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Techniques for Preserving QoS Performance in Contention-Based IEEE 802.11e Networks

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1. Introduction

WLANs are widely adopted worldwide for creating hotspots in university campuses and public or private buildings, mainly because they are easy to install and to use.

The new information and communication technologies should allow users to enjoy current as well as future applications and services in an efficient and effective way, in order to achieve a certain level of user perceived satisfaction. Such applications are mainly based on heterogeneous multimedia flows with different characteristics and requirements. Audio, text, video and voice are the basic components of multimedia flows and they have different needs for efficient delivery.

In order to define the level of degradation of a multimedia traffic traversing a network, such as a movie in streaming modality or a Voice over IP (VoIP) conversation, several Quality of Service (QoS) parameters can be taken into account. These parameters are the throughput, the maximum delay between packet transmission and final delivery (i.e., end-to-end delay), the delay jitter experienced by consecutive packets and the percentage of lost packets in the network, due to network congestion or link corruption.

Furthermore, packets correctly received after their maximum delay requirements must be considered as they were lost, because they are not useful for a satisfactory reconstruction of the flow. Hence, new mechanisms are needed for supporting QoS performance of multimedia flows.

Today, the IEEE 802.11 WLAN standard family represents one of the most widely adopted technologies for delivering different traffics through wireless networks. The diverse requirements of heterogeneous traffics contending the wireless channel heavily affect efficient delivery over WLANs.

In the legacy IEEE 802.11 (IEEE, 1999) standard, QoS support was not envisaged, but new multimedia traffics raised up the need of efficient mechanisms for QoS management; the main answer to this issue is represented by IEEE 802.11e specifications (IEEE, 2005).

IEEE 802.11e allows to improve traffic performance over WLANs (Davcevski & Janevski, 2005 ; Choi et al., 2003), by introducing an enhanced MAC scheme. However, further improvements are still possible in this direction and several modifications have been

proposed in literature to increase the performance and efficiency of the resource allocation mechanisms envisaged by 802.11e (Thottan & Weigle, 2006 ; Nafaa, 2007).

This chapter deals with the MAC contention phase of IEEE 802.11e; in particular, we aim at providing a comprehensive overview on the state of the art about techniques for enhancing performance and for preserving QoS requirements under heavy traffic conditions. Advantages and disadvantages of each technique will be exhaustively described.

In the second section, we provide an overview of the IEEE 802.11e MAC scheme, in order to understand the basics of this technology, with respect to channel access methodologies.

In the third section, we introduce the main research works related to performance enhancement through the manipulation of standard parameters. Many of these works deal with the problem of fair resource allocation in uplink and downlink directions in infra-structured WLANs.

Under heavy traffic conditions, the fairness problem can be faced through a correct dimensioning of parameters, so as to modify the resource allocation ratio between the Access Point (AP) and the wireless stations.

The efficiency increase which can be achieved by adopting the described techniques remains somewhat limited by WLAN resource availability; therefore, beyond certain traffics loads, an admission control algorithm results necessary for preserving QoS performance of existing flows in terms of throughput, delay, jitter and packet loss, and to avoid that the ingress of new flows seriously damages QoS performance of active traffics.

For this reason, the fourth part of this chapter discusses the main admission control algorithms for WLANs, by comparing and classifying the most recent works in this research area. Categorization of admission control schemes will be carried out within three main classes: measurement-based, model-based, and joint measurement and model-based admission control scheme. The main peculiarities of these schemes will be discussed.

Finally, open issues and conclusions are described in section 5 and 6 respectively.

2. The IEEE 802.11e MAC scheme

The original IEEE 802.11 standard handles traffic on a best-effort basis, through the *Distributed Coordination Function* (DCF) MAC scheme. This means that all frames are equally treated and, therefore, DCF is not suitable for managing real-time and interactive multimedia services.

For this reason, an enhancement to DCF has been introduced by 802.11e specifications for QoS deployment. The enhanced MAC scheme, named *Hybrid Coordination Function* (HCF), operates with two access modes (802.11e, 2005):

- *Enhanced Distributed Channel Access* (EDCA), which defines a new contention-based channel access scheme;
- *HCF Controlled Channel Access* (HCCA), which defines a contention-free channel access scheme.

This chapter is limited to describe QoS enhancement which could be achieved through EDCA, since this scheme is mandatory and supported by all 802.11e devices. HCCA is still rarely implemented, since it has a more complex hardware implementation (Banchs et al., 2005).

The basic mechanism of EDCA scheme is based on *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA), where collision avoidance is realized through a random back-off time before transmission. In particular, when a station has frames ready for delivery, it starts contending the channel. After the station successfully detects that the wireless channel has been idle for a certain time interval, it chooses a random back-off time within a Contention Window (CW). Frame transmission can start only if the station detects an idle channel for this additional random amount of time.

EDCA introduces differentiated channel access probabilities to frames contending for channel resources. Four Access Categories (AC) are implemented at each station supporting QoS facilities (QSTA), being it an Access Point (QAP) or a wireless host (Figure 1).

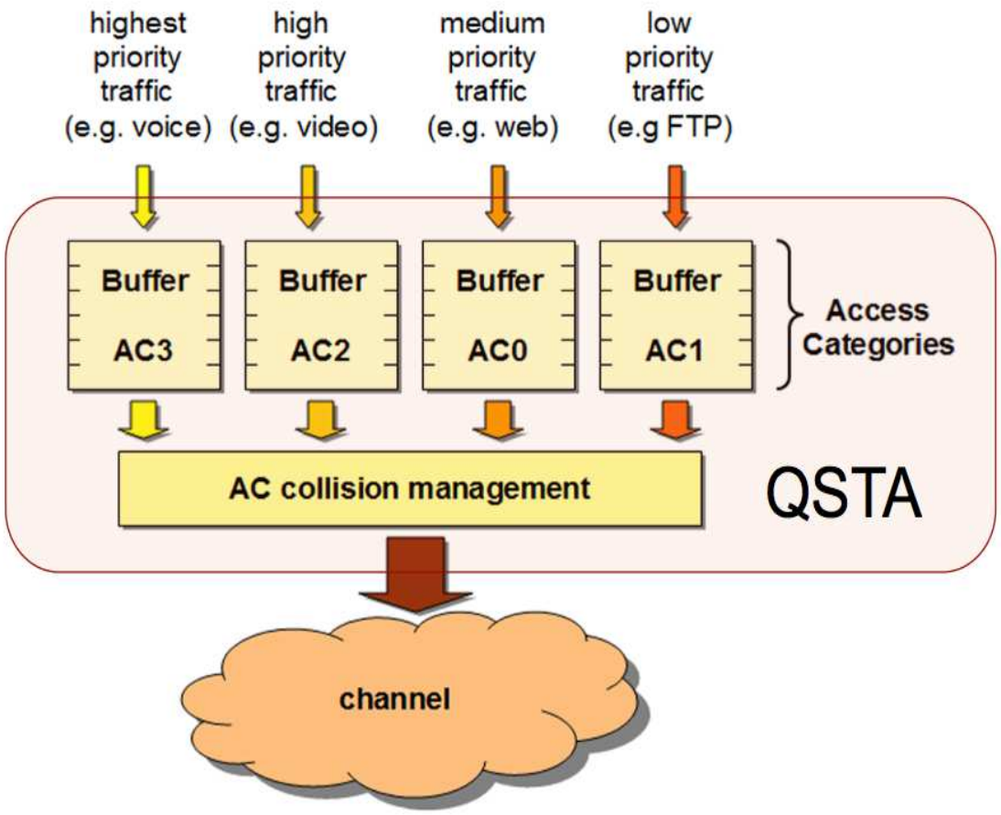


Fig. 1. Internal buffers for frame differentiation inside a QoS enabled station

Prioritization of the different traffics (e.g., voice, video, data) is realized by mapping frames to the proper AC, according to their QoS requirements, and by assigning to each AC an appropriate set of four EDCA parameters (802.11e, 2005). These parameters are used for regulating the channel contention phase and they are periodically broadcasted by the QAP through the beacon frame.

In particular, EDCA parameters are the following:

- *AIFS (Arbitrary Inter-Frame Space)* - this is a waiting time interval, named *AIFS[AC]*, whose duration is different for each AC, so as to take into account its QoS requirements. According to the CSMA/CA scheme, before starting its back-off timer, each station must detect an idle channel for at least *AIFS[AC]*. Actually, the shortest waiting time defined by 802.11e MAC is *Short Inter-Frame Space* (SIFS) and it is adopted for highest priority frames, which are short control messages, such as acknowledgments (ACKs) of data packets. Consequently, the waiting time for data frames belonging to a specific AC, *AIFS[AC]*, must be greater than SIFS and it is calculated as:

$$AIFS[AC] = SIFS + AIFSN[AC] \times SlotTime \quad (1)$$

  where *AIFSN[AC]* is an integer number greater than zero and *SlotTime* depends on the PHY in use (e.g., 20 μs for 802.11b).
- *CWmin* and *CWmax* (Contention Window parameters) - they regulate the minimum and maximum dimension of the random back-off window size. In particular, the window size is firstly initialised at *CWmin*, but after each collision the maximum back-off window size is doubled up, with an upper bound of *CWmax*. The QSTA must randomly choose its random back-off timer, less than or equal to the current value of CW (Figure 2).

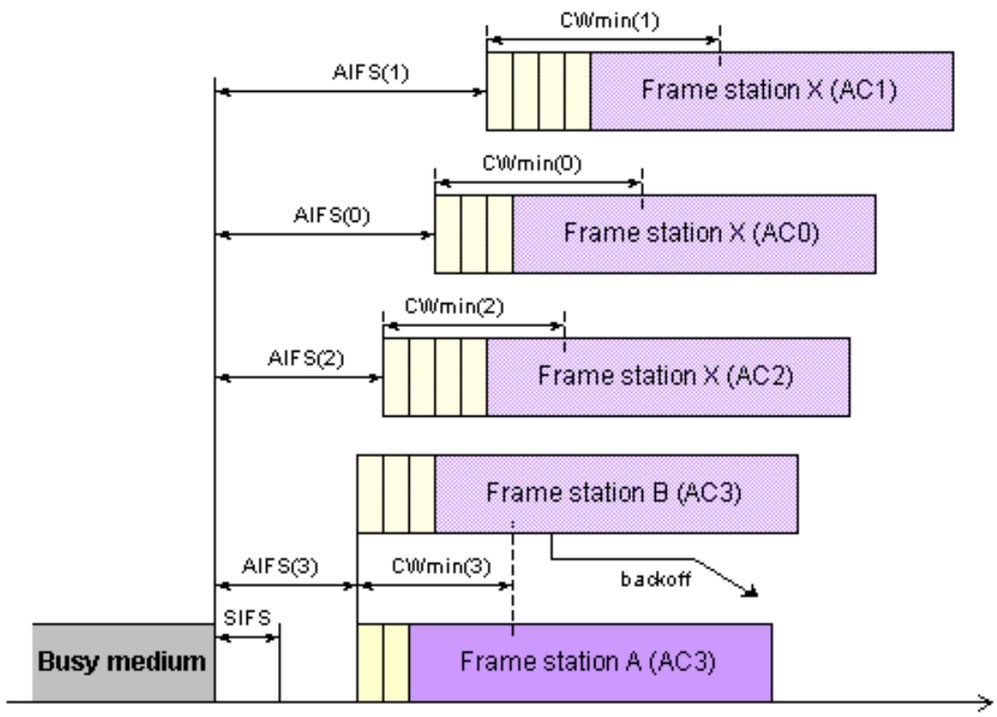


Fig. 2. EDCA contention access scheme

- *TXOPlimit* (*Transmission Opportunity limit*) - when a station wins a channel contention, it can transmit a burst of frames so as to improve MAC efficiency in case of small packets. *TXOPlimit* represents the maximum time interval a station is allowed to use the channel for transmitting a burst of frames, without the need to enter again in channel contention phase. The zero value allows the transmission of a single frame per channel access (Figure 3).

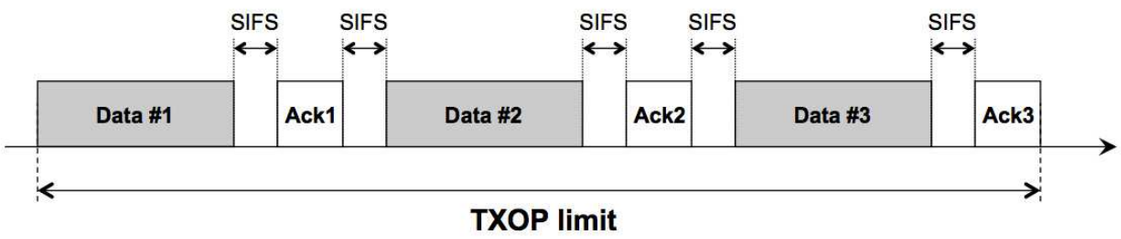


Fig. 3. *TXOPlimit* for the transmission of a burst of frames

Table I reports, for each traffic category, the EDCA parameter values indicated by the standard. VoIP traffic has the highest priority and it is assigned to AC3, video is associated to AC2, best effort (e.g., web packets) corresponds to AC0 and background traffic (e.g., ftp) has the lowest priority and it is mapped into AC1.

Traffic type	AC	Priority	AIFSN	CWmin	CWmax	TXOPlimit
VoIP	AC_VO (AC3)	3	2	7	15	3.264 ms
Video	AC_VI (AC2)	2	2	15	31	6.016 ms
Best effort	AC_BE (AC0)	1	3	31	1023	0
Background	AC_BK (AC1)	0	7	31	1023	0

Table 1. EDCA parameter set indicated in IEEE 802.11e specifications

At the beginning of each beacon interval (usually 100ms), the QAP broadcasts a beacon frame containing control information for QoS management. In particular, the "*EDCA Parameter Set*" element (Figure 4) of the beacon frame is used to send the EDCA QoS parameters to the wireless stations. Specifically, these parameters are contained inside the "*Parameter Record*" field of each AC (802.11e, 2005).

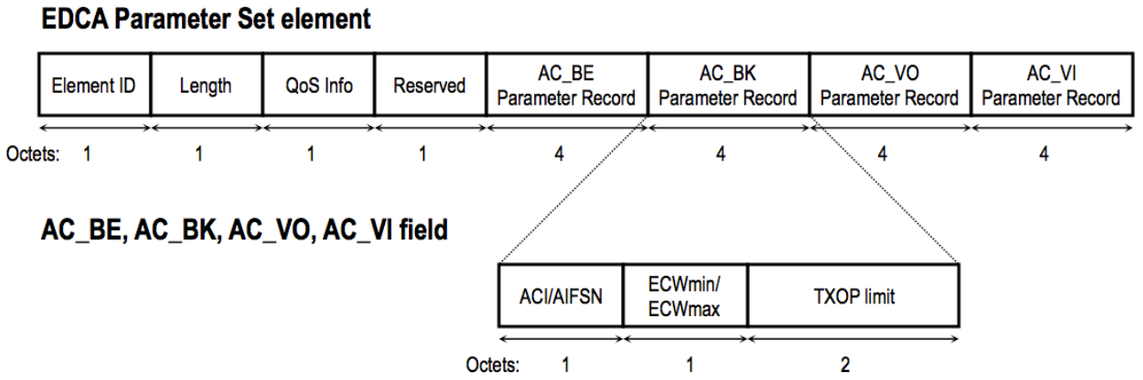


Fig. 4. QoS elements broadcasted by the QAP through the beacon frame

2.1 The fairness issue

Fairness between uplink and downlink channel allocation is a critical issue in infra-structured WLAN managed by a QAP. A QSTA must contend the uplink channel in order to transmit uplink frames towards the QAP. Downlink frames can be generated either by a wired network, i.e. by other stations connected to the Basic Service Set (BSS) through the QAP, or by other QSTAs inside the same BSS; in both cases the QAP acts as a concentrator and it must compete for channel access with all other QSTAs, before transmitting the frame.

In order to better understand the fairness problem, let us consider a WLAN composed by one BSS with n+1 stations, which include n QSTAs and one QAP. Assuming, for simplicity, that all frames have the same length and equal priority, during a certain observing period ΔT, the QAP, as well as each QSTA, gains an average channel time equal to $\Delta T/(n+1)$. In fact, all wireless stations have equal access probabilities, consequently the QAP receives the same treatment of a QSTA, in terms of channel allocation time. Each QSTA has to access the channel only for transmitting its own frames, while the QAP has to relay all downlink flows generated from wireless stations and addressed to other QSTAs. Hence, the QAP is penalized and downlink flows inevitably suffer performance degradation due to unfair channel allocation. In order to avoid this situation, the QAP should be assigned more resources than each wireless station.

In particular, we can consider two cases: a "balanced" and an "un-balanced" traffic scenario.

The balanced scenario is characterized by symmetric traffic conditions (i.e. VoIP conversation or peer-to-peer traffics), and downlink/uplink traffic volumes are similar. A fair allocation would assign to the QAP half of the channel allocation time; on the contrary, the QAP can exploit the channel only for $1/(n+1)$ of the time, for the reasons explained above.

In the un-balanced scenario, the wireless stations are more involved in downlink than in uplink direction; this reflects a common situation, in which the QSTAs are mainly involved in receiving web pages and audio/video streaming or in downloading files, while uplink traffic volume is more modest. Such a scenario would require at the QAP even more resources than those permitted by the EDCA scheme as it is (Grilo & Nunes, 2002).

Such an unfair behaviour increases collision probabilities between downlink frames, and, consequently, besides an inefficient resource allocation, the BSS is characterised by an increase of overhead, due to more back-off entities, and by a reduction of the BSS global throughput.

3. Regulation of EDCA parameters

Even if the EDCA scheme has improved QoS performance of multimedia traffics in WLANs, it is still possible to achieve even better results by suitably acting on its key parameters. In fact, a correct dimensioning of such parameters allows to reduce waiting times due to channel contentions, to achieve higher fairness between downlink/uplink allocation, and to decrease the number of collisions between frames belonging to the same AC and among different ACs.

In the following, we introduce how EDCA parameters can be tuned, so as to push the current 802.11e standard at its maximum performance, and we try to understand the limits beyond which new modifications to the standard algorithms are necessary.

The main advantages and disadvantages of the proposed modifications are also discussed.

3.1 Choice of AIFS duration

Equation (1) shows that the duration of the AIFS time interval for each AC depends on the choice of AIFSN, since slot time and SIFS duration are pre-determined values. There are several reasons which justify a modification of AIFSN with respect to the default values indicated by the standard (Table I). As it has been shown in (Thottan & Weigle, 2006), a reduction of AIFSN only for the ACs at the QAP permits to improve uplink/downlink fairness, because the QAP would be statistically advantaged during channel contention and, consequently, it has higher chances to obtain more channel time than the single QSTAs.

Moreover, a decrease of AIFSN for all stations (i.e., QAP and all QSTAs) leads to a reduction of waiting times and to an increase of WLAN global throughput. However, if AIFSN is reduced under a minimum threshold, several malfunctions could affect the 802.11e MAC.

In particular, when AIFSN is set to zero, from equation (1) we have that AIFS[AC] and SIFS coincide; so, if the random back-off algorithm selects a null CW value for a data frame, a collision can occur between that data frame and a higher priority frame, such as an ACK (Fig. 5).

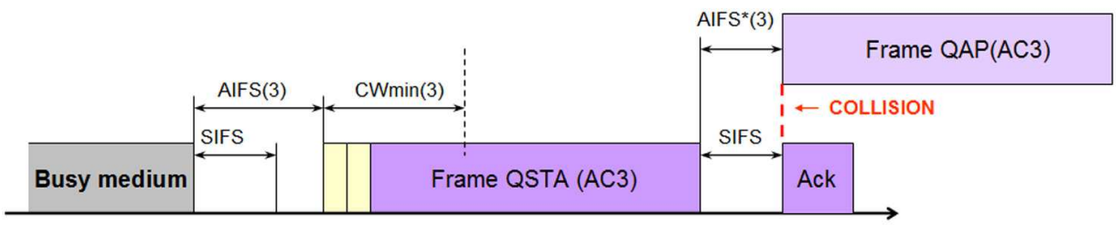


Fig. 5. Different choices of AIFSN, in relation to SIFS waiting time

A second situation, depicted in figure 6, shows the effect of setting AIFS[AC] lower than or equal to PCF Inter-Frame Space (PIFS), where PIFS represents the waiting time before entering in polling mode, as envisaged by HCCA. In such a case, the contention-free channel access mode defined by HCCA could be inhibited by EDCA data frames, and this fact cancels the reason for the existence of HCCA itself.

Moreover, when AIFS[AC] is set too low at the QAP, even if it respects the lower bounds described above, its CW would be dangerously shifted. In particular, it could happen that the AIFS related to an AC at the QAP is equal to or less than the AIFS of a higher priority AC at a QSTA. This fact is shown in figure 7, where AC2 at the QAP has higher transmission probability than AC3 at QSTAs, thus contradicting the original reason for prioritization. From the same figure, it is also evident that, when the AIFS[AC] value of a QSTA is set higher than AIFS[AC]+*CWmin*[AC] at the QAP, the QSTA frames risk starvation.

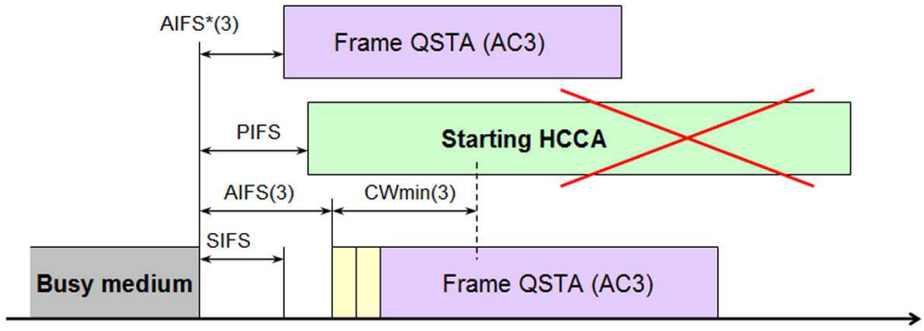


Fig. 6. Different choices of AIFSN, in relation to PIFS waiting time

A less hazardous and more interesting adjustment consists of dynamically increasing AIFSN for those ACs which are not characterised by real-time traffics, such as web or ftp, thus limiting their impact on a loaded network, as also stated in (Thottan & Weigle, 2006). Specifically, the work carried out in (Thottan & Weigle, 2006) investigates the performance of TCP traffic under different settings of EDCA parameters, by gradually adjusting AIFSN related to all the ACs of the QAP. Moreover, *CWmax* of AC1 at the QAP is halved down, in order to give more priority to the AP and to improve upstream/downstream fairness. However, in order to efficiently support QoS, it is better to operate jointly with AIFS duration, CW interval, and buffer sizes of the different ACs.

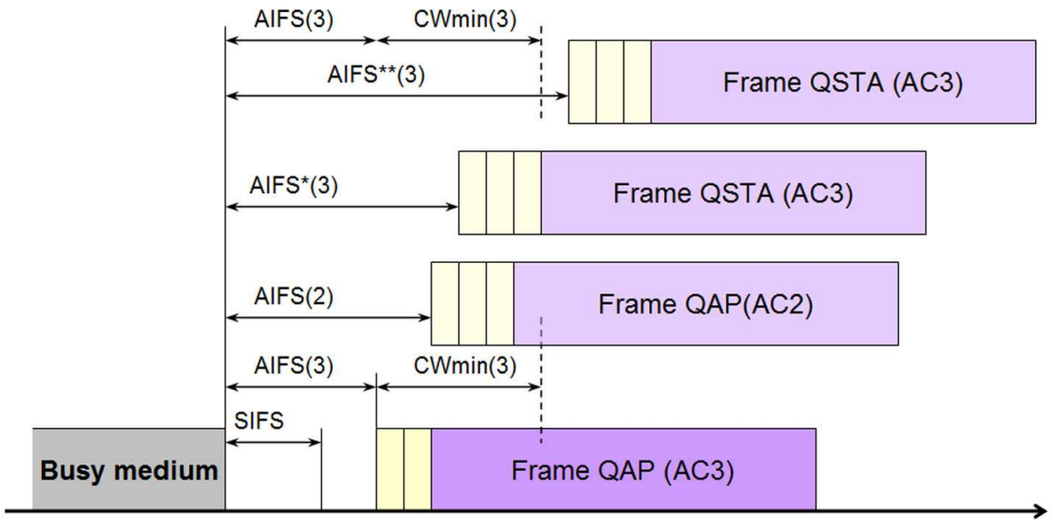


Fig. 7. Setting AIFS duration of different ACs

3.2 Choice of the contention window size

A careful tuning of the contention window parameters *CWmin* and *CWmax* can positively affect uplink/downlink fairness. In presence of light traffic conditions, low values contribute to reduce waiting times and to increase the global throughput. On the contrary, when traffic load becomes intensive, this choice could augment collision probability, because of the reduced number of slots inside a contention window (Nafaa, 2007).

(Wu et al., 2010) defines an *Adaptive Contention Window Adjustment* (ACA) scheme, which dynamically regulates the contention window size of each AC. In particular, it adjusts the CW size for each AC, according to the number of active connections for that specific AC.

Specifically, if the number of competing connections (inside the same AC) grows, the algorithm inflates the CW value, in order to reduce collision probability. On the other hand, if the number of contending stations decreases, it reduces the CW values, so as to limit frame delay.

However, this approach of changing CW size does not produce significant enhancements and, on the contrary, it introduces some drawbacks, such as a higher number of back-off entities. Moreover, an improper reduction of *CWmin* and *CWmax* for an AC at the QAP can result in assigning equal priority to a different AC of another QSTA. This happens when the BSS is characterized by many active stations and the QAP gets low values of CW parameters for improving fairness (fig. 8).

Another possibility envisages a proactive approach, by augmenting the CW size of an AC when the QAP realizes that the number of active traffic sources belonging to that AC is dangerously growing; this approach tries to prevent collisions and consequent performance degradation. This method can be joined with *TXOPlimit* adjustment.

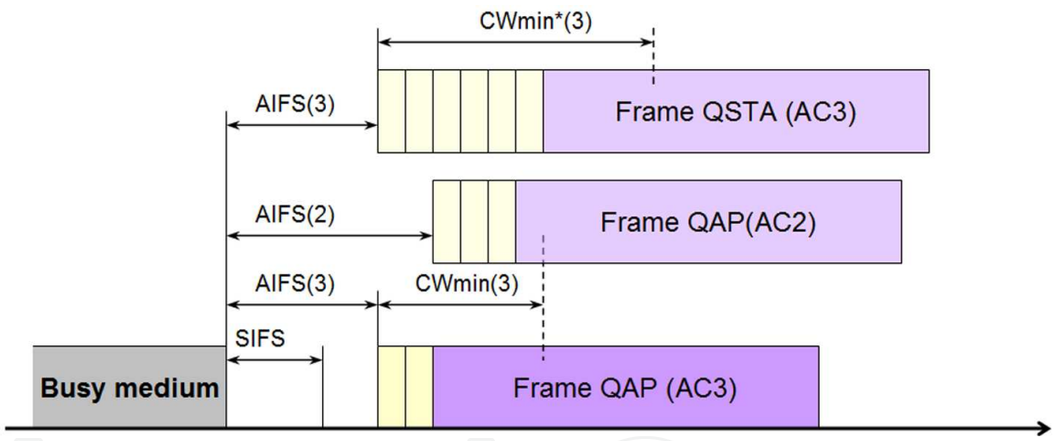


Fig. 8. Setting the contention window size

3.3 TXOPlimit regulation

Transmission of burst of frames through the adoption of *TXOPlimit* default values allows improving QoS performance of delay-sensitive traffics, such as AC3 and AC2. With the default parameters, the ACs at the QSTAs and at the QAP have the same transmission probability, and channel access times of contending stations can be better regulated with *TXOPlimit* option. Setting a unique value of this parameter for all stations (i.e., QSTA and QAP) can lead to unfair allocation between uplink and downlink traffics. In fact, the QAP has to deliver the whole downlink traffic to the QSTAs, but it contends the channel as one single entity. In order to give the QAP the possibility of transmitting all downlink frames, it is advisable to set a greater *TXOPlimit* value at the QAP with respect to QSTAs. Therefore, even under heavy traffic and with many contending stations, uplink/downlink fairness can be achieved through a careful dynamic management of the *TXOPlimit* parameter.

Of course, when an AC gains the channel, the duration of its transmission obviously influences the queue delay of the other ACs for all stations, and this can lead to frame starvation when there are many active stations. Long TXOP transmissions tend to reduce the number of channel contention opportunities and, consequently, all other stations have fewer chances to deliver their frames. As a result, it is evident that the regulation of *TXOPlimit* parameter must be carefully dimensioned.

In (Majkowski & Palacio, 2006), *TXOPlimit* is dynamically adapted on the basis of the number of frames allocated at the QAP (assuming that there is one queue for each AC). The average number of frames is considered rather than a simple measure of the actual length of AP's buffers, thus smoothing the effect of bursty arrivals. In order to avoid excessive channel occupation, TXOP maximum duration can be limited to the buffer size or to the value obtained when a certain collision probability is achieved, thus providing the optimum TXOP assignment for a given condition. This approach regulates the *TXOPlimit* value at the QAP, but it is not efficient under heavy loads in uplink direction.

In (Liu & Zhao, 2006), TXOP values are allocated in an efficient way for variable bit rate traffic with time varying profiles. TXOP is dynamically tuned according to the incoming frame size, with an estimation based on a variable bit rate video prediction algorithm, and to the current queue length. TXOP value is estimated as the sum of transmission time of the next incoming frame, of all frames in the transmission queue and of all the expected acknowledgements. The main drawback of this solution is computational complexity, introduced by the adoption of a Wavelet-Domain Predictor for the dynamic estimation of *TXOPlimit*.

In ETXOP (Ksentini et al., 2007), *TXOPlimit* is calculated each time the AC wins the contention, and the computation is based on AC's priority (inter-AC QoS) and on its flow data rate (intra-AC QoS). Each time a flow gains channel access, the algorithm checks the MAC queue in order to measure its length, to predict the number of frames and the mean frame size. Then, it computes at run time the most appropriate *TXOPlimit* that should satisfy QoS requirements of that flow. *TXOPlimit* is computed according to a distributed model which takes into account network availability, flow priority and its offered load

As the way to compute *TXOPlimit* is dependent on AC priority, for AC3 and AC2, ETXOP uses a value based on the number of frames in the corresponding MAC queue. Instead, for AC1 and AC0, ETXOP adopts static values, similarly to EDCA, aiming at limiting the number of frames sent in best effort and background bursts.

ETXOP offers more flexibility to network operators, by accommodating QoS requirements of network flows, regardless of their individual bit rates; this approach is more compliant with actual operated network practices (i.e., multi-bit rate environments).

In (Stoeckigt & Vu, 2010), authors discuss the implications of the TXOP parameter in terms of the maximum number of VoIP calls supported by IEEE 802.11 network. Here researchers give precedence to the QAP when competing for channel access, by assigning it a higher *TXOPLimit* value. However, such an increase causes the bottleneck to shift from the QAP to the wireless nodes, which have to wait an extended period of time before accessing the channel, thus increasing delays. Researchers have demonstrated that there is an optimal TXOP value, beyond which the WLAN voice capacity cannot be further improved. For this reason, an accurate recursive approximation formula has been studied, in order to calculate

the achievable voice capacity in a WLAN for a given TXOP parameter. The processing of this approximation formula requires high computational resources. Moreover, the impact of the buffer size at the QAP on the number of obtainable voice calls is investigated, and an optimal buffer size has been defined for achieving the maximum voice capacity.

In (Feng et al., 2009), *TXOPlimit* is dynamically adjusted through a Random Early Detection (RED) mechanism, based on the queue length, which reflects the current network load. RED is a buffer management algorithm, whose packet drop probability linearly increases with the average queue length. According to this solution, the traffic load conditions are monitored at QAP and QSTAs queues. If the queue length is below a lower threshold, a smaller *TXOPlimit* value is adopted; if it overcomes this threshold, *TXOPlimit* increases linearly with the queue length. If the queue length is over an upper threshold, the maximum value of *TXOPlimit* is used. This algorithm is focused on QoS enhancement for video streams (AC2) and it is quite similar to (Majkowski & Palacio, 2006).

In (Andreadis & Zambon, 2007), a new algorithm is proposed, named *Dynamic-TXOP* (DTXOP), for the dynamic assignment of TXOP maximum duration. DTXOP is periodically updated according to the current traffic conditions of each specific AC, by computing the number of QSTAs involved in this AC and the amount of lost frames for each connection.

Unlike previous approaches, this algorithm is also able to reduce the QAP channel occupation time when uplink demand is greater than downlink demand.

Specifically, the proposed algorithm counts the number of lost frames of each AC in downlink/uplink directions, and the number of QSTAs demanding QoS requirements, during the *i-th* observing time interval (set equal to the beacon interval, 100ms). The term "lost frames" here refers to frames transmitted but not yet acknowledged by the destination station during the observing time. Lost frames are monitored because they are considered the main symptom of transmission problems, regardless of the events that caused such problems. Moreover, the number of QSTAs contending the channel is another key parameter involved in uplink/downlink fairness.

The described algorithm allows to enhance significantly QoS performance of multimedia traffics and to increase the WLAN global throughput. Although the major enhancements are denoted in real-time applications, such as video (AC2) and VoIP (AC3), TCP sessions such as web and file transfers (AC1 and AC0) are not significantly unfavoured, due to a global improvement in system's throughput and fairness.

3.4 Block ACK

In order to increase throughput and to reduce channel inefficiency introduced by ACK transmissions, a new acknowledgement scheme, called Block ACK, has been defined in IEEE 802.11e. This scheme allows transmitting consecutively multiple frames, inter-spaced by a SIFS interval. The acknowledgement of the transmitted block of frames is performed through a single aggregated ACK, called block ACK, thus avoiding the transmission of one ACK for each data frame.

The Block ACK frame is transmitted as a response to a control frame, called block ACK request frame (Fig. 9).

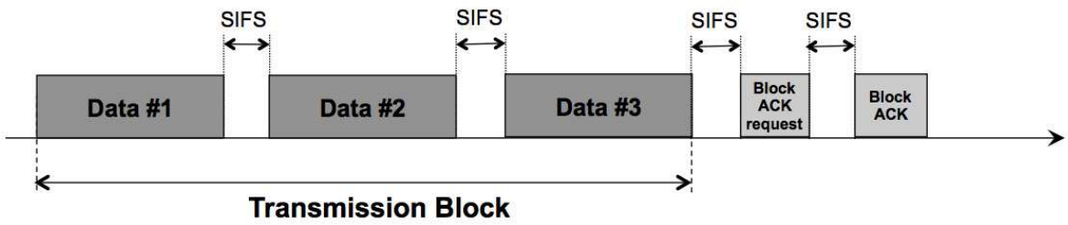


Fig. 9. Transmission of a block of frames and related Block ACK

Furthermore, the originator and the recipient have to set up this new acknowledgement policy, by exchanging an "add block ACK request" and an "add block ACK response" management frame. After this initialization, the frames that constitute the data block are transmitted and collectively acknowledged. The maximum number of data frames in a data block is specified during the initial setup phase, according to the buffer size at the receiver.

Since a data block can be composed of several data bursts, several TXOPs can be required for transmitting a data block (TXOP only determines the number of frames in a data burst).

The Block ACK scheme increases the aggregate throughput performance, due to a better efficiency of the MAC level acknowledgement mechanism. On the other hand, it increases delay, due to postponed acknowledgements. This delay is approximately proportional to the number of wireless stations contending the channel access.

Recent studies have been dedicated to the IEEE 802.11e block ACK scheme and to its performance evaluation.

In (Lee et al., 2010), a mathematical analysis of throughput and delay performance has been carried out, according to different channel access modes, channel errors (i.e. additive white Gaussian noise) and re-sequencing delay at the receiver. The accuracy of this model has been verified by comparing the numerical results with the ns-2 (NS2, 2011) simulation results. Also noisy environment were considered, showing that channel errors deteriorate throughput and delay performance due to retransmissions, and the adoption of *RequestToSend/ClearToSend* (RTS/CTS) technique over an error-prone wireless channel further degrades delay performance.

The work in (Yuan et al., 2004) introduces an adaptive block ACK scheme for infra-structured WLANs: high-rate hosts, experiencing good channel conditions, are given transmission priority by increasing the size of their data burst within a block-ACK.

In (T. Li et al., 2006), researchers show that an optimal block size, which maximizes the efficiency of block ACK mode, can be computed for each block transmission. The optimal block size is intuitively equal to the number of frames available in the transmission queue prior to delivery.

In (Wall & Khan, 2009), a novel distributed *Adaptive Block Size* scheme (ABS) is introduced. It dynamically adapts the block size on the basis of channel status and traffic characteristics, in order to achieve higher throughput and QoS efficiency. Specifically, the sender dynamically adapts the block size according to a specific function, assuming lower block size values when higher delays are experienced. Each block size adaptation has to be communicated between the sender and the recipient. This algorithm is focused on data delivery before

lifetime expiry, and it provides protection from losses for real-time multimedia traffics. Being it a distributed scheme, ABS is applicable both to infra-structured and ad hoc WLANs.

4. Admission control schemes for WLANs

Under heavy traffic loads, 802.11e mechanisms for QoS support are no more sufficient and an admission control algorithm is needed, in order to avoid that the ingress of new traffic flows seriously damages the performance of active traffics. Several admission control algorithms were designed to play a central role at the aim to avoid network saturation and to protect QoS performance.

Furthermore, admission control algorithm is a key component to correctly manage QoS-based wireless networks, in order to adapt them to traffic load variations.

Specifically, in order to admit a new flow, it is important to satisfy two basic conditions:

- there are enough resources to meet the QoS demands of the new traffic;
- the upcoming traffic does not provoke a degradation of active traffics (i.e., bandwidth is efficiently exploited).

In this section we provide an overview of the state of the art on IEEE 802.11e admission control schemes proposed for preventing QoS degradation under heavy traffics.

Admission control algorithms can be distinguished in three categories, based on different criterions and methodologies:

- Measurement-based (threshold based and resource sharing based);
- Model-based;
- Measurement-aided, model-based.

4.1 Measurement-based admission control

In the measurement-based schemes, admission control decisions are supported by continuous measurements of network conditions, such as throughput and delay.

A threshold-based approach envisages that the QAP, and the QSTAs, if needed, measures the traffic conditions and the network status. Suitable upper or lower bound thresholds, delimiting the correct network load, are used to take the decision on the admission of new traffics.

The solution proposed in (Nor et al., 2006) introduces a *Network Utilization Characteristic* (NUC) of a new flow as a decision criterion for admission. NUC is defined as the fraction of channel utilization needed to transmit the flow over the network. If the total NUC, calculated as the sum over all the active flows and the new flow, is below a specific NUC threshold, the new flow is admitted.

This scheme is of easy implementation and can guarantee the QoS of high priority flows when the channel is heavily loaded, but it negatively affects the throughput of low priority flows to the detriment of fairness. Moreover, it appears critical the choice of NUC threshold values.

In order to enhance fairness among different QoS classes, an interesting solution could consist in the reservation of a minimum amount of resources for each class. This is the approach of resource sharing based admission control, as proposed in (Wu et al., 2010). Its idea is the following: the acceptance of a new traffic is performed only if QoS is preserved to a certain level which varies for different prioritized ACs. In other words, the QAP can accept a new AC admission request, only if both following criteria are satisfied:

- the average bandwidth requirements of all the existing AC traffics, with priority higher than or equal to the new flow, are preserved;
- the minimum reserved bandwidth of all existing traffics with priority lower than the new traffic is satisfied.

Similarly to the previous solution, (Xiao & H. Li, 2004) defines a fully distributed admission control algorithm, in which individual QSTAs accept or reject voice/video streams on the basis of local measurements.

During the beacon interval, the QAP calculates the amount of resources needed for transmitting all AC flows and it announces a transmission budget (i.e., the allowed channel time for each AC) via beacons sent to the QSTAs. According to the transmission count related to the previous beacon period and to the transmission budget announced by the QAP, each QSTA determines an internal transmission limit per AC, for each beacon interval. The local voice/video transmission time per beacon interval must not exceed the internal transmission limit per AC.

Also in (Kim et al., 2010) the admission control algorithm decides whether the flow can be admitted, basing on channel status and traffic information provided by the incoming flow. However, resource allocation to each AC is an extremely challenging issue, due to collisions among different ACs. For this reason, a priority access mechanism is introduced in order to carry out a correct channel contention among flows within the same AC, thus favouring high priority ACs and avoiding collisions between flows with different priority.

At each new admission request, average channel time usage ratio, average collision probability, and average back-off time are computed for each AC. These measurements allow the QAP to accurately predict the channel time usage for the admission of a new flow.

4.2 Model-based admission control

The model-based schemes build their performance metrics for evaluating the status of the network, on the basis of analytical models for the wireless system.

The Markov Chain Model is commonly adopted for IEEE 802.11 WLANs, but it has some limitations when EDCA parameters are introduced. For these reasons, researchers are working on new models for IEEE 802.11e (Chen et al., 2006).

In (Bellalta et al., 2007), an EDCA analytical model is adopted in order to estimate the minimum aggregated bandwidth required by all flows. By using this value and the maximum achievable data rate, the MAC parameters are adjusted on the basis of a set of predefined thresholds.

Although this solution takes in account all EDCA parameters and the uplink/downlink fairness issue, it remains difficult to define the correct threshold.

Furthermore, since analytical models are obtained on the basis of a few hypotheses to calculate QoS metrics of all flows, they do not accurately reflect the characteristics of real traffics and real channel time usage after a new flow has been admitted.

The study in (Cano & Bellalta, 2007) presents a model-based admission control scheme working jointly with a simple uplink/downlink fairness solution, which adopts different MAC parameters for the QAP and for the QSTAs. In particular, AIFS at the QAP is one unit lower than the value used at QSTAs, and its TXOP is increased proportionally to the number of downlink flows; furthermore, the *CWmin* value of uplink flows is set proportionally to the number of contending QSTAs.

When a new traffic needs to be activated, the admission control algorithm estimates if this operation preserves QoS for the existing flows. Estimation is performed by adopting the EDCA mathematical model developed in (Bellalta et al., 2007) to obtain the packet level performance of the system at both flow-level (blocking probability, average number of active flows, average bandwidth used etc.) and at packet level (flow throughput, packet delays, losses, etc.).

4.3 Measurement-aided, model-based admission control

A hybrid approach based on measurement-based and model-based schemes is arising as the main method for designing and implementing admission control algorithms.

The algorithm described in (Ksentini et al., 2007) is performed at each station and it takes into account measurements on network load, as well as the required data rate of the flow requesting for admission. Furthermore, this admission control scheme is able to predict the network conditions and hence, to estimate the achievable QoS performance, according to a channel model elaborated under the ETXOP assumption. Considering a specific AC, for each flow the QSTA starts estimating the maximum number of frames which can be inserted by that flow in the transmission queue, under the current network conditions. Afterwards, the QSTA checks whether this value satisfies the data rate required by the new flow. If the condition is verified, then the candidate flow is accepted, otherwise it is rejected.

Another scheme, described in (Zhu & Fapojuwo, 2007), estimates the achievable per-frame throughput and access delay and it verifies whether the ingress of new flows satisfies throughput and delay requirements. The new concept of *Virtual Service Interval* (VSI) is here introduced: VSI is calculated on the basis of network conditions and of the required access delays of flows with different priorities.

Performance metrics of throughput and delay are processed for each flow, on a frame-by-frame basis. These metrics are determined through a frame-based network model. In particular, the average service interval (i.e. channel occupation time) of admitted and applicant flows is calculated. The new flow is admitted if the average service interval is smaller than VSI.

This admission control method can be applied to both variable-bit-rate and constant-bit-rate traffics, since it considers per frame throughput and access delay as decision criteria.

The solution proposed in (Bensaou, 2009) is a threshold based admission control, according to which the QAP continuously monitors the channel and measures the contention probability. When a new flow requests admission, the authors adopt for this AC the non-

saturation homogeneous equivalent model of DCF, in order to estimate the equivalent number of competing entities of the same AC. QAP computes the achievable bandwidth and expected delay of the new flow. If the bandwidth and delay requirements of new and admitted flows are all satisfied, then the new flow is admitted.

This solution is very simple, and more feasible if compared to other solutions, but the adoption of analytical model of a non-saturated IEEE 802.11 DCF introduces inaccuracy to the admission control in IEEE 802.11e EDCA scenarios.

The solution proposed in (Andreadis et al., 2008), based on a continuous monitoring of BSS channel resources, defines a resource sharing scheme for allocating the total bandwidth through resource reservation for each AC. For each new flow, the algorithm computes its resource utilization percentage by estimating the maximum achievable WLAN throughput. The key point of the proposed algorithm resides on the estimation of the channel global capacity, performed through the calculation of the average size of frames circulating in the network. In fact, the BSS global throughput is strictly correlated with the mean size of the frames generated by the transmitting stations (i.e., global throughput decreases with small frames) (Mangold et al., 2002). In (Andreadis et al., 2008), an experimental model for throughput has been proposed as a function of the average frame size. Based on this model, the estimation of the global throughput is constantly updated each time a new flow demands to be activated in the BSS.

In this way, a source with low throughput demands, but generating small frames, should be rejected, otherwise it would provoke a decrease of network throughput and of QoS performance of active traffics.

Furthermore, UDP flows (e.g., VoIP and video, usually mapped to AC3 and AC2) behave more aggressively with respect to TCP ones (e.g., ftp and web) and they are usually assigned a higher EDCA priority. For this reason, the admission control is restricted only to AC3 and AC2 classes, since AC0 and AC1 adapt themselves to the remaining bandwidth.

The activation of a new AC3 or AC2 traffic requires the following operations:

- evaluation of the frame size and of the required throughput for the new flow;
- re-computation of the current resource sharing percentages, checking whether the admission of the new flow would violate the sharing scheme;
- if the sharing scheme is not violated, the new AC flow is accepted, otherwise it is rejected.

The described algorithm is based on a low-collision and high-efficiency estimation model, so it works well in a scenario with increased uplink/downlink fairness. In fact, it is designed to work jointly with DTXOP algorithm (Andreadis & Zambon, 2007). The admission control scheme is able to exploit uplink/downlink fairness enhancements provided by DTXOP, in order to fine-tune the channel access control to the different ACs, without bandwidth waste or, on the other hand, QoS degradation of active flows.

5. Open issues

The main challenges regarding the enhancement of QoS performance for heterogeneous traffics in contention-based 802.11 networks are strictly linked to the dynamic adaptation of the *TXOPlimit* parameter and to the design of suitable admission control schemes.

Concerning TXOP, a key issue remains the way to correctly choose *TXOPlimit* value in order to preserve QoS of each flow, without penalizing network utilization of all competing flows. In fact, although large *TXOPlimit* values permit to increase performance of a specific traffic, on the other hand it causes high delays for other active traffics, with the risk of frame starvation and QoS degradation.

For this reason, finding the optimal transmission opportunity configuration (i.e. adopting recursive algorithms, thresholds, etc.) remains an open issue towards QoS management of heterogeneous traffics in a wireless network under different conditions.

Further network parameters could also be considered in the design of innovative *TXOPlimit* adaptation algorithms; for example, such algorithms can be calibrated for mobile or vehicular scenarios, by taking into account factors like channel noise, link quality, modulation, etc...

As regards the design of suitable admission control schemes, several issues have still to be faced. In particular, QoS performance should not be limited to the single wireless hotspot, but it should be preserved for the whole end-to-end path; consequently, methods to optimally map QoS requirements between different network layers have to be investigated, in order to dynamically adjust QoS on upper layers, while underlying network condition changes.

Furthermore, it is also interesting to explore how 802.11e techniques interact with applications and with higher-layer QoS schemes, and how Quality of Experience can be related to the Quality of Service concept.

Another possible field of investigation to achieve *TXOPlimit* regulation and admission control resides in the cross-layer approach and in game theoretical analysis methods.

Finally, the need to evaluate the trade-off between QoS techniques and energy consumption arises as a crucial point. For example, in EDCA, service differentiation and traffic prioritization can expand waiting times, thus affecting energy consumption. Since mobile devices are characterized by limited battery resources, these issues are very important in mobile networks and they require a very careful analysis.

6. Conclusion

The IEEE 802.11e standard is a concrete attempt in support of QoS, but this approach is not sufficient when the traffic volume increases. In this chapter we have provided an overview of the main techniques introduced to improve QoS performance in WLANs. A key concept for enhancing performance of IEEE 802.11e EDCA is the uplink/downlink fairness when allocating channel access time.

Firstly, the solutions related for fine-tuning EDCA parameters have been explored, mainly focusing on adaptation mechanisms of the *TXOPlimit* value, as a way to increase uplink/downlink fairness in resource allocation.

However, in presence of excessive traffic loads which lead to network saturation, admission control appears necessary for QoS preservation. For this reason, the major admission control algorithms for WLANs have been classified and discussed, as possible solutions for facing QoS degradation of active sources under heavy traffics. The joint adoption of fairness enhancement techniques and admission control schemes can increase efficiency and QoS performance.

We hope this work represents a valid contribution to clarify the state of the art about current studies on how to preserve QoS in contention-based (EDCA) IEEE 802.11e networks under heavy loads.

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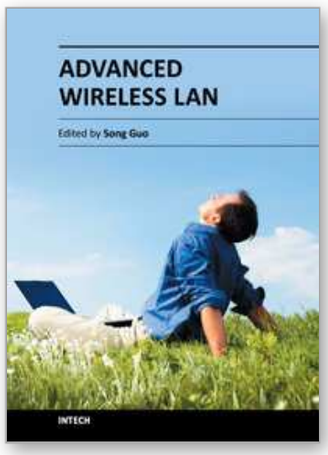
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The past two decades have witnessed starling advances in wireless LAN technologies that were stimulated by its increasing popularity in the home due to ease of installation, and in commercial complexes offering wireless access to their customers. This book presents some of the latest development status of wireless LAN, covering the topics on physical layer, MAC layer, QoS and systems. It provides an opportunity for both practitioners and researchers to explore the problems that arise in the rapidly developed technologies in wireless LAN.

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