

# A Control-theoretic Modeling Approach for Service Differentiation in Multi-hop Ad-hoc Networks

Yimeng Yang, Boudewijn R. Haverkort, Geert J. Heijenk  
*Design and Analysis of Communication Systems*  
University of Twente, 7500AE, Enschede, The Netherlands  
{y.yang, b.r.h.m.haverkort, geert.heijenk}@utwente.nl

## Abstract

*This paper proposes a control-theoretic modeling approach for service differentiation in multi-hop ad-hoc networks, in which a new priority scheme is applied by considering variable control gains and so-called Transmission Opportunity (TXOP) limits. The model is studied and evaluated based on an IEEE 802.11 DCF WLAN system using the well-known 20-sim dynamic system simulator. The use of the control-theoretical framework, as opposed to an ns-2 simulation, has as advantage that results are obtained much more quickly, and that the model remains much more structured and formalized. By means of the implemented model, the average queue length, queuing delay and network throughput can be evaluated. Simulation results show that our approach is able to satisfy QoS requirements of high-priority stations in both single-hop and multi-hop ad-hoc networks.*

## 1. Introduction

IEEE 802.11 [1] is currently the most deployed wireless Medium Access Control (MAC) technology in many different environments (e.g., office, home, public hotspots/hotzones). IEEE 802.11 based Wireless Local Area Networks (WLANs) are easy to install and can provide convenient and robust network connectivity. The basic 802.11 MAC defines two access functions, namely, the Distributed Coordination Function (DCF), which works as a ‘listen before talk’ scheme based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), and the Point Coordination Function (PCF) providing centrally controlled collision-free and time-bounded services. In this paper we have an interest in WLANs without central control, therefore, only the DCF scheme is considered.

With the growth of interest in wireless networks for multimedia services, the IEEE 802.11e [2] working

group has enhanced the 802.11 MAC DCF by developing a QoS-supporting WLAN standard EDCA (Enhanced Distributed Coordination Access). The 802.11e EDCA WLAN system is composed of a set of QoS enabled mobile stations (QSTAs), and every QSTA has at most 4 queues, one for every Access Category (AC), acting as a Virtual station (VSTA) with its own QoS requirements. The EDCA controls the access to the medium on the basis of VSTAs, and the AC differentiation among VSTAs is achieved by assigning different configurable access parameters. The proper configured access parameters in EDCA will be beneficial to prioritize services with different QoS requirements. However, there are still some difficulties in parameter assignment and adjustment according to current network situation.

Almost all recent work on the performance of wireless networks has been based on analytical modelling approaches or discrete-event simulation results. A simple and fairly accurate mathematical performance model of the 802.11 DCF has been investigated and analyzed in [3] to derive the saturation throughput under single-hop network scenarios. Later, also the priority schemes in 802.11e EDCA were considered in [4, 5]. The improved model [5] predicts not only the throughput but also the transmission delay in both saturated and unsaturated cases; however, the average queuing delay of each VSTA is not taken into account, and the model is still limited to single-hop networks. A stochastic model has been presented in [6, 7] to evaluate the flow-level behaviour of a simple 802.11 two-hop wireless network, but this model is limited in its ability to model more complex network scenarios.

Discrete-event simulations, such as [8, 9], usually consider the network protocols in a more detailed way compared to the analytical models. However, they often do not provide as much insight into the essentials of the behaviour of systems [6]. Besides this, running simulations under certain system parameter settings is

very time-consuming and may encounter some unpredictable errors as well.

In this paper, we introduce a modelling framework for service differentiation in multi-hop ad-hoc network, which relies on concepts from control theory. It extends a centralized feedback control model for resource management [10]. The contribution of our model is presented in a number of aspects:

- A control-theoretic modelling approach is adopted to study service differentiation capabilities in IEEE 802.11-based ad-hoc networks. Models are analysed using the 20-sim analysis tool [11].
- The use of the control-theoretical modelling framework, as opposed to an ns-2 simulation, has as advantage that results are obtained much more quickly, and that the model remains much more structured and formalized. Besides, the model can be easily extended with control algorithms, and enables for using insights from control theory in analysis.
- One of the channel access parameters, TXOP limit, defined in IEEE 802.11e is also considered in our model, thus, experiments can be performed with different *TXOPs* to study proper settings under both saturated and unsaturated traffic load conditions, for both single-hop and multi-hop ad-hoc networks.
- Our model extends current analytical results for a single-hop network to scenarios where packets are forwarded through multiple hops in a single interference domain. In the current paper, results for a 2-hop network are given, but the analysis can easily be extended to more hops, provided the content for the same channel resources. Extension of our model to multiple hops, with each node having its own interference domain, only partially overlapping with those of the other nodes, is subject to further study.
- Finally, compared to existing analytical approaches, our model provides additional performance metrics, such as the queue length at each station.

The rest part of the paper is organized as follows. Section 2 introduces background of IEEE 802.11 DCF. Section 3 describes our control-theoretic modelling method for ad-hoc networks. Section 4 presents our performance criteria, validates the model, and shows simulation results. In Section 5 the paper is concluded.

## 2. IEEE 802.11 DCF operation and differentiation parameters of 802.11e EDCA

In the 802.11 DCF, to reduce the hidden and exposed terminal problem inherent in CSMA, a Request To Send/Clear To Send (RTS/CTS) mechanism is defined as an extension to the basic channel access. When a station has a packet to transmit, it starts to sense the medium. If the channel is idle for a Distributed Inter-Frame Space (DIFS), an RTS frame will be transmitted. After receiving it, the destination station replies with a CTS frame after a Short Inter-Frame Space (SIFS). The data packet can be transmitted after another SIFS only if the RTS/CTS exchange is successful, and an Acknowledgement (ACK) will be sent by the destination as a notification of complete packet reception. All other stations that hear the RTS and/or CTS will update their Network Allocation Vector (NAV) based on the information carried in both RTS and CTS indicating the length of the packet to be transmitted, and refrain from accessing the medium. Alternatively, if the channel is sensed busy, the Collision Avoidance (CA) mechanism is applied in order to reduce collisions among stations sharing the medium by utilizing a random backoff time after an idle period of length DIFS. The duration of this additional backoff is determined as multiple slot times (the slot time size,  $\sigma$ , is set equal to the time needed at any station to detect the transmission of a packet from any other station [3]), uniformly selected in the interval  $(0, CW-1)$ . The value  $CW$  is called Contention Window, which depends on the number of recent failures in transmitting a packet, as follows. For the first transmission trial, the  $CW$  is set to be a minimum value,  $CW_{\min}$ . After each unsuccessful transmission,  $CW$  is doubled until a maximum value  $CW_{\max} = 2^m CW_{\min}$  ( $m$  is defined to be the ‘maximum backoff stage’) is reached. The backoff timer is decremented when the medium is idle, is frozen when the medium is sensed busy again, and is resumed only if the medium has been idle for longer than DIFS. A station gets the chance to transmit when its backoff timer expires, and this backoff process will repeat after the current transmission.

For service differentiation, four configurable access parameters:  $CW_{\min}$ ,  $m$ ,  $AIFS$ , and TXOP limit have been proposed by the 802.11e EDCA. In EDCA, a smaller  $CW_{\min}$  and  $m$  are assigned to the VSTA with a higher priority, so that it gets on average a higher share of the channel capacity, since the high-priority VSTA will on average have a shorter backoff period compared to a lower priority VSTA.  $AIFS_i$  is the duration of time a VSTA  $i$  has to monitor the channel after a successful or unsuccessful packet transmission before stepping into a new round of the backoff process (it replaces the DIFS). If the channel is sensed busy during this  $AIFS_i$  period, the VSTA  $i$  should continue monitoring until the channel is idle for a

complete  $AIFS_i$ . Therefore, a smaller  $AIFS$  is preferred by high-priority VSTAs to start their backoff counting down earlier than those with lower priorities. Besides, the EDCA allows a VSTA to transmit multiple consecutive packets in case of a successful channel access; however, it can not occupy the channel for a period of time longer than the TXOP limit. Thus, different TXOP limits can be adopted by VSTAs belonging to different ACs. In this paper TXOP limit is also considered in our modelling approach to provide service differentiation among stations with different QoS requirements in 802.11 DCF WLAN systems.

### 3. Control-theoretic modeling approach

#### 3.1. Modeling framework

In ad-hoc networks, all the stations with packets to transmit will contend for the channel. To model the behaviour of the channel access mechanism, we adopt a discrete (integer) time scale as depicted in Figure 1. Note that, in fact,  $t$  represents an epoch in discrete time and implicitly, the time interval preceding it. Note that the duration of the time interval preceding  $t$ ,  $TD(t)$ , i.e., the time between  $t-1$  and  $t$ , is not always the same. It is defined as the time for a specific event that happens currently in the network, i.e., a successful transmission, a collision, a backoff slot time counting down (if the CSMA/CA mechanism is applied), or the channel

being idle.

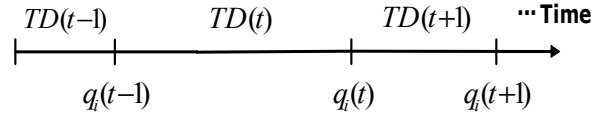
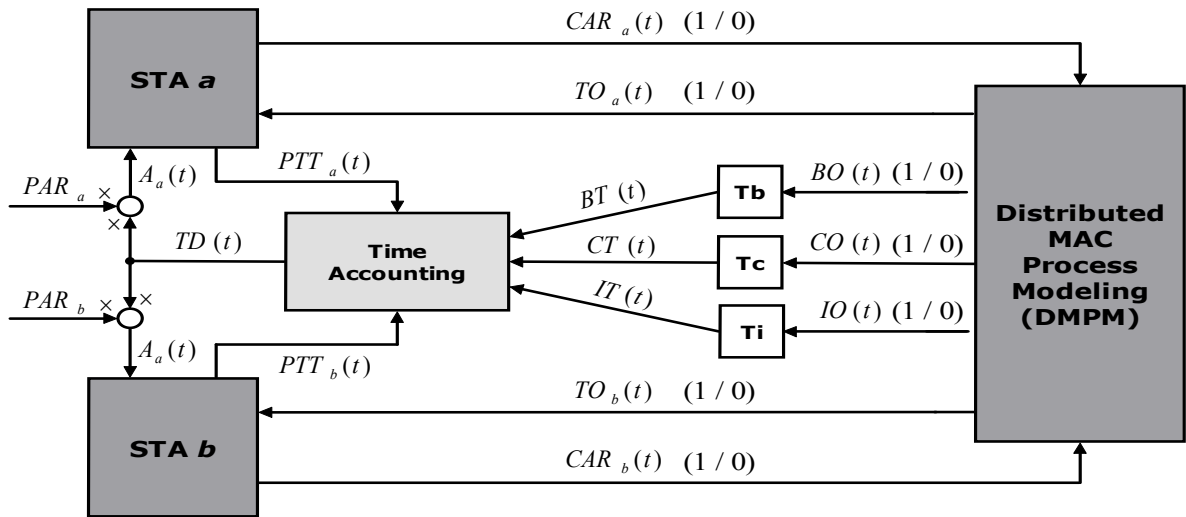


Figure 1. Timing scheme for ad-hoc networks

According to the timing scheme described above, a control-theoretic modelling method for ad-hoc networks is proposed and illustrated in Figure 2. We see that two stations, STA  $a$  and  $b$ , are described in the model, which share the same channel capacity in a distributed manner without any coordination function. For each STA  $i$  ( $i = a, b$ ), its Channel Access Request  $CAR_i(t)$  will be set to 1 (instead of 0), in case STA  $i$  intends to compete for the medium access in the current time interval  $t$  (the CAR generation mechanism will be described in Section 3.2). Based on the requests collected from all the stations within the network, the Distributed MAC Process Modelling (DMPM) module will do the channel arbitration, and activates one of the possible events by setting its corresponding output to 1. The possible outputs of the DMPM module are illustrated in Table 1. The Packet Transmission Time in the current time interval,  $PTT_i(t)$ , will be derived from each STA  $i$ , and the corresponding Backoff Time  $BT(t)$ , Collision Time  $CT(t)$  and Idle Time  $IT(t)$  are expressed as follows:



<b>A</b> - Num. of packets Arrived;	<b>CO</b> - Collision Opportunity;	<b>BT</b> - Backoff time;
<b>PAR</b> - Packet Arrival Rate;	<b>IO</b> - Idle Opportunity;	<b>CT</b> - Collision Time;
<b>CAR</b> - Channel Access Request;	<b>Tb</b> - A backoff slot time;	<b>IT</b> - Idle Time;
<b>TO</b> - Transmission Opportunity;	<b>Tc</b> - Average time of a collision;	<b>PTT</b> - Packet Transmission Time;
<b>BO</b> - Backoff Opportunity;	<b>Ti</b> - An idle time unit;	<b>TD</b> - Time Duration;

Figure 2. The framework of control-theoretic modeling for ad-hoc networks

**Table 1. Output assignment of the DMPM module**

Events\Outputs	$TO_a(t)$	$TO_b(t)$	$BO(t)$	$CO(t)$	$IO(t)$
Success of a	1	0	0	0	0
Success of b	0	1	0	0	0
A Backoff slot time counting down	0	0	1	0	0
Collision between a & b	0	0	0	1	0
Idle medium	0	0	0	0	1

$$\begin{cases} BT(t) = T_b \times BO(t), \\ CT(t) = T_c \times CO(t), \\ IT(t) = T_i \times IO(t), \end{cases} \quad (1)$$

where  $T_b$  is the size of a backoff slot,  $T_c$  is the average time the channel is sensed busy by each station during a collision, and  $T_i$  is an idle time unit allocated to wait for any new coming packets. Finally, the duration of the current interval,  $TD(t)$ , obtained by means of the Time Accounting function block, should coincide with the time spent on the enabled event in  $t$ , and determines the current packet arrivals of each station:

$$A_i(t) = PAR_i \times TD(t), \quad i = a, b, \quad (2)$$

where  $A_i(t)$  is the number of packets that will arrive at STA  $i$  at time  $t$ , and  $PAR_i$  is the constant packet arrival

rate of  $i$ .

In Figure 2, the DMPM describes the distributed MAC behavior of the network, and on the left side, each station generates its new  $CAR_i$  based on the capacity distribution result ( $TO_i$ ) "computed" previously.

The non-linearity of the model makes it difficult to derive the analytical solution using control theory; whether the model can be linearized is a subject for further study.

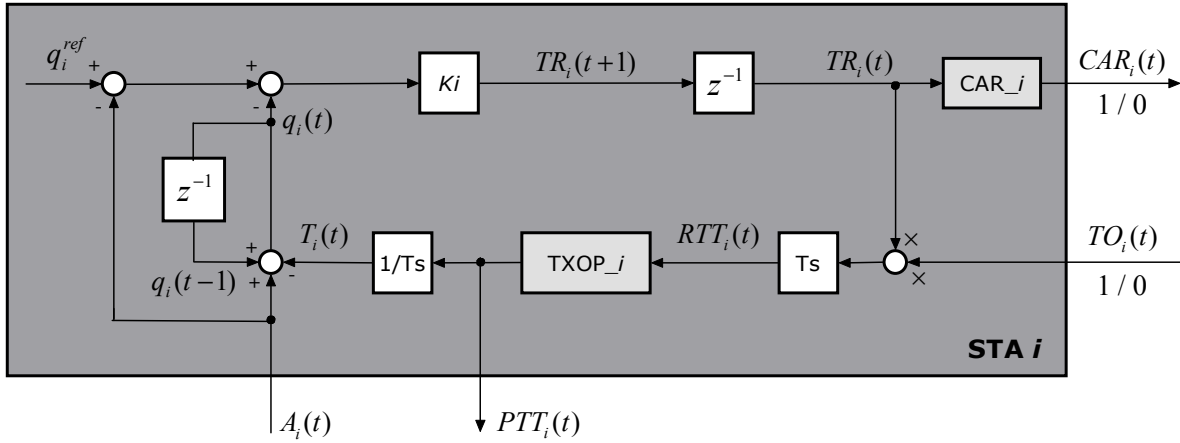
### 3.2. Station modeling

The detail of each station (STA  $i$  in Figure 2) is presented in Figure 3. For STA  $i$ , the queue length at the end of time interval  $t$  is equal to that at the end of the previous interval  $t-1$ , plus the number of packets that arrived and minus those transmitted within  $t$ . This discrete-time linear model can be expressed as:

$$q_i(t) = q_i(t-1) + A_i(t) - T_i(t). \quad (3)$$

In order to empty the queue, a Transmission Request for the following time interval,  $TR_i(t+1)$ , will be initiated, which is determined by the difference between a target and the compensated actual queue length  $q_i(t) + A_i(t)$ , where  $A_i(t)$  is the number of arriving packets during  $t$ :

$$R_i(t+1) = K_i \times |q_i^{ref} - q_i(t) - A_i(t)|, \quad (4)$$



- $q_i^{ref}$  - Reference queue length;
- $q$  - Actual queue length;
- $z^{-1}$  - Delay;
- $T$  - Num. of packets transmitted;
- $K$  - Control gain;
- TR - Transmission Request;
- RTT - Required Transmission Time;
- Ts - Average time of a successful packet transmission;

**Figure 3. The model of STA  $i$**

and where  $q_i^{ref}$  is a constant reference value set as the target queue length of STA  $i$ , and  $K_i$  ( $0 \leq K_i \leq 1$ ) is the control gain. Different values of  $K_i$  can be adopted according to different priorities of stations. For instance, stations with higher QoS requirements need a larger gain to request and transmit more packets per successful channel access. In contrast, the other stations should transmit less than what they have or even give up to request in certain specific network situation. As a result, more capacity and medium access opportunities can be achieved by higher-priority stations.

The transmission request of STA  $i$  in the current interval  $t$ ,  $TR_i(t)$ , has to be judged by a Channel Access Request (CAR) function block, and its output,  $CAR_i(t)$ , can be expressed as:

$$CAR_i(t) = \begin{cases} 1, & TR_i(t) \geq 1, \\ 0, & TR_i(t) < 1, \end{cases} \quad (5)$$

which will be further processed by the DMPM module (as described in Section 3.3). According to the Transmission Opportunity assigned by the DMPM, that is,  $TO_i(t)$ , the Required Transmission Time (RTT) at time  $t$  can then be derived as follow:

$$RTT_i(t) = T_s \times (TR_i(t) \times TO_i(t)), \quad (6)$$

where  $T_s$  is the duration of time for a successful packet transmission. In addition, a TXOP limit,  $TXOP_i$ , is also applied in each station to restrict its capacity occupancy:

$$PTT_i(t) = \begin{cases} RTT_i(t), & RTT_i(t) < TXOP_i, \\ TXOP_i, & RTT_i(t) \geq TXOP_i, \end{cases} \quad (7)$$

where  $PTT_i(t)$  is the packet transmission time that will be accounted by the Time Accounting function block as shown in Figure 2.

### 3.3. IEEE 802.11 DCF modeling

As we have presented in Section 3.1, various distributed MAC mechanisms, e.g., 802.11 DCF, 802.11e EDCA, etc, can be studied by implementing them into the DMPM module. In this section, a simple 802.11 DCF model will be introduced.

The proposed model is illustrated in Figure 4. Based on the channel access requests gathered from all  $M$  stations,  $CAR_i(t)$ , where  $i = (1, \dots, M)$  denotes any station within the network, the number of active stations (whose  $CARs$  are nonzero) in the current interval  $t$ ,  $N(t)$ , can be calculated. In case  $N(t)$  is equal to 0, the output  $IO(t)$  is assigned 1, and then the other outputs will be all zeros ( $nonI(t) = 0$ ), which means that the channel is idle at  $t$ . In contrast ( $nonI(t) = 1$ ), the probabilities of the other three possible events (one

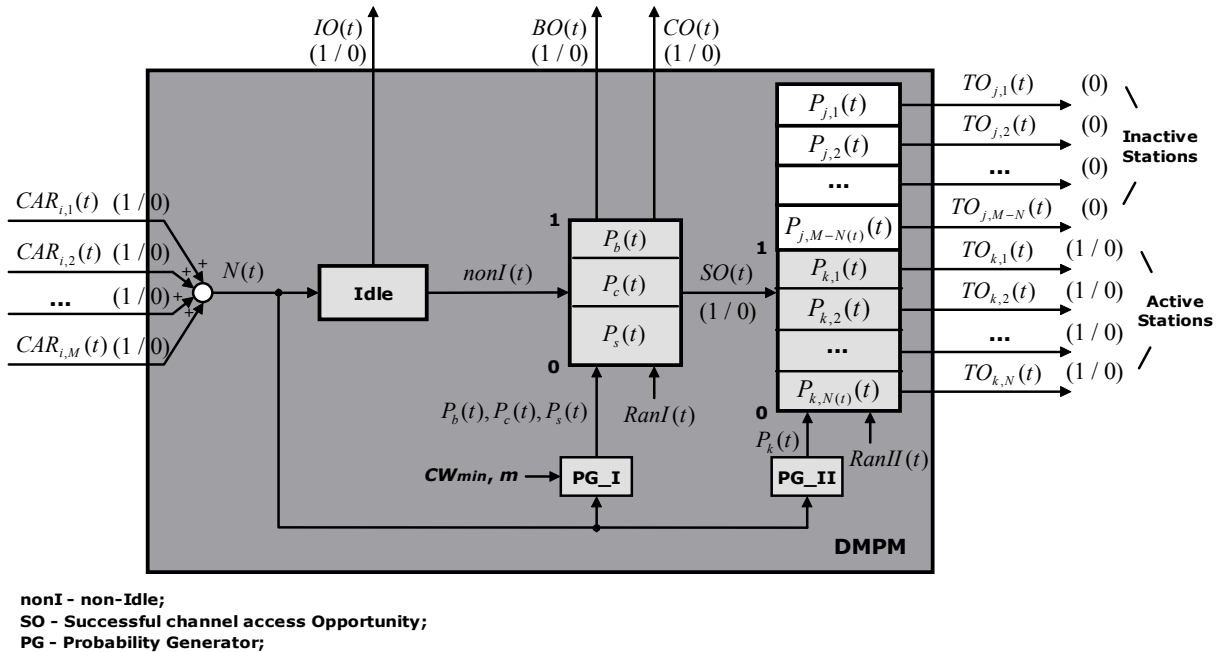


Figure 4. IEEE 802.11 DCF model

empty slot time backoff, collision, and a successful channel contention), expressed by  $P_b(t)$ ,  $P_c(t)$  and  $P_s(t)$  respectively, will be generated based on a look-up table (derived by using the analytical model of Bianchi [3]) kept in the block Probability Generator PG\_I by considering input parameters  $N(t)$ ,  $CW_{\min}$  and  $m$ . A random value,  $RanI(t)$ , will be uniformly selected from the interval  $[0, 1]$  to enable one of these three events, by assigning the corresponding output, i.e.,  $BO(t)$ ,  $CO(t)$  or  $SO(t)$ , to 1.

If there will be a successful channel access at time  $t$ , ( $SO(t) = 1$ ), another random value,  $RanII(t)$ , will be obtained based on the same method as  $RanI(t)$  to decide who wins out of the  $N(t)$  active stations. As a result, the winner's output,  $TO_{k,w}(t)$  ( $k$  denotes any active station with  $CAR(t) = 1$ , and  $w \in [1, N(t)]$ ), is set to 1 instead of 0. Note that all  $N(t)$  active stations should have the same probability,  $P_k(t)$ , calculated by PG\_II to win the channel competition, since there is no priority differentiation defined by 802.11 DCF, that is:

$$P_k(t) = \frac{1}{N(t)}. \quad (8)$$

All other inactive stations, denoted  $j$ , will keep silence at time  $t$ , and all their transmission opportunities  $TO_j(t)$  are set to 0.

To model other distributed MAC processes, e.g., the 802.11e EDCA, using the model by Engelstad et al [5], the PG\_I and PG\_II function blocks can be easily redefined.

## 4. Model validation and performance evaluation

### 4.1. Performance metrics

In order to validate the model, three performance criteria are defined as follows:

1) *Average Queue Length (QL)* denotes the average number of packets remaining in the queue of each station  $i$  in a stable network system, which can be expressed as:

$$QL_i = \frac{\sum_{n=1}^N \overline{q_i(t_n)} \times TD(t_n)}{\sum_{n=1}^N TD(t_n)}, \quad (9)$$

where

$$\overline{q(t_n)} = \frac{q(t_{n-1}) + q(t_n)}{2}, \quad (10)$$

is the average queue length at time epoch  $t_n$ ;  $TD(t_n)$  is the time duration of  $t_n$ , and  $N$  is the number of time intervals simulated. Note that the denominator of equation (9) is just equal to the simulation duration.

2) *Average Queuing Delay (QD)* is used to measure the average time that a packet waits in the queue before its successful packet transmission, which is equal to the average queue length divided by the packet transmission rate, that is:

$$QD_i = \frac{QL_i}{\sum_{n=1}^N T_i(t_n) / \sum_{n=1}^N TD(t_n)}, \quad (11)$$

where  $T_i(t_n)$  is the number of packets transmitted at time epoch  $t_n$ .

3) *Network Throughput (NT)* is used to evaluate the efficiency of the channel capacity utilization, which is normalized as the time used to transmit all the payload information divided by the simulation duration, i.e.,

$$NT = \frac{\sum PD}{\sum_{n=1}^N TD(t_n)}, \quad (12)$$

where  $PD$  is the average duration of a packet payload.

### 4.2. Model validation

Results for the 802.11 DCF model presented in Section 3.3 are obtained using a software tool for modeling and analysis of control systems, called 20-sim. 20-sim allows to simulate specified control systems to obtain performance results. The probabilities for backoff, collision, and successful transmission for the lookup table in PG\_I (Figure 4) are obtained by solving the set of nonlinear equations from Bianchi's model [3] using Maple. Validation of the model as a whole is done by comparing the network throughput obtained with 20-sim with that obtained with the thoroughly validated analytical model of Bianchi, which calculates the network throughput under saturation conditions (the queue of each station is assumed to be always nonempty). We adopt the same assumption by setting all the  $CARs$  to 1, and the parameters used to get numerical results for both the simulation runs and the analytical model are listed in Table 2, which are all derived based on the parameter settings specified in [3]. The RTS/CTS access mechanism is studied and results of the network throughput for the extreme case of as low as 2 and 3 stations with different  $CW_{\min}$  settings are tabulated in

**Table 2. System parameter specification for model validation**

Parameter	Value
$PD$	8184 $\mu s$
$T_b$	50 $\mu s$
$T_c$	417 $\mu s$
$T_s$	9568 $\mu s$

Table 3, where  $n$  is the number of stations within the network,  $CW_{\min}$  is the minimum contention window size and  $m$  denotes the maximum backoff stage, as illustrated in Section 2.

Comparison results show that our 802.11 DCF model is fairly accurate, and the difference between the simulation and analysis is negligible. Note that there are 10000 time intervals ( $N = 10000$ ) simulated for 10 times in each experiment, and all the results in Table 3 are obtained with a 95% confidence interval smaller than 1% of the obtained result (higher accuracy can be obtained when  $n$  is larger).

**Table 3. Network throughput comparison**

RTS/CTS, $m = 3$	Ours 802.11 DCF	Bianchi's
$n = 2, CW_{\min} = 32$	0.818486	0.818905
$n = 2, CW_{\min} = 128$	0.732376	0.731765
$n = 3, CW_{\min} = 32$	0.827561	0.827884
$n = 3, CW_{\min} = 128$	0.767659	0.767257

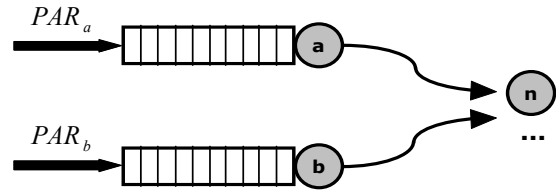
Note that we extend the use of Bianchi's model, which has been developed for a saturated case, to non-saturated cases. We do this by applying a decomposition approach, where we measure the number of active stations in each time interval  $t$ , and consider the system for that number of stations under the saturated condition. The accuracy of this decomposition has been discussed in [7].

### 4.3. Performance evaluation

Based on the validated 802.11 DCF model, the performance of the 802.11 DCF WLAN system with service differentiation and with unsaturated nodes can then be evaluated using the same software package 20-sim. Unless otherwise specified, all the following experiments simulate 30000 time intervals and run 10 times assuming the parameters reported in Table 2.

The corresponding results in different network scenarios are presented below.

**4.3.1. Single-hop network scenario.** A single-hop network scenario is designed to study how to differentiate the QoS between streams. Two stations  $a$  and  $b$  will send their data to some other stations with constant bit rates  $PAR_a, PAR_b$ , respectively, as shown in Figure 5. The system parameters used to evaluate this scenario are listed in Table 4. We aim to drain the queue of each station  $i$  ( $i = a, b$ ) by setting its reference queue length to 0. There are 60 and 30 packets arriving to station  $a$  and  $b$  in every second, respectively. Unsaturated conditions can also be simulated in our model, and  $10\mu s$  (a small value of  $T_i$  is chosen to avoid the waste of channel capacity) will be allocated to wait for any new coming packets when the channel is idle.



**Figure 5. Single-hop network scenario**

**Table 4. System parameter specification under single-hop scenario**

Parameter	Value
$q_i^{ref}$	0
$PAR_a$	60 $pkts / s$
$PAR_b$	30 $pkts / s$
$T_i$	10 $\mu s$
$CW_{\min}$	128
$m$	3

Based on the scenario and system parameter specification, experiments with different system gains  $K_i$  and TXOP limits  $TXOP_i$  are designed to investigate the actual queue length  $q_i$  at the end of each time epoch  $t$ . The simulation results are shown in Figure 6.

Figure 6(a) shows the results of the basic 802.11 DCF by setting the  $TXOP_i$  to  $T_s$ , i.e., only one packet is allowed to be transmitted when station  $i$  gains the channel access opportunity. We see that the network is saturated, and the queue length of STA  $a$  builds up under the specified packet arrival rates. In Figure 6(b), we enlarge the  $TXOP_i$  to 20 times of  $T_s$ , so that in practice no limit is applied to the packet transmission. Results show that the network becomes unsaturated due to the fact that multiple packets can be transmitted



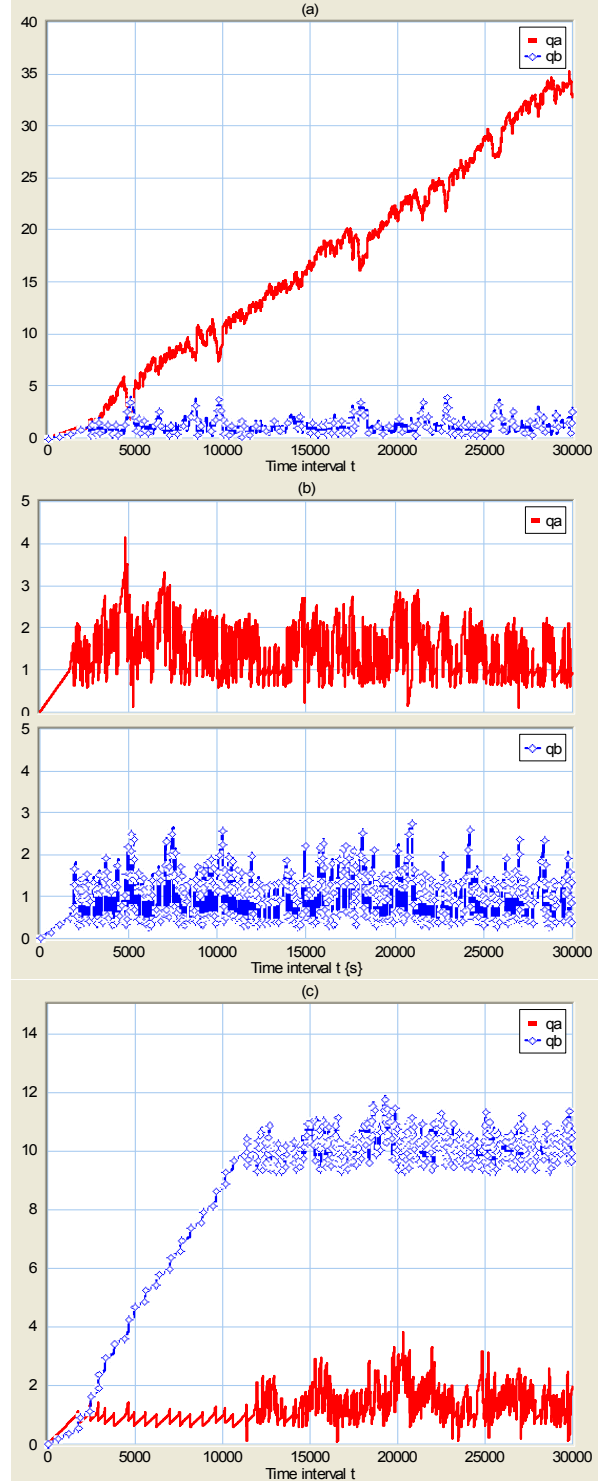
per successful channel contention, and the queue lengths of both STA  $a$  and  $b$  tend to fluctuate but remain bounded and fairly low. More capacity may still be acquired by STA  $a$  with higher packet arrival rate via further decreasing the system gain  $K_b$ , as shown in Figure 6(c). Based on the specified  $K_b$ , STA  $b$  will not attempt to access the channel until its queue length reaches 10, and after that, only 10 percent of the packets in the queue will be requested to transmit in each time interval  $t$ ; as a result,  $q_b$  stabilizes around 10.

The corresponding average queue length, queuing delay and network throughput are presented in Table 5, in which the values of  $QL_i$ ,  $QD_i$  and  $NT$  are obtained with 95% confidence intervals smaller than 7%, 1% and 1.6% of the obtained results, respectively.

**Table 5. Performance comparison on different  $K_i$  and  $TXOP_i$  parameter settings**

	Case (a) $TXOP_i = T_s,$ $K_a = K_b = 1;$	Case (b) $TXOP_i = 20T_s,$ $K_a = K_b = 1;$	Case (c) $TXOP_i = 20T_s,$ $K_a = 1, K_b = 0.1;$
$QL_a$	$\infty$	1.516233	1.494533
$QL_b$	1.352679	1.038317	10.072195
$QD_a$ (s)	$\infty$	0.025332	0.024999
$QD_b$ (s)	0.045283	0.034739	0.354138
$NT$	0.699437	0.734858	0.722057

We see in Figure 6(a) that  $q_a$  is built up as the simulation time is passing by; therefore, the value of  $QL_a$  and  $QD_a$  can be seen as infinity under this saturated network condition. As the TXOP limit is increasing, the network becomes unsaturated. Under the parameter settings  $K_a = K_b = 1$ , the queuing delay of STA  $a$ ,  $QD_a$ , is smaller than that of  $b$ , even if  $QL_a > QL_b$ . That is because a higher  $QL_a$  makes STA  $a$  send more requests than  $b$  for the packet transmission within the same duration of time. Besides, the network throughput is increased in this case due to the fact that bulks of packets can be transmitted instead of only one, in case of a successful channel acquisition. Moreover,  $QL_a$  and  $QD_a$  may be further decreased by choosing a smaller  $K_b$ , whereas, care should be taken in  $QD_b$  that the value has to be acceptable as well. Owing to a larger  $TXOP_i$  adopted in case (b) and (c), the values of the corresponding throughput  $NT$  are increased. However, the  $NT$  in case (c) is slightly lower compared to that in case (b), since a smaller  $K_b$  in (c) results in a



**Figure 6. (a)  $q_i(t)$  obtained with  $TXOP_a = TXOP_b = T_s, K_a = K_b = 1;$   
(b)  $q_i(t)$  obtained with  $TXOP_a = TXOP_b = 20T_s,$   
 $K_a = K_b = 1;$   
(c)  $q_i(t)$  obtained with  $TXOP_a = TXOP_b = 20T_s,$   
 $K_a = 1, K_b = 0.1;$**



larger  $QL_b$  and less packets are allowed to be transmitted by  $b$  per successful channel access.

**4.3.2. Multi-hop network scenario.** In this section, the service differentiation parameter TXOP limit is investigated to improve multi-hop network performance. A simple two-hop network scenario is considered, in which both STA  $a$  and  $b$  have the same packet arrival rate,  $PAR_i$  ( $i = a, b$ ), and a third station  $c$  forwards packets received from both  $a$  and  $b$  towards other stations, as illustrated in Figure 7. Note that station  $c$  has to contend for access to the medium with stations  $a$  and  $b$ . This scenario models the case of a bottleneck station (STA  $c$ ) with higher QoS requirements compared to other stations (STA  $a$  and  $b$ ).

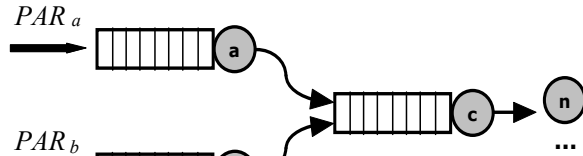


Figure 7. 2-hop network scenario

Table 6. System parameter specification under 2-hop scenario

Parameter	Value
$q_a^{ref}$	0
$q_b^{ref}$	0
$q_c^{ref}$	0
$TXOP_a$	$T_s$
$TXOP_b$	$T_s$
$T_i$	$10 \mu s$
$CW_{min}$	128
$m$	3

The system parameters are specified as shown in Table 6. We give a target queue length 0 to all the stations  $a$ ,  $b$  and  $c$ , and the TXOP limits of the low-priority stations,  $TXOP_a$  and  $TXOP_b$ , are both assigned to be  $T_s$  in order to restrict their packet transmission. The other parameter specification are adopted the same as listed in Table 4.

Experiments are designed to evaluate the average queue length of the bottleneck  $c$  ( $QL_c$ ) by varying its TXOP limit under different traffic load conditions. The simulation results are shown in Figure 8. Note that the  $QL_c$  in the three different traffic load scenarios ( $PAR_i = 20\text{pkts/s}$ ,  $PAR_i = 25\text{pkts/s}$  and  $PAR_i = 50\text{pkts/s}$ ) are obtained with 95% confidence intervals smaller than

5.6%, 7.7% and 7.6% of the obtained results, respectively.

We see that under a relatively light traffic load condition ( $PAR_i = 20\text{pkts/s}$ ), a small TXOP limit  $T_s$  is adoptable by  $c$  due to the fact that the network is unsaturated in this case. However, as the traffic load is increased to  $PAR_i = 25\text{pkts/s}$ ,  $QL_c$  will be built up, which means more capacity is required by the bottleneck station  $c$ . This can be achieved by enlarging its TXOP limit. When  $TXOP_c$  is assigned  $5T_s$ , the  $QL_c$  is below 3, and an even smaller  $QL_c$  can still be obtained by further increasing the  $TXOP_c$  to  $10T_s$ , as shown in Figure 8. Note that  $QL_c$  will never build up to infinity, no matter how large  $PAR_i$  is, since the TXOP limits of STA  $a$  and  $b$  is small ( $TXOP_a = TXOP_b = T_s$ ), so that packet arrivals from both  $a$  and  $b$  to  $c$  are restricted in any case.

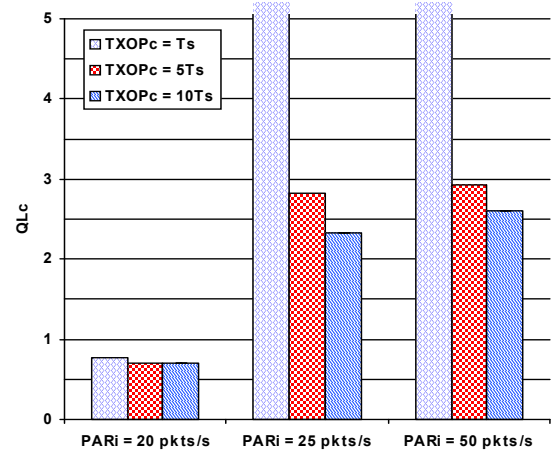


Figure 8. Average queue length in STA  $c$ ,  $QL_c$ , for three traffic scenarios and TXOP limits

Note that with our modeling approach, the CPU usage is about 50% (Intel P4 CPU 3.0GHz), and no more than 3 seconds are used for simulating 30000 time intervals. The CPU time and memory usage (at most 30MB) will be slightly increased when more stations and number of time intervals are simulated, however, the influence is moderate.

The extension from a two-hop to a multi-hop network scenario in a single interference domain is feasible by using our modeling approach. After deciding on the total number of stations within the network, the interconnections between each station and the DMPM module as well as the Time Accounting function block have to be set up. By following this procedure, a variation of network topologies can be easily set up.

## 5. Conclusion and future work

In this paper, a control-theoretic modeling approach has been presented to study service differentiation in multi-hop ad-hoc networks. We have presented a model that can capture the behavior of nodes and the access mechanism in detail. The model, which is used to evaluate the performance of simple single- and multi-hop networks in this paper, can be extended to model more complex multi-hop networks. Using the software package 20-sim, we have implemented the model and evaluated the average queue length, queuing delay and throughput performance of a QoS enabled IEEE 802.11 DCF WLAN system. The formalized control-theoretical framework incorporates well-known analytical results so that performance evaluation results can be obtained in a fast and efficient way compared to an ns-2 simulation, in both saturated and unsaturated network conditions.

Our analysis results show that the QoS requirements of high-priority stations can be satisfied based on tunable control gains and TXOP limits under our specified network scenarios.

In the current paper, the performance of simple network scenarios with static differentiation parameters (i.e., gain and TXOP limit allocation) have been studied. Our future research will focus on dynamically controlling and adapting these parameters in dynamic network environments. Further possible directions of research are investigating other differentiation parameters, modeling more complex ad-hoc networks, testing and adapting the model by considering the wireless nature of the medium (e.g., random packet arrivals and losses, fluctuating traffic, etc.), and integrating the centralized and distributed medium access schemes to study the full-scale of the IEEE 802.11(e) protocol. In order to make our models analytically tractable, we will aim at simplification and linearization of the models. Finally, we will try to extend our analysis to the case of a multi-hop network, where each node is contending for channel access with only a subset of the set of nodes, i.e., each node has its own interference domain.

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