Evaluation of QoS Provisioning Capabilities of IEEE 802.11E Wireless LANs

Frank Roijers[1], Hans van den Berg[1,2], Xiang Fan[1,2], and Maria Fleuren[1]

[1] TNO Telecom, Delft, The Netherlands.
[2] Univerisity of Twente, Department of Design and Analysis of Commmuncation Systems, Enschede, The Netherlands.

Abstract. Several studies in literature have investigated the performance of the proposed IEEE 802.11E standard for QoS differentiation in WLAN, but most of them are limited both with respect to the range of the parameter settings and the considered traffic scenarios. The aim of the present study is to systematically investigate (by simulations) the impact of each of the QoS differentiation parameters, under more realistic traffic conditions. In particular, we investigate flow-level performance characteristics (e.g., file transfer times) in the situation that the number of active stations varies dynamically in time.

1 Introduction

A major drawback of existing versions of the IEEE 802.11 WLAN standards, notably the widely used IEEE 802.11B version, is that they are not capable of providing any service guarantees. The most widely deployed IEEE 802.11B MAC protocol, the so-called Distributed Coordination Function (DCF), is a random access scheme based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Current research and standardization efforts are aiming at enhancements of the DCF MAC protocol enabling the support of multi-media applications with stringent QoS requirements. In particular, the Enhanced Distributed Coordination Function (EDCF) of the IEEE 802.11E standard [8], which is currently being finalized, provides several parameters enabling QoS differentiation among the traffic originating from applications with different service characteristics. Existing studies on the QoS provisioning capabilities of IEEE 802.11E are limited both with respect to the range of the parameter settings and the assumptions about the traffic generated by the WLAN stations/users. Therefore, the aim of the present study is to systematically investigate (by extensive simulations) the impact of the QoS differentiation parameters, under more realistic traffic conditions.

Related Literature
For the 802.11B version several analytical models have been developed in order to study the system's saturation throughput as a function of the number of (persistently) active stations. The most well-known model is the one developed by

Bianchi [2]. It is based on a Markov chain describing the behavior of a single station attempting to send its packets. Foh and Zuckerman [4] and Litjens et al. [11] investigate the flow-level performance of 802.11B WLAN when the number of active stations varies in time, e.g. due to the random initiation and completion of file transfers. In particular, building on Bianchi's work [2], they obtain accurate approximations for the mean flow transfer delay.

Most performance studies of the QoS-enabled 802.11E WLAN are based on simulation. Relatively few papers present an analytical approach. E.g., [16] propose extensions of the Markov chain analysis presented in [2] for the 802.11B version, in order to capture the impact of variation of the AIFS parameter (one of the EDCF parameters) on the saturation throughputs. Both analytical models yield accurate results. The simulation studies usually consider more general scenarios (sometimes also capturing the impact of higher layer protocols like TCP), but a systematic study of the impact of each of the EDCF parameters on WLAN performance is lacking. In particular, [3, 6, 10, 12] compare the 802.11B version with the 802.11E version, but only for the default parameter settings; other papers (e.g., [1, 5, 9, 15]) consider a broader range of parameter values but only for some of the QoS differentiation parameters. Most of the studies mentioned above assume a fixed number of persistently active stations. In some cases (see e.g., [1, 3, 5, 6]) the impact of adding one or two additional (persistently active) stations is studied by plotting the throughputs as function of the time. However, flow-level performance studies, which take into account that the number of active stations varies dynamically in time, are not available.

Contribution

Our first contribution is a systematic evaluation of the IEEE 802.11E QoS differentiation parameters (EDCF parameters) CW_{min},CW_{max}, AIFS and the TXOP_{limit} in the situation with persistently active stations. The impact of the parameter setting is studied by simulations of a WLAN scenario with two different service classes. The main performance metrics that are investigated are the throughputs per service class and their ratio.

Our second contribution is a thorough investigation of the EDCF's capabilities to provide QoS guarantees in a (more realistic) scenario with a dynamically varying number of active stations. We consider three different service classes: voice, video and (TCP controled) data traffic. The main performance metrics, studied by simulation, are packet loss, packet delay (particularly important for voice) and data flow (file) transfer time.

Outline

The remaining of this paper is organized as follows. In Section 2 the main principles of the 802.11E MAC protocol and its mechanisms to provide QoS differentiation are explained. In Section 3.2 the simulation scenarios are described both for the packet level study (assuming persistently active stations) and the flow level study. In Section 4 the results of the simulation studies are presented and discussed. Section 5 concludes this paper.

2 IEEE 802.11E QoS Enhanced Wireless LAN

In this section we briefly explain the IEEE 802.11B Distributed Coordination Function (DCF) and its enhancements as specified in IEEE 802.11E ([8]) in order to support QoS differentiation. We concentrate here on the so-called BASIC mode of the DCF which we considered in our performance study.

2.1 IEEE 802.11B Distributed Coordination Function

In BASIC access scheme, when a station wants to transmit a data packet, it first senses the medium to determine whether or not the channel is already in use by another station (*physical carrier sensing*). If the channel is sensed idle for a contiguous period of time called DIFS (Distributed InterFrame Space), the considered station transmits its packet. In case the channel is sensed busy, the station must wait until it becomes idle again and subsequently remains idle for a DIFS period, after which it has to wait another randomly sampled number of time slots before it is permitted to transmit its data packet. This *backoff* period is sampled from a discrete uniform distribution on $\{0, \cdots, \mathrm{CW}_r - 1\}$, with CW_r the contention after r failed packet transfer attempts (CW_0 is the initial contention window size). The backoff counter is decremented from its initially sampled value until the packet is transferred when the counter reaches zero, unless it is temporarily 'frozen' in case the channel is sensed busy before the backoff counter reaches zero. In the latter case the station continues decrementing its backoff counter once the medium is sensed idle for at least a DIFS period.

If the destination station successfully captures the transmitted data packet, it responds by sending an ACK (ACKnowledgment) after a SIFS (Short InterFrame Space) time period. If the source station fails to receive the ACK within a predefined time-out period, the contention window size is doubled unless it has reached its maximum window size CW_{max}, upon which the data packet transfer is reattempted. The total number of transmission attempts is limited to r_{max}. Once the data packet is successfully transferred, the contention window size is reset to CW_0 and the entire procedure is repeated for subsequent data packets.

A station has a finite size InterFace Queue (IFQ) where IP packets, which arrive from higher OSI-layers, have to wait for their turn to content for the medium. IP packets that find the IFQ full upon arrival will be dropped.

2.2 IEEE 802.11E Enhanced Distributed Coordination Function

An 802.11E station (QSTA) deploys multiple Traffic Categories (TCs); traffic is mapped into a particular TC according to its service requirements. Each TC contents, independently of the other TCs, for the medium using the CSMA/CA mechanism decribed in Section 2.1 according to its own set of EDCF parameters values. These EDCF parameters are CW_{min}, CW_{max}, AIFS and the TXOP_{limit}.

The parameters CW_{min} and CW_{max} have the same functionality as in the DCF. The parameter AIFS (Arbitrary InterFrame Space) differentiates the time that each TC has to wait before it is allowed to start contending after the medium has become free. An AIFS is at least a DIFS period possibly extended by a discrete number of time slots. The TXOP_{limit} (TRansmittion OPportunity limit) is the duration of time that a TC may send after it has won the contention, so it may send multiple packets within a TXOP_{limit}.

The backoff counters of the TCs of a particular station can reach zero at the same moment, a so-called *virtual collision*. The highest priority TC may actually put its packets on the medium, the lower priority TCs react as if they experienced a collision, so they have to double their contention window CW_r and start a new contention for the medium, however the parameter r counting the number of attempts is not increased.

3 Description of the Simulation Scenarios

3.1 System Model

We consider a single Basic Service Set (BSS) with stations contending for a shared radio access medium with a channel rate of $r_{\text{WLAN}} = \{1, 11\}$ Mbit/s. The physical layer preamble is always transmitted at 1 Mbit/s and the rate of the MAC layer preambles is $\{1, 2\}$ Mbit/s. All stations are assumed to have comparable radio conditions so that a uniform channel rate can be assumed. Only the BASIC-access mode is considered in the simulations.

The simulations are performed using the Network Simulator NS-2 [13] extended by the EDCF implementation of the TKN Group of the Technical University of Berlin [14]. This implementation contains the differentiation parameters explained in the previous section. Packet capture, which is the possibility that a packet with a strong signal may survive a collision, is turned of in this study.

3.2 Traffic Scenarios

EDCF performance is studied for two main traffic scenarios. In Scenario 1, the impact of the EDCF QoS differentiation parameters is studied assuming persistently active traffic sources (stations). In Scenario 2, the QoS differentiation capabilities of EDCF in the case of non-persistent traffic sources (i.e., a dynamically varying number of active stations) are investigated.

Scenario 1: Persistent Traffic Sources
In Scenario 1 the number of active stations remains fixed during a single simulation. Each station generates traffic in the upstream direction and is assumed to always have traffic available for transmission. The traffic consists of 1500 Byte IP/UDP packets and all data and headers are transmitted at 1 Mbit/s.

We consider two TCs with different 802.11E parameter settings, a high priority class TC_0 and a lower priority class TC_1. In each scenario only the 802.11E parameter under investigation is varied, the other parameters are set according to their 802.11B equivalents. The investigated parameter settings are (802.11B values are denoted in boldface): $\text{CW}_{min} = \{7, 15, \mathbf{31}, 63\}$, $\text{CW}_{max} = \{31, 63, 127, \mathbf{1023}\}$, $\text{AIFS} = \{\mathbf{0}, 1, 2, 5\}$ and $\text{TXOP}_{limit} = \{\mathbf{0}, 0.03, 0.06, 0.1\}$ sec.

Two series of experiments are performed: (i) experiments where the total number of active stations is increased in subsequent simulations, while the mix of active TC_0 and TC_1 stations remains equal (50%-50%), and (ii) experiments where the number of active stations for one of the TCs is increased in subsequent simulations. In both cases the saturation throughput per station of each Traffic Categorie is determined and compared.

Scenario 2: Dynamic User Scenario (Non-Persistent Traffic Sources)
In Scenario 2, the number of active stations varies dynamically during a simulation due to e.g., the initiation and completion of speech calls or web page downloads. Three different Traffic Categories are considered corresponding with Voice over IP (VoIP, an interactive service), Video-on-Demand (VoD, a streaming service) and Web Browsing (an elastic data service). For each of these services we will consider below the main characteristics and modeling assumptions made in our simulations; specific modeling assumptions are summarized in Table 1.

VoIP is a real-time, interactive service and requires the end-to-end delay to be less than 150 ms. Besides the delay also the packet loss is constrained; it should be less than a few percent. In the simulations new VoIP calls are initiated according to a Poisson process and a VoIP-call is modeled by two UDP CBR streams (80 Kbit/s each).

VoD traffic is sent at a fixed rate from a video server to a user. The most important QoS-constrained for streaming video is packet loss as video-codecs are very sensitive to loss. Packet delays are less important. In the simulations a VoD traffic stream is modeled by a UDP CBR packet stream (480 Kbit/s). The VoD calls are generated by a fixed number of users; the time between the completion of a VoD call and the initiation of a new call by a particular user is exponentially distributed.

Web-Browsing is controlled by TCP. The most important QoS metric for this application type is the web page download time or, closely related, the throughput during a web page download. In the simulations web page downloads are

VOICE OVER IP		VIDEO-ON-DEMAND		WEB-BROWSING	
Flow level parameters					
Transport prot.	UDP	Transp. prot.	UDP	Transp. prot.	TCP
Downstream	CBR	Downstream	CBR	Downstream	TCP data
Upstream	CBR	Upstream	-	Upstream	TCP ACKs
Arrival process	Pois. Proc.	Arr. process	ON-OFF	Arr. process	Poiss. Proc.
ON-time distr.	exp.	ON-time distr.	exp.	file size distr.	exp.
avg ON-time	180 sec	avg ON-time	300 sec	avg file size	15 KBytes
Arrival rate	1/60	OFF-time distr	exp.	Arrival rate	4
		ON-OFF ratio	1 : 4		
Packet level parameters					
IP packet size	200 Bytes	IP packet size	1500 Bytes	IP packet size	1500 Bytes
bit rate	80 Kbit/s	bit rate	480 Kbit/s		

Table 1. Service Classes.

initiated according to a Poisson process. Web pages are retrieved from a web server that is connected to the AP by a fixed link with a certain capacity and transmission delay. The capacity is chosen such that it is not a bottleneck and no packets will be lost.

In Scenario 2 the WLAN operates at 11 Mbit/s. Starting with a certain mix of offered traffic (determined by the default parameter settings shown in Table 1) we study the effects of increasing the traffic load due to one service class, while the traffic load due to the other service classes remains unchanged. The performance metrics of interest are packet loss, packet delay and delay jitter and the mean web page download time; because of lack of space we will omit in this paper the performance results for the VoD and WB service classes. In the simulations, the total number of users simultaneously present in the system is at most 50 as new users are blocked when already 50 users are present.

4 Numerical Results

4.1 Scenario 1: Persistent Traffic Sources

This section presents the results of the Persistent Traffic Sources scenario described in Section 3.2. Due to space limitations within this paper, we will present here only the conclusions of this study.

The simulations results show the impact of the four QoS differentiation parameters. Each parameter can provide differentiation for a Traffic Categorie and each parameter has its own qualities and a system load where it performs best. Distinguishing three criteria listed below, we can summarize the results of our study as given in Table 3, distinguishing between the effects for a high and a lower number of stations present.

– Differentiating capability: ability to give preference to one Traffic Category over the other.
– Fairness: ability to share the capacity among the TCs as intended, according to an a-priori defined ratio independent of the number of active users.
– Efficiency: ability to achieve a high aggregate throughput.

WLAN PHYSICAL		WLAN MAC		FIXED NETWORK	
data rate	11 Mbits/s	MAC overhead	224 bits	delay	10 ms
basic rate	2 Mbits/s	r_{max}	3	capacity	100 Mbit/s
SIFS	10 μs	IFQ length	50 packets	TCP/UDP	
DIFS	50 μs	max # STAs	50	TCP header	20 Bytes
EIFS	304 μs			TCP receiver W_{max}	20 packets
PHY header	48 μs			UDP header	20 packets
PLCP header	144 μs			IP	
Time slot	20 μs			IP header	20 Bytes

Table 2. System and traffic model parameter settings, based on the DSSS PHY layer.

	DIFFERENTIATION		FAIRNESS		CAPACITY	
NUMBER OF STATIONS	LOW	HIGH	LOW	HIGH	LOW	HIGH
CW_{min}	++	+	−	++	0	−
CW_{max}	0	++	+	−−	0	−−
AIFS	+	++	0	−	0	++
$TXOP_{limit}$	+	+	++	++	+	++

Table 3. Qualitative assessment of the EDCF differentiating parameters.

The results of our study indicate how the QoS parameters can be applied to meet certain QoS requirements. The $TXOP_{limit}$ has perfect capabilities (cf. Table 3) w.r.t. to all above-mentioned criteria. However, a drawback of setting a large value of $TXOP_{limit}$ is the increase in delay and delay jitter. CW_{min} differentiates well, but for high loads the system capacity decreases. AIFS and CW_{max} both differentiate very well and become even more effective in situations with high load; noted that CW_{max} is only used in situations with many retransmissions.

Thus, the 'optimal' choice of the QoS differentiation parameters settings depend on the specific objectives of the operator; e.g. VoIP protection (because of its high delay sensitivity) or some guaranteed througput for Web Browsers of protection of low priority of an operator.

4.2 Scenario 2: Dynamic User Scenario (Non-Persistent Traffic)

This section presents the results of the flow level simulations decribed in Section 3.2 and Table 1. The load of 0.17 corresponds to traffic settings of Table 1, which corresponds to an average of 3 VoIP, 2 VoD and 12 WB users. The load is varied by varying the arrival rate of only VoIP. Note that although a 'net' load of 0.17 seems to be light traffic, in fact it is already heavy traffic and the 'gross' load is close to 1. VoIP users have a high gross load caused by inefficient channel usage due to their small packet size. A high number of users also results in a decrease of the channel capacity, so the gross load per user increases.

Performance of 802.11B First the results of the dynamic scenario over an IEEE 802.11B DCF are presented, so all service classes have the same priority. The left graph of Figure 1 shows that the downstream direction performance metrics are worse than for the upstream direction for all loads. Already for load 0.15 all three downstream performance metrics are above the QoS targets. The downstream direction performs worse as the majority of all traffic is sent downstream via the AP to the stations. The AP becomes the bottleneck, queueing occurs at its IFQ resulting in larger delays and possibly into packet losses.

The right graph shows the transfer times of Web Browsers for the same scenario. An increase of the load results in a higher number of VoIP users in the system and WB users' TCP will adapt to the lower remaining available capacity.

Performance of 802.11E (Without Use of $TXOP_{limit}$) IEEE 802.11E EDCF differentiates the service classes by mapping them into different Traffic Categories. VoIP, VoD and WB are mapped into the highest, second highest and lowest prior-

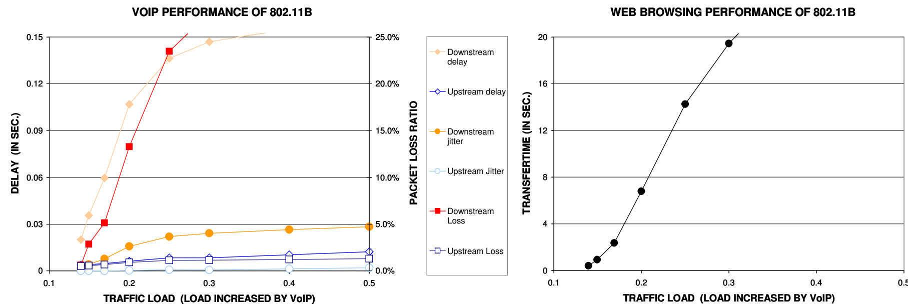

Fig. 1. VoIP and WB performance of 802.11B , load increased by VoIP traffic.

ity class respectively. The values of the differentiation parameters per TC, whose differentiating capabilities are mainly determined by relative differences in their values (e.g. see Section 4.1), are set according to Table 4 (left). To provide high priority for VoIP all parameters have low values. Low CW_{min} provides fast contention and fast retransmissions after a collision in order to fulfill the delay constraints, AIFS also provide fast contention and CW_{max} provide fast retransmissions. The EDCF parameters for WB are chosen equally to 802.11B (except for AIFS) and the VoD parameters are set in between the other Traffic Categories.

Figure 2 illustrates that the downstream packet loss improved tremendously compared to 802.11B (note that the scale of the packet loss axis has changed) and for low loads all the performance metrics are within the requirements. For higher loads ($\rho > 0.27$) the downstream packet loss is above 1%, so still the performance of the downstream direction has to be improved.

The right graph shows that although WB traffic has the lowest priority, compared to the DCF it performs slightly better. The performance improvement is caused by a higher aggregate throughput as the EDCF parameter values of the higher priority classes are smaller than the normal 802.11B DCF parameters.

Performance of 802.11E (with Large $TXOP_{limit}$ for Downstream VoIP) The downstream direction is the bottleneck as most of the traffic is sent via the AP and the channel efficiency is low due to the small size of the VoIP packets. To improve the performance of the AP an extra TC is added for downstream VoIP (see Table 4 (right)), so the AP is now allowed to send multiple VoIP packets after its VoIP Traffic Category has won a contention.

	TC_1	TC_2	TC_3
TRAFFIC	VOIP	VOD	WB
CW_{min}	7	15	31
CW_{max}	63	255	1023
AIFS	2	3	4
$TXOP_{limit}$	0	0	0

	TC_0	TC_1	TC_2	TC_3
TRAFFIC	VOIP DOWN	VOIP UP	VOD	WB
CW_{min}	7	7	15	31
CW_{max}	63	63	255	1023
AIFS	2	2	3	4
$TXOP_{limit}$	0.06 sec	0.03 sec	0	0

Table 4. Parameter settings for EDCF TCs. Left: without $TXOP_{limit}$. Right: with $TXOP_{limit}$.

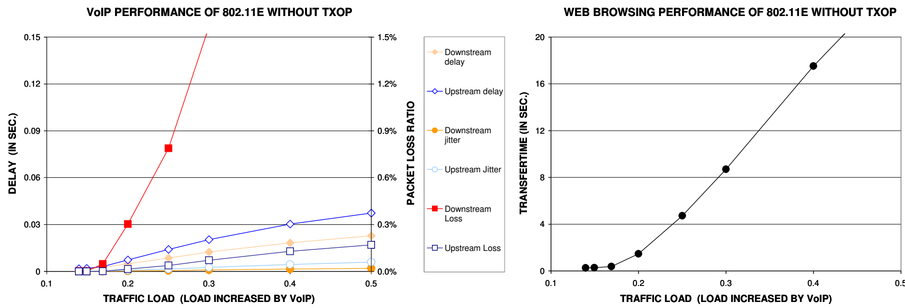

Fig. 2. VoIP and WB performance of 802.11E.

The left graph of Figure 3 illustrates that the downstream packet loss remains the bottneck as the performance is only slightly improved. The small improvement is caused as the AP wins the same amount of contentions, and if it wins, it is allowed to sent multiple VoIP packets, so its buffer is emptied faster. The delay and delay jitter in the upstream direction perform worse than in figure 2 due to the TXOP$_{limit}$, but they are still within the requirements. The performance of WB (right graph) is also similar to the previous scenario. Further improvement of VoIP performance metric packet loss can be obtained by enlarging the TXOP$_{limit}$ (even for all TCs), however this will introduce extra delay and jitter. for all TCs.

Finally, other simulations (not presented due to lack of space) show that the performance of VoIP, as the highest priority TC, is hardly influenced if the load is increased by WB traffic.

5 Concluding Remarks

In this paper we have studied the EDCF mechanism for QoS provisioning in WLAN. First, extensive simulations of scenarios with persistent users illustrate the QoS differentiating capabilities of the EDCF parameters. The impact of the EDCF parameters is not ambiguous and depends on the system characteristics, e.g. the number and types of users. The results are summarized in Table 3.

Second, we haved studied the impact of the EDCF parameters in a scenario with three service types and dynamic arrivals and departures of users. It is shown that the plain 802.11B is not capable of fulfilling service requirements of interactive services. 802.11E improves the performance, however a major drawback is

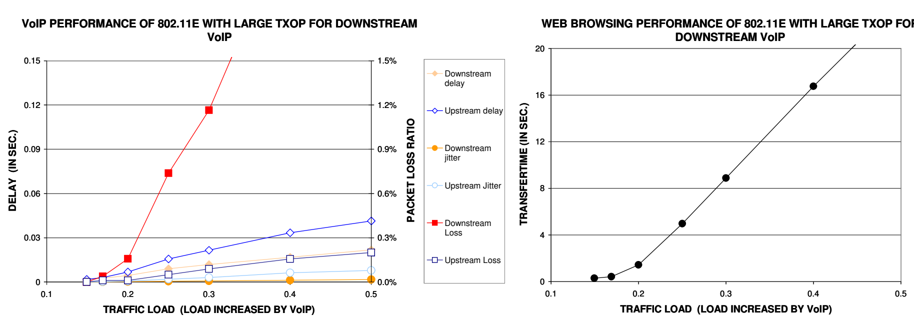

Fig. 3. VoIP and WB performance of 802.11E with large TXOP$_{limit}$ for downstream VoIP.

that the Access Point becomes the bottleneck in the downstream direction. The performance can be improved by implementing extra TCs especially for the AP with preferential treatment.

The EDCF is only capable of providing service differentiation, and not of delivering absolute QoS guarantees. The best approach to attempt to give absolute guarantees is to deploy Call Admission Control (CAC). The results of the present study can be used to determine CAC boundaries on the number of users per type that may be present in the system.

6 Acknowledgements

This work has been partially funded by the Dutch Ministry of Economics Affairs under the program "Technologische Samenwerking ICT-doorbraakprojecten", project TSIT1025 BEYOND 3G.

References

1. I. Aad and C. Castelluccia, Priorities in WLANs, Computer Networks, vol. 41, no. 4, pp 505-526, 2003.
2. G. Bianchi, Performance analysis of the IEEE 802.11 distributed coordination function, IEEE Journal on Selected Areas in Comm., vol. 18, no. 3, pp. 535-547, 2000.
3. S. Choi, J. del Prado, S. Shankar N, S. Mangold, IEEE 802.11E Contention-Based Channel Access (EDCF), ICC 2003, Anchorage AL, USA, 2003.
4. C.H. Foh and M. Zukerman, Performance analysis of the IEEE 802.11 MAC protocol, Proceedings of European Wireless '02, Florence, Italy, 2002.
5. P. Garg, R. Doshi, R. Greene, M. Baker, M. Malek, X. Cheng, Using IEEE 802.11E MAC for QoS over Wireless, Proceedings of the IPCCC 2003, Phoenix, Arizona, 2003.
6. D. He, Ch. Shen, Simulation Study of IEEE 802.11E EDCF, IST Project Moby Dick.
7. IEEE P802.11B/D7.0, Supplement: higher speed physical layer extension in the 2.4 GHz band, 1999.
8. IEEE P802.11E/D3.0, Draft supplement: enhancements for Quality Of Service , 2002.
9. J. Kim and C. Kim, Performance analysis and evaluation of IEEE 802.11E EDCF, Wireless Communications and Mobile Computing 2004, 4:55-74.
10. A. Lindgren, A. Almquist, O. Schelen, Evaluation of Quality of Service Schemes for IEEE 802.11 Wireless LAN, Proceedings of IEEE LCN, pp. 348–351, 2001.
11. R. Litjens, F. Roijers, J. L. van den Berg, R. J. Boucherie and M. J. Fleuren, Performance analysis of wireless LANS: An integrated packet/flow level approach, Proceedings of ITC 18, Berlin, Germany, 2003.
12. S. Mangold, S. Choi, P. May, O. Klein, G. Hiertz and L. Stibor, IEEE 802.11E Wireless LAN for Quality of Service, European Wireless 2002, Florence, Italy, 2002.
13. Network Simulator 2: http://www.isi.edu/nsnam/ns.
14. http://www.tkn.tu-berlin.de/research/802.11e_ns2/.
15. T. Raimondi and M. Davis, Design Rules for a Class-based Differentiatied Service QOS Scheme in IEEE 802.11E Wireless LANs, MSWiM'04, Venice, Italy, 2004.
16. J. Zhao, Z. Guo, Q. Zhang and W. Zhu, Performance study of MAC for service differentiation in IEEE 802.11, Proc. of IEEE GLOBECOM 2002, Taipei, Taiwan, 2002.