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Performance analysis of IEEE 802.11 DCF and 802.11e EDCA based on queueing networks

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Abstract: The authors propose a new analytical model based on BCMP closed queueing networks in order to evaluate the performance of IEEE 802.11 DCF MAC protocol when all nodes are in the transmission range of each other, that is, a single hop wireless *ad hoc* network. By the proposed model, some performance metrics such as saturation and non-saturation throughput, distributions of channel access delay and the number of packets in the MAC buffer are derived. An extension of the proposed model is used for the analysis of IEEE 802.11e EDCA and the same performance metrics are evaluated for this protocol. Analytical results on IEEE 802.11e prove that differentiation in service is possible and channel share for each service type may be well assigned by tuning the MAC protocol parameters. Simulation results show consistency with our analytical results.

1 Introduction

WLANs based on IEEE 802.11 [1, 2], as the well-known examples of single-hop wireless *ad hoc* networks, have gained great interest among both users and researchers. The ease of implementation and low cost of the related chipset have helped the standard to open its way through a wide range of applications, for example, personal area networks, wireless internet and vehicular *ad hoc* networks. The importance of these applications motivates the researchers to model and investigate the MAC protocol of the standard as accurately as possible. This matter is very important, especially when we want to apply IEEE 802.11 MAC protocol for the case of multi-hop wireless *ad hoc* networks.

Much research works have been done for the performance analysis of IEEE 802.11 MAC protocol [3–10], that is, *Distributed Coordination Function* (DCF), and for IEEE 802.11e MAC protocol, that is, *Enhanced Distributed Channel Access* (EDCA) [11–13]. The latter standard deals with some QoS issues that were neglected in IEEE 802.11 DCF.

Most of the previous research works concern the channel throughput in saturation status, that is, each node always has a packet to transmit. In fact, the modelling and performance analysis of IEEE 802.11 DCF has been mainly started by Bianchi in [4], where he proposed a two-dimensional Markov chain to model IEEE 802.11 DCF in saturation status. Besides Bianchi, other performance analyses for IEEE 802.11 DCF have been performed as in [5–8]. In [5], the authors derived analytical results on a model based on Bianchi's work and also assumed a channel error probability. Authors in [6] derived the same performance metrics for IEEE 802.11 DCF in saturation status using the idea of queueing networks. Their results match those of [4], but in scenarios with large number of nodes the results obtained through the method in [6] are more precise than those of [4]. It is due to the fact that Bianchi's model neglected the retry limit specified in the standard. In [7], the authors presented a new backoff scheme that considerably enhances the saturation throughput and fairness of DCF. In [8], the authors presented the packet jitter analysis in IEEE 802.11 DCF. These analyses were all based on the Markov chain model presented in [4].

For the case of IEEE 802.11e and in the saturated load condition, there has been a similar trend. In [12–14], the authors presented extensions to the model in [4] to evaluate the performance metrics of IEEE 802.11e in saturation status.

The saturation status, seldom happen in a real network because in this case the queueing delay is infinite and many communication services cannot be supported. Thus, the analysis in saturation status does not evaluate the network in general scenarios. In [9], an extension to the Markov chain in [4] was presented. An idle state was added to the Markov chain of [4] in order to model IEEE 802.11 DCF in non-saturation status. In this status, the node was assumed to either have a packet to transmit or not. However, the model in [9] lacks the ability to assume a MAC buffer. Moreover, the authors in [11] presented a queueing network to model IEEE 802.11 DCF under the condition of non-saturated traffic load. Another research on IEEE 802.11 DCF in non-saturation status is the work in [10], where the authors modelled each node as an $M/G/1/K$ queueing station. They derived the relations for the service time of the queue using the transform method. The model in [10] analyses the IEEE 802.11 node in non-saturated traffic load, but it demands calculation of some Z-transforms in an iterative method in order to find the probability of transmission. The work in [10] also has not taken into account the queueing behaviour of the wireless nodes, that is, the steady-state distribution of MAC buffer length and channel access delay. Compared to research works on IEEE 802.11 DCF, there has been less work on IEEE 802.11e EDCA in non-saturation status.

With respect to the above, less research works have considered the performance analysis of IEEE 802.11 MAC in non-saturation status, that is, the conditions in which nodes do not always have a packet to transmit. On the other hand, regarding the deployment of WLANs and the strong need to provide different types of services including delay-sensitive and real-time services, non-saturation analysis and the corresponding performance metrics are very important. The important point in non-saturation status is the fact that a node is allowed to be idle for some period of time, which is a more realistic assumption than that of the saturation status. In non-saturation status, with respect to QoS parameters of different services, some new metrics, for example, channel access delay distribution and MAC buffer length distribution need to be considered. In fact, channel access delay distribution is the most important parameter in computing total delay distribution (including transmission delay and queueing delay) and MAC buffer length distribution. To the best of our knowledge, the analytical evaluation of these performance metrics for IEEE 802.11 DCF and IEEE 802.11e EDCA in non-saturation status has not been reported in the literature.

In this paper, we focus on the analytical modelling of IEEE 802.11 MAC protocols (DCF and EDCA) in both saturation and non-saturation statuses. The desired performance metrics that are obtained through the proposed model are throughput, channel access delay distribution and queue length distribution, at the MAC layer. The proposed model is based on a BCMP (Baskett, Chandy, Muntz and Palacios) queueing network composed of $M/G/\infty$ queues [15] and applying Z-transform in order to compute the desired performance metrics. Our model is suitable for Poisson input traffic at each node. Finally, our simulation results show that our model has good accuracy and reliability.

Following this introduction, Section 2 is dedicated to an overview of IEEE 802.11 DCF and 802.11e EDCA. In Section 3 we present a new proposed model for IEEE 802.11 DCF, and Section 4 extends the proposed model for the analysis of EDCA. Section 5 presents the numerical results as well as a comparison between simulation and analysis. Finally, Section 6 concludes the paper.

2 Overview of IEEE 802.11 and IEEE 802.11e MAC protocols

2.1 IEEE 802.11 DCF

The IEEE 802.11 DCF is the channel access scheme for most of today's WLANs. According to [1], when a wireless node wants to transmit a packet at its buffer, it does not transmit it instantly. If the channel remains idle for a *Distributed Inter-Frame Space* (DIFS), the node chooses a random delay (backoff), which is actually an integer multiple of a time slot duration. This random delay is uniformly chosen in the range $[0, \mathrm{CW}_{min} - 1]$, where CW_{min} is the minimum contention window size of the node and is one of the parameters of DCF. At the beginning of each time slot, the node down-counts its backoff value provided that the backoff value is non-zero. If the channel is sensed busy, that is, another node transmits a packet at this time slot, the node stops down-counting and enters a frozen state. Thus, the time slot corresponding to the time interval between two consecutive values of the backoff counter may be extended. Therefore, the corresponding time interval is random and is called a *virtual time slot*.

After the channel is sensed idle again for the duration of a DIFS, the node resumes down-counting. At the time the backoff value reaches zero, the node transmits its packet. If the transmission fails, the node doubles its contention window size (exponential backoff). The process of doubling the contention window size keeps on after each failure until reaching a maximum, CW_{max}. At this stage, if the transmission failure occurs again, the contention window is not doubled anymore. The node repeats the last stage of backoff process at most for a pre-defined retry limit and drops the packet if it has not been transmitted yet. At last, the contention window size is reset to its minimum value for the next packet to transmit.

According to the standard, when a packet enters an empty buffer and the channel is sensed idle for a DIFS, the packet is transmitted immediately. Otherwise, it enters the first backoff stage. In this case, according to the backoff process the node will be frozen until the channel is sensed idle for a DIFS.

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There are two modes of operation for IEEE 802.11 DCF. The first mode is the basic access mode in which the transmitter transmits its data packet and waits for the reception of an acknowledge message. A collision is reported if no acknowledge is returned within an acknowledge time-out. The second mode is the RTS/CTS handshaking mode. In this mode, the node first transmits a short packet called *Request To Send* (RTS). Each node around the transmitter, which receives the RTS packet, postpones its transmission for the time specified in the RTS header. Upon receiving the RTS packet at the receiver side, the receiver generates a *Clear To Send* (CTS) packet to acknowledge the reception of the RTS packet. At this time, nodes around the receiver put off their transmission for the duration of current transmission. When the transmitter receives the CTS packet, it transmits its data.

In the second mode, the backoff process is applied on RTS packets. Thus, the CTS packet plays the role of an acknowledge message for the RTS packet. Therefore, the second mode is advantageous in two ways; first, it reduces the possibility of a hidden terminal problem by the use of CTS packets and second, the overhead paid for a transmission failure (due to collision) is reduced as long as the size of data packet is considerably more than that of RTS and CTS packets.

2.2 IEEE 802.11e EDCA

The IEEE 802.11e EDCA is an extension to IEEE 802.11 DCF that provides service differentiation and QoS. In EDCA, the node separates its arrival traffic into four categories, each one called an *Access Category* (AC). Each AC, numbered from 0 to 3, has its own parameters, that is, inter-frame space duration, minimum contention window size, maximum contention window size, etc. The AC0 is the lowest priority class of service and is served after the others. Instead of DIFS, there is an *Arbitration Inter-Frame Space* (AIFS) in EDCA, which is a function of the AC. According to [2], $\text{AIFS(AC)} = \text{SIFS} + \text{AIFSN(AC)} \times T_{\text{slot}}$, where AIFSN(AC) is an integer denoting the AIFS number of the corresponding AC, T_{slot} denotes the duration of a time slot and SIFS is the short inter-frame space.

When the backoff counter reaches zero, a packet is transmitted if no other packet from a higher priority category is ready to be transmitted. If there is such a coincidence, the packet with higher priority is transmitted while the lower priority packet(s) experience a *virtual collision*, that is, the packets in lower priority queues act as if a collision occurs.

According to the specifications of IEEE 802.11e, service differentiation is the advantage of EDCA compared to DCF. It is due to applying the priority in transmission (as in the virtual collision handler) as well as different transmission rates resulted through the use of different contention window and other backoff parameters, for different access categories.

3 Proposed analytical model for IEEE 802.11 DCF

3.1 Description of the model and the related simplifications

With respect to discussions in the previous section, the state of a wireless node in an IEEE 802.11 DCF-based network may be exactly presented by the backoff counter value and the backoff stage the node resides in. In order to include the queueing behaviour of the MAC buffer, another metric may be added to the previous set of states, which would be the current number of packets in the queue. The node also operates in non-saturation status so it is likely to be in an idle state where the node has nothing to transmit. In our modelling approach, we consider a symmetric situation among wireless nodes such that they have similar parameters. Thus, we focus on modelling the behaviour of a typical wireless node (i.e. the customer in the queueing network) and include the effects of other wireless nodes on the typical node. For a typical wireless node, we propose a queueing network model such that each backoff stage is mapped on a queue (similar to [6]) and the typical wireless node plays the role of a single customer. Therefore, our proposed model is a closed queueing network (see Fig. 1). In the proposed model, when the wireless node has no packet to transmit, the corresponding customer in the queueing network is in the queue *IDLE*. The queueing network in Fig. 1 consists of a two-dimensional array of queues besides the queue IDLE. For each queue placed at the (k, i)th position of the array of queues, column i denotes the current backoff stage while row k indicates the number of packets currently in the MAC buffer; thus, the packet under backoff or transmission process is not included. It is worth mentioning that for the sake of simplicity and analytical tractability, we ignore the possible case of immediate transmission of the packet arriving at an empty node, in our analyses. Thus, we assume that each packet arriving at an

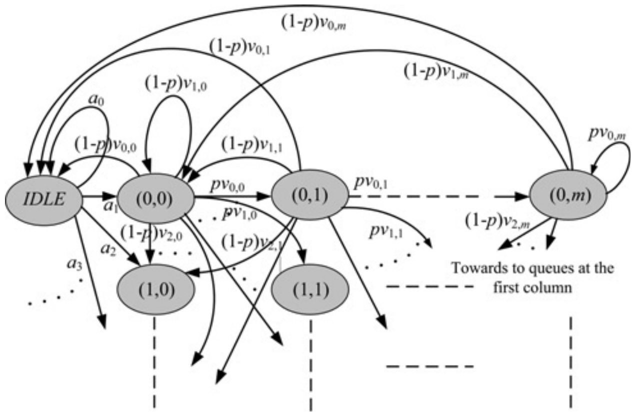

Figure 1 *Queueing network model proposed for IEEE 802.11 DCF*

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idle node (empty node), enters the first backoff stage in a synchronised manner prior to transmission. Therefore, in the proposed model (Fig. 1), the single customer moves randomly among different queues with some probabilities. Since there is only one customer in the queueing network, without loss of generality, the queues may be easily considered as $M/G/\infty$ queueing systems; hence the network is a closed BCMP queueing network [15], correspondingly.

In the proposed model, we focus on the state of the wireless node in a slotted manner. In fact, we consider each slot as the virtual time slot, because according to the description of IEEE 802.11 DCF, the wireless nodes are synchronised and within a virtual time slot they are frozen. Therefore, the packets arrived at the queue IDLE within a virtual time slot are observed at the beginning of the next slot. However, the packets arrived at the other queues within a virtual time slot are observed at the end of the current backoff stage. In fact, when a wireless node is not empty, the number of packets at its buffer is not effective on the other nodes. Thus, in our queueing network, the number of packets arrived at a wireless node and within its backoff stage is considered in the routing probability of the customer from the current queue towards the other queues, at the end of the current backoff stage. As indicated in Section 1, the packet generation process at the MAC layer is assumed to be a Poisson process; hence, we are able to compute the probability corresponding to the number of packets in the MAC buffer at each virtual time slot, depending upon the state of the customer (i.e. the corresponding queue) and the number of packets newly arrived, in the preceding virtual time slot.

With respect to the above discussion, when the customer of the closed queueing network is in the queue (k, i), it denotes that there have been k packets in the buffer just after the beginning of the current backoff stage and the current packet to be transmitted is in the backoff stage i. After the service time in the queue (k, i) is finished, that is, the backoff timer expires, the customer leaves for different queues in the queueing network. If the transmission is successful (with probability $1-p$), the customer is routed to the queue $(j+k-1, 0)$, if j packets arrived in the previous backoff stage. Moreover, the packet is routed to the queue IDLE if there is no packet in the MAC buffer and no packet is arrived in the previous backoff stage (i.e. $k=j=0$). However, if a collision occurs (with probability p) then the customer leaves for the queue $(j+k, i+1)$ (i.e. the next exponential backoff stage), again depending on the number of arrived packets (j) during its previous backoff stage. If i denotes the last backoff stage, the customer is routed to $(j+k, i)$ in the case of collision.

Service time of the queue IDLE is considered a virtual time slot. For the case of queues (k, i), the service time is a random number of virtual time slots between 1 and $2^i CW_{\min}$ $(0 \le i \le m)$, where $CW_{\min}$ refers to the minimum contention window size. It is worth noting that we have included the last slot corresponding to successful packet transmission in the backoff process delay (i.e. the service time of the corresponding queue). For the sake of simplicity, it is assumed that a node may have an infinite number of transmission retries before being dropped.

According to the above discussion, the traffic equations of the proposed queueing network are as in the following

$$\alpha_{\text{IDLE}} = \alpha_{\text{IDLE}} a_0 + (1-p)\sum_{i=0}^{m} \alpha_{0,i} v_{0,i} \tag{1}$$

$$\alpha_{k,0} = \alpha_{\text{IDLE}} a_{k+1} + (1-p)\sum_{i=0}^{m}\sum_{j=0}^{k+1} \alpha_{k+1-j,i} v_{j,i} \tag{2}$$

$$\alpha_{k,i} = p\sum_{j=0}^{k} \alpha_{k-j,i-1} v_{j,i-1} \tag{3}$$

$$\alpha_{k,m} = p\sum_{j=0}^{k} (\alpha_{k-j,m-1} v_{j,m-1} + \alpha_{k-j,m} v_{j,m}) \tag{4}$$

where $\alpha_{k,i}$, $v_{k,i}$, a_k, denote the arrival rate of customers at the queue (k, i), the probability of having k packet arrivals during the backoff stage i and the probability of k packet arrivals during a virtual time slot, respectively. Moreover, p denotes the collision probability and m is the last backoff stage. Assuming T^v_{slot} as the length of a virtual time slot and with the assumption of Poisson arrival process, it follows that

$$a_k = \mathrm{e}^{-\lambda T^v_{\text{slot}}} \frac{(\lambda T^v_{\text{slot}})^k}{k!} \tag{5}$$

where λ is the packet arrival rate at the MAC buffer of the wireless node. According to the recent result, and assuming backoff delay as a random number of consecutive i.i.d. virtual time slots and W as the minimum contention window size for the node (equal to $\text{CW}_{\min}$), it follows that

$$v_{k,i} = \sum_{n=1}^{2^i W} \frac{1}{2^i W} \mathrm{e}^{-\lambda n T^v_{\text{slot}}} \frac{(\lambda n T^v_{\text{slot}})^k}{k!} \tag{6}$$

In a closed queueing network, traffic equations are not independent of each other. Thus, we consider the arrival rates of all queues relative to the arrival rate of the queue IDLE, α_{IDLE}. Hence, we consider α_{IDLE} equal to one in (1). According to (2)–(4), the traffic equations have the form of convolution and therefore it implies the idea of the transform methods that considerably simplifies the solution of the traffic equations. By considering the form of (2)–(4), some simple manipulations, and applying Z-transform it readily follows that

$$\sum_{k=0}^{\infty} z^{k+1}\alpha_{k,0} = \sum_{k=0}^{\infty} z^{k+1} a_{k+1} + (1-p)\sum_{k=0}^{\infty}\sum_{i=0}^{m} \times (\alpha_{k+1,i} * v_{k+1,i}) z^{k+1}$$

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$$\Rightarrow z\alpha_0(z) = A(z) - a_0 + (1-p)\sum_{i=0}^{m}(V_i(z)\alpha_i(z) - \alpha_{0,i}v_{0,i}) \tag{7}$$

$$\sum_{k=0}^{\infty} z^k \alpha_{k,i} = p\sum_{k=0}^{\infty}(\alpha_{k,i-1} * v_{k,i-1})z^k \Rightarrow \alpha_i(z) = p\alpha_{i-1}(z)V_{i-1}(z);\ 1 \le i \le m-1 \tag{8}$$

$$\sum_{k=0}^{\infty} z^k \alpha_{k,m} = p\sum_{k=0}^{\infty}((\alpha_{k,m-1} * v_{k,m-1}) + (\alpha_{k,m} * v_{k,m}))z^k \Rightarrow \alpha_m(z) = \frac{p\alpha_{m-1}(z)V_{m-1}(z)}{1-pV_m(z)} \tag{9}$$

where * denotes convolution and

$$A(z) = Z\{a_k\} = e^{\lambda T^{v}_{\text{slot}}(z-1)} \tag{10}$$

$$V_i(z) = Z\{v_{k,i}\} = \frac{A(z)}{2^iW}\frac{1-[A(z)]^{2^iW}}{1-A(z)} \tag{11}$$

From (7)–(9), it easily follows for $\alpha_0(z)$ that

$$\alpha_0(z) = \frac{A(z) - a_0 - (1-p)\sum_{i=0}^{m}\alpha_{0,i}v_{0,i}}{z-(1-p)\sum_{i=0}^{m}F_i(z)} \tag{12}$$

where

$$F_i(z) = \begin{cases} V_i(z)V_{i-1}(z)\cdots V_0(z)p^i, & i \le m-1 \\ \dfrac{F_{m-1}(z)p}{1-pV_m(z)}, & i = m \end{cases} \tag{13}$$

The term $(1-p)\sum_{i=0}^{m}\alpha_{0,i}v_{0,i}$ is the departure rate from the queues at first row of Fig. 1 (except the queue IDLE) and routed to the queue IDLE. Then, according to (1) it equals the rate leaving the queue IDLE towards other queues which equals $\alpha_{\text{IDLE}}(1-a_0) = 1-a_0$, regarding the normalisation $\alpha_{\text{IDLE}} = 1$, as expressed before. Therefore, the equation for $\alpha_0(z)$ reduces to

$$\alpha_0(z) = \frac{A(z)-1}{z-(1-p)\sum_{i=0}^{m}F_i(z)} \tag{14}$$

By assuming a constant probability of transmission for each node at each virtual time slot, probability of collision equals

$$p = 1-(1-\tau)^{N-1} \tag{15}$$

where N, τ are the number of nodes in the wireless network and the probability of transmission by a typical wireless nodes at a typical virtual time slot, respectively. It is worth noting that (15) is the same as transmission probability in saturation status (considered in [4]). In fact, we include the effect of non-saturation status or equivalently the buffer emptiness in τ in our analysis. The probability of transmission in a virtual time slot is computed as in the following

$$\tau = \frac{1}{N_Q}\frac{N\alpha_T}{N} = \frac{\alpha_T}{N_Q} \tag{16}$$

where N_Q is a normalisation constant and α_T is the transmission rate of a typical wireless node (regarding virtual time slot as the time unit), that is, the departure rate from all queues (except for the queue IDLE), denoting the rate at which the customer leaves a backoff stage. Actually, the transmission probability at each typical virtual time slot equals the ratio of the average number of transmitting nodes to the total number of nodes. On the other hand, α_T indicates the number of average transmitted packets of a typical wireless node at each virtual time slot. Since at each slot a wireless node can transmit at most one packet and regarding symmetry among wireless nodes in this paper, $N\alpha_T$ indicates the average number of transmitting nodes. Thus, the ratio of $N\alpha_T$ over N equals τ as in (16). Furthermore, regarding (8), (9), (12) α_T in our queueing network is computed as in the following

$$\alpha_T = \sum_{i=0}^{m}\sum_{k=0}^{\infty}\alpha_{k,i} = \sum_{i=0}^{m}\alpha_i(z)\big|_{z=1} = \alpha_0(z)\big|_{z=1} \times\left(\sum_{i=0}^{m-1}F_i(z)\big|_{z=1} + \frac{pF_{m-1}(z)\big|_{z=1}}{1-pV_m(z)\big|_{z=1}}\right) = \alpha_0(z)\big|_{z=1}\left(\sum_{i=0}^{m-1}p^i + \frac{p^m}{1-p}\right) = \frac{1}{1-p}\alpha_0(z)\big|_{z=1} \tag{17}$$

Since the arrival rates $\alpha_{k,i}$'s in (17) are considered relative to α_{IDLE} we have applied a normalisation factor $(1/N_Q)$ in (16). In order to compute N_Q we focus on the number of customers in the proposed closed queueing network. The number of customers in this network equals one, since it represents a typical wireless node. On the other hand, the number of customers in a queueing network at each traffic state equals sum of the number of customers at all queues at that traffic state. Therefore, the number of customers in a closed queueing network equals sum of the average number of customers at all queues. Thus, according to Little's law we have the following equation

$$N_Q = \alpha_{\text{IDLE}}\overline{T}_{\text{IDLE}} + \sum_{(k,i)=(0,0)}^{(\infty,m)}\overline{N}_{k,i} = 1 + \sum_{i=0}^{m}\sum_{k=0}^{\infty}\overline{T}_{k,i}\alpha_{k,i} \tag{18}$$

where $\overline{N}_{k,i}$, $\overline{T}_{k,i}$ denote the average number of customers and the average service time, of the queue (k,i), respectively. In addition, $\overline{T}_{\text{IDLE}}$ is the average service time of the queue IDLE that equals a virtual time slot, that is, the time unit in our model (regarding the discussions in this section about the slotted nature of our analysis). According to the random duration of each backoff stage (i.e. between 1, 2^iW) it follows that

$$N_Q = 1 + \sum_{i=0}^{m}\sum_{k=0}^{\infty}\alpha_{k,i}\frac{2^i W + 1}{2} = 1 + \sum_{i=0}^{m}\frac{2^i W + 1}{2}\alpha_i(z)\big|_{z=1}$$
$$= 1 + \left[\frac{W}{2}\left(\frac{(2p)^m - 1}{2p-1} + \frac{(2p)^m}{(1-p)}\right) + \frac{1}{2(1-p)}\right]\alpha_0(z)\big|_{z=1} \quad (19)$$

Then, regarding N_Q in (19) as the normalisation constant and (17), transmission probability τ in (16) leads to the following equation

$$\tau = \frac{[1/(1-p)]\alpha_0(z)\big|_{z=1}}{1 + \big[(((2p)^m - 1)/(2p-1) + (2p)^m/(1-p)) \times (W/2) + [1/(2(1-p))]\big]\alpha_0(z)\big|_{z=1}} \quad (20)$$

By concurrent solution of (20) and (15), the probability of transmission in a virtual time slot is obtained. Moreover, according to the fact that $\alpha_0(z)\big|_{z=1} = 0/0$ (see (10)–(14)), by using the l'Hôpital's rule, it follows that (as shown at the bottom of the page)

3.2 Evaluation of the throughput

According to the results obtained in the previous section, and the definition of throughput [4], the following equation may be derived

$$S = \frac{P_S T_{\text{Packet}}}{T^v_{\text{slot}}} \quad (22)$$

$$T^v_{\text{slot}} = P_S T_S + (1 - P_0 - P_S)T_C + P_0 T_{\text{slot}} \quad (23)$$

$$P_S = N\tau(1-\tau)^{N-1}, \; P_0 = (1-\tau)^N \quad (24)$$

where S, P_S, and P_0 are the normalised throughput of the network, the probability of successful transmission at a typical virtual time slot and the probability of having no transmission in a typical virtual time slot, respectively. Moreover, T_{slot}, T_S, T_C and T_{Packet} denote the duration of a typical time slot (not a virtual time slot), the average duration of a successful transmission, the average duration of a collision and the average transmission time of a packet (a part of T_S), respectively.

3.3 Maximum allowable packet arrival rate for having a finite queueing delay

As far as the mean service time of the MAC queue is less than the mean inter-arrival time of the packets, the mean length of the queue in MAC is finite and therefore there is always a finite average delay for an incoming packet. The queueing system becomes unstable when the probability of visiting the system in idle state is zero. According to the proposed model, this probability is the probability that the customer in the queueing network resides in the queue IDLE. Since our queueing network is a BCMP one comprised of $M/G/\infty$ queues, we have a product-form solution for the stationary probability distribution [16]. On the other hand, the number of customers in the queueing network equals one; hence the stationary probability that the customer is at each queue equals the traffic intensity of that queue [16]. Then, regarding the normalisation constant derived in (19), we have the following relation (as shown at the bottom of the page)

where $q_{k,i}$, q_0, $\overline{T}_{k,i}$, $\overline{T}_{\text{IDLE}}$ denote the probability that the customer resides at the queue (k,i), the probability that the customer resides at the queue IDLE, the average service time of the queue (k,i), and the average service time of the queue IDLE (i.e. virtual time slot that is the time unit in our model). Therefore, the minimum packet arrival rate, which results in an infinite value for the quantity $\alpha_0(z)|_{z=1}$, leads to the instability of the wireless node. This rate is the supremum of allowable packet arrival rates in order to still have a finite queueing delay. At this rate the wireless node

$$F_i'(z)|_{z=1} = p^i\sum_{j=0}^{i} V_j'(z)|_{z=1} = p^i\sum_{j=0}^{i}\frac{\lambda T^v_{\text{slot}}}{2}(2^j W + 1) = \frac{p^i(i + 1 + W(2^{i+1} - 1))\lambda T^v_{\text{slot}}}{2}; \; i \le m-1 \Rightarrow$$
$$F_m'(z)|_{z=1} = \lambda T^v_{\text{slot}}\frac{p^m(1-p)(m + W(2^m - 1)) + p^{m+1}(2^m W + 1)}{2(1-p)^2} \Rightarrow$$
$$\alpha_0(z)|_{z=1} = \frac{A'(z)|_{z=1}}{1 - (1-p)\sum_{i=0}^{m}F_i'(z)|_{z=1}}$$
$$= \frac{\lambda T^v_{\text{slot}}}{1 - (1-p)(\lambda T^v_{\text{slot}}/2)[[(1 + (2p)^m W)/(1-p)^2] - [(p^m + W)/(1-p)] + [W(1 - (2p)^m)/(1-2p)]]} \quad (21)$$

$$q_{k,i} = \frac{\alpha_{k,i}}{N_Q}\overline{T}_{k,i} = \frac{\alpha_{k\,i}\overline{T}_{k,i}}{1 + \big[(W/2)([(2p)^m - 1)/(2p-1)] + [(2p)^m/(1-p)]) + [1/(2(1-p))]\big]\alpha_0(z)|_{z=1}} \quad (25)$$

$$q_0 = \frac{\alpha_{\text{IDLE}}}{N_Q}\overline{T}_{\text{IDLE}} = \frac{1}{1 + \big[(W/2)([((2p)^m - 1)/(2p-1)] + [(2p)^m/(1-p)]) + [1/(2(1-p))]\big]\alpha_0(z)|_{z=1}} \quad (26)$$

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is saturated (probability of being in the queue IDLE is zero). For this value of packet arrival rate and further, (20) is reduced to

$$\tau = \frac{2}{1+(1-p)W\left([((2p)^m-1)/(2p-1)]+[(2p)^m/(1-p)]\right)} \quad (27)$$

which is the same result as that of [4] for the transmission probability in saturation status. According to (21), the packet arrival rate corresponding to the border of saturation (λ^{sat}) is the solution to the following equation

$$1-(1-p)\frac{\lambda^{\text{sat}}T^{v}_{\text{slot}}}{2} \times \left[\frac{1+(2p)^m W}{(1-p)^2}-\frac{p^m+W}{1-p}+\frac{2W(1-(2p)^m)}{1-2p}\right]=0 \quad (28)$$

For packet arrival rates lower than this value (λ^{sat}), the node is not in saturation status; hence there is always a stationary distribution for different number of packets in the MAC buffer.

3.4 Queue length distribution of the MAC buffer

As discussed in Section 3.1, each row of the queueing network corresponds to the state of the MAC buffer. Therefore, knowing the arrival rates at each queue in Fig. 1, it is possible to obtain an expression for the steady-state probability of the MAC buffer length. By assuming q_k as the probability of having k packets in the wireless node (packets in the buffer as well as the packet under transmission) and considering (25) as the steady-state probability of the closed queueing network, it follows that (as shown at the bottom of the page)

The mean number of packets in the wireless node is actually the value of $Q'(z)|_{z=1}$.

3.5 Channel access delay distribution

By knowing the probability of collision per wireless node (p), it is also possible to derive the distribution of channel access delay, that is, the service time of the MAC layer. The total number of slots for successful transmission of a packet, knowing that it has suffered k collisions, is derived as in the following

$$N_D|_k = n_0+n_1+\cdots+n_k \quad (30)$$

where $N_D|_k$ refers to the total number of virtual time slots during channel access delay if the kth transmission is successful, and also n_i refers to the number of virtual time slots during the ith backoff stage. By applying the Z-transform on both sides of (30) and regarding independent n_i's, it follows that

$$E(z^{n_i}) = \sum\nolimits_{k=1}^{W_i}\frac{z^k}{W_i} = \frac{z(1-z^{W_i})}{W_i(1-z)} \Rightarrow N_D(z)|_k = z^k\frac{1-z^{W_0}}{W_0(1-z)}\cdots\frac{1-z^{W_k}}{W_k(1-z)} \quad (31)$$

where W_k denotes the contention window size corresponding to the backoff stage k. For the overall number of virtual time slots during channel access delay (N_D), it follows that

$$N_D(z) = \sum\nolimits_{i=0}^{\infty}(1-p)p^i N_D(z)|_i = \sum\nolimits_{i=0}^{\infty}(1-p)(pz)^i\left[\frac{1-z^{W_0}}{W_0(1-z)}\cdots\frac{1-z^{W_i}}{W_i(1-z)}\right] \quad (32)$$

Now, by knowing the distribution of the number of virtual time slots for successful transmission of a packet, and also knowing the distribution of virtual time slot duration, the channel access delay is resulted as in the following

$$T(s) = P_S e^{-sT_S}+P_C e^{-sT_C}+P_0 e^{-sT_{\text{slot}}} \quad (33)$$

$$D(s) = \sum_{n=0}^{\infty}P(N_D=n)(T(s))^n = N_D(z)|_{z=T(s)} \quad (34)$$

where $T(s)$ and $D(s)$ are Laplace transforms of the virtual time slot duration and the overall channel access delay probability distributions, respectively. As we indicated before, in computing $D(s)$ we include the last virtual time slot, that is, the slot corresponding to successful packet transmission.

4 Extension to the IEEE 802.11e

According to previous discussion about IEEE 802.11e EDCA, it consists of some IEEE 802.11 DCF agents in each wireless node. Each agent has its own parameters including DIFS, minimum contention window size and the maximum number of backoff stages. Each of these agents is called an AC. Here we propose a technique to extend the results of IEEE 802.11 DCF to the case of IEEE 802.11e EDCA.

$$q_{k+1} = \frac{\sum_{i=0}^{m}\alpha_{k,i}\overline{T}_{k,i}}{N_Q} = \frac{\sum_{i=0}^{m}\alpha_{k,i}(2^iW+1/2)}{N_Q} \xrightarrow{Z-\text{Transform}} Q(z)-q_0 = \frac{z\alpha_0(z)\sum_{i=0}^{m}F_i(z)(2^iW+1/2)}{N_Q}$$
$$\Rightarrow Q(z) = \frac{1+z\alpha_0(z)\sum_{i=0}^{m}F_i(z)[(2^iW+1)/2]}{1+[(W/2)([((2p)^m-1)/(2p-1)]+[(2p)^m/(1-p)])+[1/(2(1-p))]]\alpha_0(z)|_{z=1}} \quad (29)$$

Each AC in IEEE 802.11e EDCA can be modelled through the scheme used for IEEE 802.11 DCF, having its own MAC parameters and packet arrival rate. The problem is to derive the probability of transmission for each AC, since they are not independent of each other. For the case of AC with the highest priority, probabilities of transmission and collision in a virtual time slot are the same as IEEE 802.11 DCF. Each node transmits a packet (of all ACs) at each slot with probability τ, computed as in the following

$$\tau = \tau_K + \tau_{k-1}(1-\tau_K) + \cdots + \tau_0(1-\tau_1)\cdots(1-\tau_K) \quad (35)$$

where τ_i is the probability that in a virtual time slot a packet of the ith AC is ready for transmission (i.e. its corresponding backoff counter reaches zero). Moreover, K denotes the number of ACs in a wireless node. Therefore, for the highest priority AC (i.e. the Kth AC according to Section 2.2) the corresponding collision probability (p_K) is computed as in the following

$$p_K = 1-(1-\tau)^{N-1} \quad (36)$$

For the other ACs (i.e. excluding AC with the highest priority) at a wireless node and in a typical virtual time slot, a collision happens whenever a packet from an AC with higher priority at the same node is ready for transmission or when there is another transmission from other nodes (irrespective of their corresponding AC numbers), at the same slot. Thus, for the jth AC it follows that

$$p_j = (1-(1-\tau)^{N-1})(1-\tau_{j+1})\cdots(1-\tau_K) + \tau_{j+1}(1-\tau_{j+2})\cdots(1-\tau_K) + \cdots + \tau_K; \quad 0 \le j \le K-1 \quad (37)$$

where (37) is written with respect to the fact that if backoff counters for two or more packets with different priorities reach zero at the same slot and at the same node, the packet with the higher priority is transmitted and the other packet(s) encounter a virtual collision.

Probability of transmission for each node and each AC is derived by concurrent solution of (35)–(37) and (20) corresponding to each AC. By solving for probability of transmission and collision, other performance metrics corresponding to each AC are derived similar to the methods described for IEEE 802.11 DCF.

5 Numerical results

In this section, we evaluate the desired performance metrics, that is, normalised throughput, channel access delay distribution and buffer length distribution for a single-hop *ad hoc* network based on IEEE 802.11 MAC protocol in basic access mode. In order to confirm our analytical results, we have implemented an event-driven simulator in C++ environment. Moreover, in order to apply some statistical manipulations on the results of the simulation, we employ MATLAB environment. In our simulation, we focus on MAC scheme. To this end, we consider UDP traffic composed of fixed size packets and ignore the physical layer non-idealities, for example, noise and fading. Our simulation environment is considered slotted. We also consider Poisson distribution for the packet arrivals at the MAC layer of each wireless node destined to another wireless node (e.g. access point in a WLAN), equivalent to unicast traffic. A list of parameters exploited in both simulation and analysis is presented in Table 1.

According to (15) and (20), by a concurrent solution for p and τ it is possible to evaluate throughput according to (22). Fig. 2 depicts the results for throughput of the network with a specific window size and two different numbers of nodes both through simulation and analysis. As it is obvious from the figure, for a wide range of packet arrival rate per node, the throughput is a linear function of the packet arrival rate. It is worth noting that the proposed queueing model in this paper is able to evaluate the network throughput for the packet arrival rates up to the border of saturation.

Table 1 Parameters used in numerical analyses

Parameter	Value
Average packet transmission duration, T_{Packet}	8192 μs
Duration of a time slot, T_{slot}	50 μs
Average duration of a successful transmission (same for all ACs), T_S	8928 μs
Average duration of a collision, T_C	8713 μs
The number of ACs, K	2

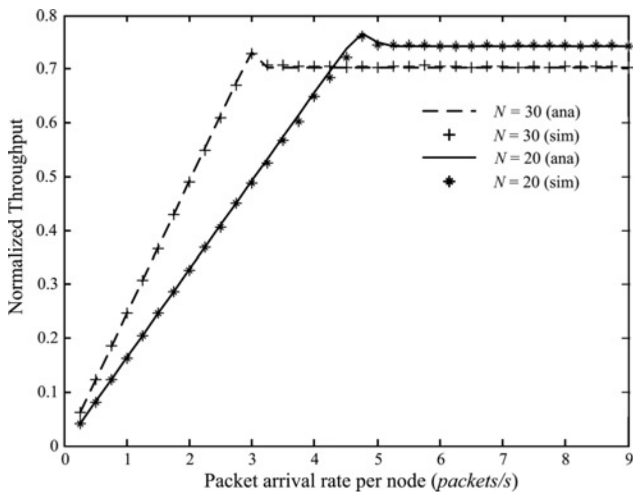

Figure 2 *Throughput of the network as a function of input traffic (CW_{min} = 64, m = 6)*

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Saturation throughput is computed by using (27) similar to [4]. As we observe the simulation results are completely matched with the results of [4] that indicates the accuracy of our simulation. Fig. 3 also represents the variations of the probability of transmission versus the packet arrival rate. At it is observed by increasing the packet arrival rate at the MAC layer of each wireless node the saturation status is obtained. In this case, the probability of transmission remains constant for this rate and beyond.

Based on our discussion in Section 4, in order to have a finite average waiting time in the queue for a new packet arrived in the MAC layer, there would be a limit for the packet arrival rate. This limit is the marginal rate that leads the system into saturation. This rate is resulted by concurrent solution of (15), (20) and (27). Fig. 4 depicts this value of arrival rate as a function of the number of wireless nodes.

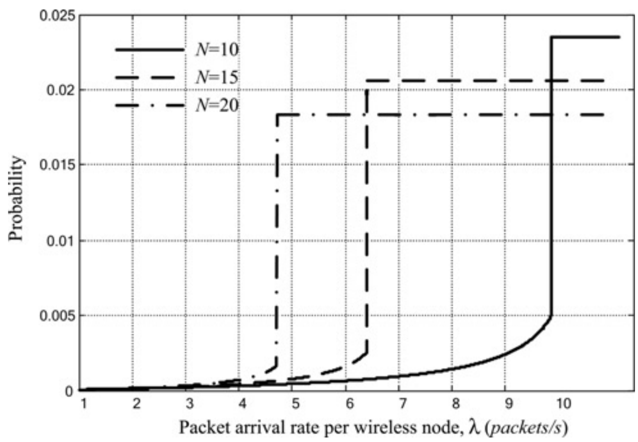

Figure 3 *Probability of transmission in a time slot as a function of input traffic rate (CW_{min} = 64, m = 6)*

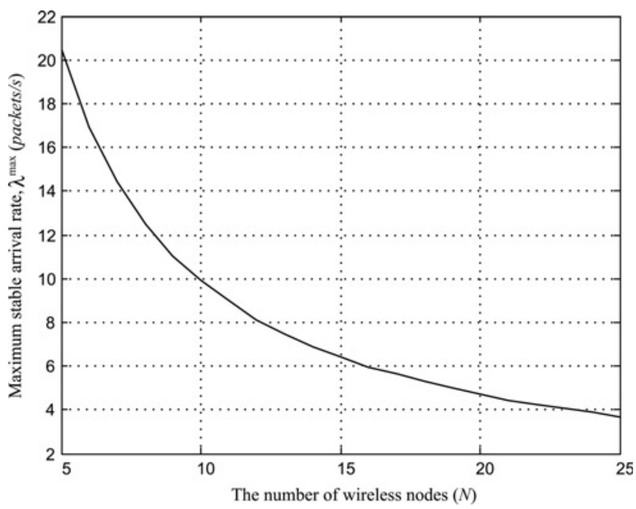

Figure 4 *Maximum input traffic rate per node (λ^{sat}) to yield a finite queueing delay (stable queues) (CW_{min} = 64, m = 6)*

According to the results obtained by (29), the distribution of the packets in the wireless node may be found by the inverse Z-transform of $Q(z)$. Fig. 5 depicts the distribution of the number of packets for two packet arrival rates both through simulation and analysis. As Fig. 5 suggests, there is a small difference between the results predicted by analytical approach to those obtained through simulation. It is worth noting that in our model we observe the MAC buffer status at the beginning of the backoff stages when the node is non-empty. In other words, according to discussions in Section 3.1 the packets arrived into MAC buffer are considered in the routing probabilities among the queues in our model. Since the service time at the queue IDLE and at each of the other queues equal a virtual time slot and a backoff stage, respectively, the packets arrived into MAC buffer and within the service times are not observed in our model until the end of the current service time. Thus, the probabilities q_k in our proposed model do not indicate the MAC buffer status throughout the real times (i.e. continuously). When the network is busier the longer service times occur more frequently and the above difference is more obvious. It is worth mentioning that this does not lead to any problem for channel access delay distribution. In fact, for a typical wireless node, when a packet is in the backoff stage the other packets arrived within the current backoff duration are not sensed until the packet in backoff is successfully transmitted. Therefore, the packets arrived within a backoff stage do not affect on the channel access delay distribution. On the other hand, if a wireless node is empty, that is, the corresponding customer in the equivalent queueing network is in the queue IDLE, packets arrived at that node can affect the status of the other nodes. However, regarding the virtual time slot as the service time of the queue IDLE and the assumption of synchronisation among wireless nodes (see Section 3.1), the packets arrived in the queue IDLE does not also affect the channel access delay distribution in our modelling approach.

According to (29)–(34), the channel access delay distribution is calculated. Fig. 6 depicts the channel access delay distribution for a network consisting of ten nodes.

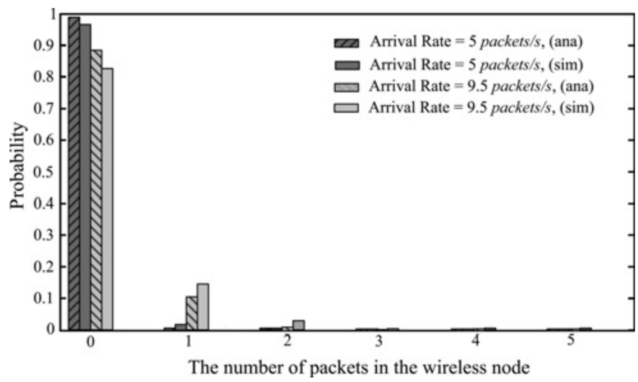

Figure 5 *Distribution of the number of packets in the wireless node for different packet arrival rates (N = 10, CW_{min} = 64, m = 6)*

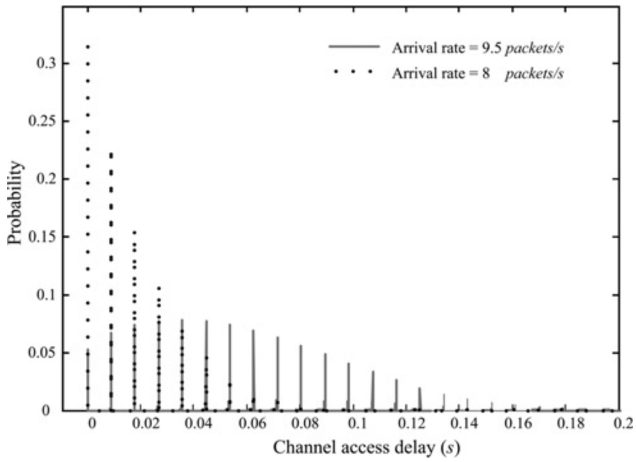

Figure 6 *The channel access delay distribution (i.e. MAC queue service time without packet transmission time) of a node ($CW_{min} = 64$, $m = 6$, $N = 10$)*

From this distribution, we observe that the channel access delay is discrete in nature. Moreover, we are able to compute the mean and variance of the distribution. Hence, regarding a Poisson arrival process for the arrived packets at the MAC layer, each wireless node is modelled as an $M/G/1$ queue. Therefore, by exploiting Pollaczek-Khintchine theorem [15], we are able to obtain the total mean delay (comprising channel access delay and queueing delay) in the network. In Fig. 6, it is easily observed that increasing the packet arrival rate increases both mean and variance of the channel access delay. It is worth noting that in Fig. 6 we have excluded the virtual time slot corresponding to successful packet transmission; thus we have a probability for zero delay.

As discussed above, by a little extension of the results obtained from IEEE 802.11 DCF's model, the performance metrics of IEEE 802.11e may be extracted in a similar way. Fig. 7 represents the maximum allowable packet arrival rate for one category as a function of the packet arrival rate of the other. According to Fig. 7, the allowable range for packet arrival rates exhibits approximately a triangular form, that is, sum of the packet arrival rates of the access categories must be less than a constant value in order to have a finite average delay.

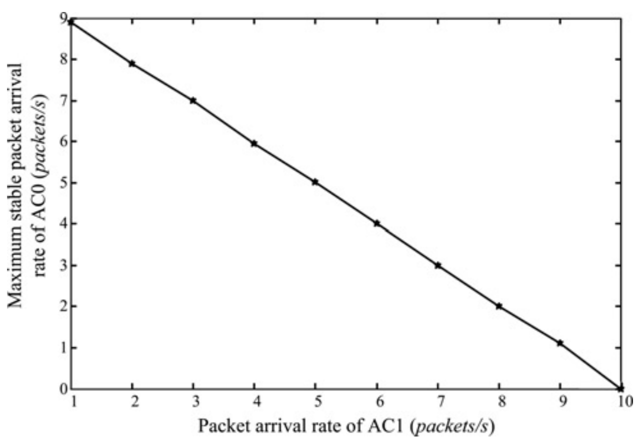

Figure 7 *Maximum packet arrival rate of AC0 versus packet arrival rate of AC1 in order to have stable queues ($CW_{min,1} = 32$, $m_1 = 2$, $CW_{min,0} = 64$, $m_0 = 6$, $N = 10$)*

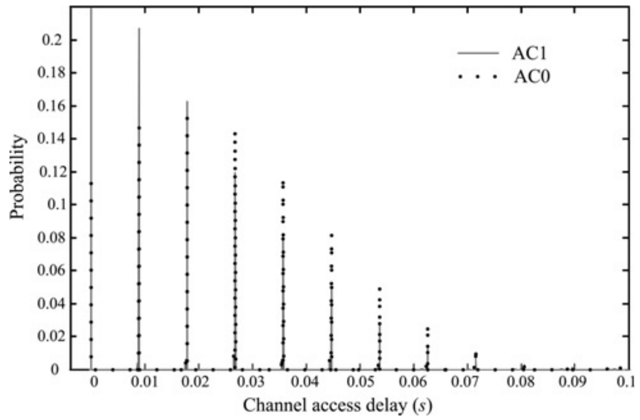

Figure 8 *Channel access delay distribution for AC0 and AC1 ($CW_{min,1} = 32$, $m_1 = 2$, $CW_{min,0} = 64$, $m_0 = 6$, $N = 10$)*

Fig. 8 depicts the channel access delay (excluding packet transmission time similar to Fig. 6) distribution of each AC as a function of the packet arrival rates. Again it is assumed that there is only two ACs and their packet arrival rates equal 5 packets/s. As it is observed, the channel access delay for the higher priority AC (AC1) is concentrated on smaller delays when compared to lower priority AC (AC0). Similar to IEEE 802.11 DCF, each AC can be considered as an $M/G/1$ queueing system when its service time distribution is obtained as in Fig. 8. Therefore, we are able to compute the mean and the distribution of the total delay, comprised of channel access delay and queueing delay.

6 Conclusion

A new modelling approach for performance analysis of IEEE 802.11 DCF and IEEE 802.11e EDCA was presented. This new model was based on BCMP closed queueing networks. According to the new model a thorough performance analysis of the IEEE 802.11 contention-based MAC schemes became possible. Through this new simple and intuitive model, performance metrics such as the throughput, the distribution for the number of packets in MAC buffer and the channel access delay were derived for both IEEE 802.11 DCF and IEEE 802.11e EDCA. Performance measures were discussed both analytically and through simulation and there was an acceptably accurate match between the results of simulation and analytical models.

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