pp. 1753 – 1764, June 2009.

[19] I. Koukoutsidis, V. A. Siris, "802.11e EDCA Protocol Parameterization: A Modeling and Optimization Study," IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), pp.1-9, 2007.

[20] [Online] Availabe: http://www.tkn.tu-berlin.de/research/802.11e_ns2.