Adaptive Control in Wireless Networks

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1. Introduction

In wireless networks, where all mobile stations share the same unreliable medium (the air), channel access control is crucial. The role of the medium access control mechanism becomes even more important nowadays, since the mobile users' network demands have greatly increased. Initially, the wireless networks were employed as simple extensions of the wired ones, thus, the requirements for this new kind of computer networks were not high. The first wireless computer communications were mainly involving traditional data transmissions of low demands. Modern wireless networks are expected to serve "heavy" multimedia transmissions as well. Now, the medium access control has to efficiently adapt to the different network conditions, the different demands and characteristics of the served transmissions.

There is a great number of medium access control methods proposed in the literature. A categorization of these methods is provided in this chapter. Some of the proposed methods are quite generic and can be theoretically employed in a large number of networks, while others are more specialized and target, for example, exclusively on wireless local area networks. The type and the specific features of the used access control mechanism significantly defines the overall network behavior. Modern wireless network access control is expected to efficiently provide QoS.

Obviously, different types of traffic have different transmission requirements. This chapter discusses on the traffic classification and the special characteristics of each class. Supporting real-time traffic of strict QoS requirements (low delay-jitter, high throughput) in a wireless local area environment is quite challenging. There are some relevant protocols proposed, but the most significant one is the Hybrid Control Channel Access (HCCA), which is part of the IEEE 802.11e standard (IEEE 802.11e – Amendment 8, 2005). Here, an operation overview of HCCA is provided.

This chapter presents an alternative proposal in wireless network adaptive control, which is called POAC-QG (Priority Oriented Adaptive Control with QoS Guarantee). POAC-QG is a complete centralized channel access mechanism, it is able to guarantee QoS for all types of multimedia network applications, it enhances the parameterized traffic with priorities, and it supports time division access using slots. Furthermore, it instantly negotiates the quality levels of the Traffic Streams (TSs) according to their priorities, supporting multiple streams to the best quality it can achieve. POAC-QG compared to HCCA, provides higher channel utilization, adapts better to the characteristics of the different traffic types, differentiates the traffic streams more efficiently using priorities, and generally exhibits superior performance.

2. Medium Access Control and QoS Support for Wireless LANs

The protocols that control channel access are responsible for ensuring efficient and fair sharing of the available bandwidth. There are various relative proposals in the literature for different kinds of network conditions (Nicopolitidis et al., 2003; a. Papadimitriou et al., 2003; Chlamtac et al., 2003; Issariyakul et al., 2003). In wireless networks, the role of the MAC protocol is crucial. The available resources are limited, so there is a great need for efficient control of the transmissions. QoS support is also strongly related with the access control mechanism. A QoS supportive MAC protocol is able to distinguish different types of traffic and treat them accordingly. Usually, traffic is prioritized and high priority data is favored by the access control mechanism.

2.1 Classification of Traffic

Traffic can be categorized according to the transmission requirements (Chandra et al., 2000). Various ways to classify traffic have been proposed. First of all, we can distinguish between non-real-time (such as background data) and real-time traffic (such as voice and video). Background data traffic is not time-critical. It does not require low delay or jitter, but it demands reliable packet delivery. Usually, it is considered as low priority traffic and an acknowledgement mechanism is used to ensure reliability. On the other hand, real-time traffic mainly concerns digital voice and video transmission and is time-bounded. Low packet delay is required in order to have qualitative audio and video reproduction. Jitter must be also kept at low values, because the packet buffer size is limited and the lifetime of the packets is small. For these reasons, high jitter increases the packet drop ratio. Live voice and video transmissions are even more demanding, because they involve extra delay caused by the real-time digital encoding at the source. However, some packet losses or bit errors can be allowed, because high reliability is not essential.

Traffic is also classified according to the way packets are generated (Akyildiz et al., 1999). When packets of the same size are generated at constant time intervals, then traffic is characterized as Constant Bit Rate (CBR). Numerous real-time voice and video digital encoders, such as G.711 and MPEG-4 respectively, produce CBR traffic. The advantage of this kind of traffic generation is that transmission time intervals can be reserved at the beginning of the communication and remain unchangeable and sufficient for its whole duration. The disadvantage is that usually this type of encoders are not bandwidth optimized, although they are rather fast. Variable Bit Rate (VBR) traffic is produced when the generated packets are not of the same size or the generation time interval is not constant. VBR traffic is common in both background data and real-time transmissions. Background data VBR traffic is usually called nrt-VBR (non-real-time Variable Bit Rate), while rt-VBR (real-time Variable Bit Rate) traffic mainly concerns compressed voice and video transmission. VBR voice-audio and video encoders, such as MPEG Audio Layer 3 and H.261 respectively, are not particularly bandwidth demanding, but the encoding time is rather long. Furthermore, the initially reserved average bandwidth for a rt-VBR communication is usually not capable to provide sufficient QoS, because the transmission requirements change dynamically. Since bandwidth is limited, particularly in wireless networks, the use of efficient VBR digital coding techniques is necessary. For this reason, adaptive control mechanisms that can efficiently support both CBR and VBR traffic seem nowadays quite useful. A summary of this traffic classification is given in Table 1.

Traffic Type	Examples	Characteristics
CBR (Constant Bit Rate)	real-time voice-video	efficient bandwidth reservation fast digital encoding increased produced data
nrt-VBR (non-real-time Variable Bit Rate)	background data transmission	high reliability required delay-jitter tolerant
rt-VBR (real-time Variable Bit Rate)	real-time audio-video	changeable bandwidth requirements increased encoding delay compressed produced data

Table 1. Traffic classification

2.2 Medium Access Control Protocols for WLANs

QoS support in ad-hoc WLANs is definitely a hard objective. The absence of central control is the reason why QoS cannot be guaranteed. However, the use of packet priorities can partially provide QoS, thus, there are some distributed MAC protocols that favor high priority packets. In decentralized WLANs, the level of QoS support depends on the network characteristics, such as load and number of stations. Specifically, distributed access mechanisms are contention based, thus, high load and increased number of stations cause high collision rate and low channel utilization. Under these conditions, packet delay and jitter are increased. Thus, QoS cannot be really guaranteed in ad-hoc WLANs. The EY-NPMA (Elimination Yield – Non Preemptive Multiple Access) protocol (HIPERLAN – ETSI Functional Specification, 1998; b. Papadimitriou et al., 2003), used in HIPERLAN (HIgh PERformance Local Area Network), which is standardized by ETSI (European Telecommunications Standards Institute), and the EDCA (Enhanced Distributed Channel Access) protocol used by IEEE 802.11e provide partial QoS for ad-hoc WLANs.

Infrastructure wireless networks, where central control is employed, are more suitable for supporting QoS. The access control and the schedule mechanism are implemented in the AP, which is responsible for giving transmission permissions to the wireless stations. One of the centralized access methods that provide QoS involves station polling according to the previous or following packet priorities. This method does not include bandwidth reservation. The AP analyzes the feedback and decides which station should be allowed to transmit, taking into account packet priorities. These polling schemes usually ensure low collision rate and high channel utilization, and they can provide QoS but with no guarantees. The POAP (Priority Oriented Adaptive Control) (Lagkas et al., 2008), the QAP (QoS supportive Adaptive Polling) (Lagkas et al., 2006) and the GRAP (Group Randomly Addressed Polling) (Chen & Lee, 1994) protocols belong to this class of access mechanisms.

The MAC protocols that can actually guarantee QoS in a WLAN are the reservation centralized protocols. The access mechanisms of this class give the ability to the different TSs to reserve bandwidth. According to this model, the stations send transmission requests to the AP asking for transmission intervals, usually using a contention based scheme. The scheduling algorithm implemented in the AP decides the bandwidth distribution in the contention free period according to the stations' requests, the priorities, the available resources etc. This type of channel access method guarantees QoS by ensuring that the packet delay of a TS will not exceed an agreed maximum limit, however the values of the actual packet delay and jitter vary and depend on the specific MAC protocol. The usual drawbacks of this model include the waste of bandwidth at the contention based period, because of the high collision probability, and the inability to efficiently support all types of real-time traffic. Specifically, if the assigned transmission periods remain constant for the whole duration of the communication, then VBR traffic cannot be efficiently supported. Representative reservation centralized WLAN MAC protocols are: DQRUMA (Distributed-Queuing Request Update Multiple Access) (Karol et al., 1995), MASCARA (Mobile Access Scheme based on Contention and Reservation for ATM) (Bauchot et al., 1996), DSA++ (Dynamic Slot Assignment) (Petras & Kramling, 1996), DTDMA (Dynamic Time Division Multiple Access) (Raychaudhuri et al., 1997), and PRMA (Packet Reservation Multiple Access) (Kim & Widjaja, 1996; Dyson & Haas, 1999; Bianchi et al., 1997). Variants of these protocols have also been proposed in literature. The general concept of the previously mentioned protocols is focusing on the real-time traffic and the use of a simple contention based scheme, like Slotted ALOHA, for the transmission of the requests and the non-real-time data. The hybrid solution proposed by the IEEE 802.11e workgroup is examined in the next section. This classification of the QoS supportive MAC protocols is presented in Table 2.

Protocol Type		**Examples**	**Characteristics**
Distributed		EY-NPMA EDCA	no infrastructure required low performance poor QoS support
Centralized	Random Access	POAP QAP GRAP	high performance not guaranteed QoS support low feedback requirements
	Reserved Access	DQRUMA MASCARA DSA++ DTDMA PRMA HCCA POAC-QG	increased QoS guarantee not optimal channel utilization high feedback requirements

Table 2. A classification of medium access control protocols that support QoS

3. The IEEE 802.11e Hybrid Control Function

The WLAN standard that has dominated the market is IEEE 802.11, which provides data rates up to 100 Mbps (802.11n). Currently, the majority of the deployed 802.11 products support data rates up to 54 Mbps (802.11a/g). The employed MAC protocol does not support QoS. However, some modifications that enhance partial QoS support have been proposed (Ni et al., 2004).

3.1 The Operation of HCF

IEEE formed the 802.11e workgroup, because of the increased need for QoS in modern WLANs. The 802.11e channel access mechanism is called HCF and it comprises a contention based scheme (EDCA) and a contention free scheme (HCCA). HCCA is able to guarantee QoS to some degree. It operates in infrastructure mode and its role is to efficiently support real-time voice and video communications. EDCA is designed to support prioritized traffic similar to DiffServ, whereas HCCA supports parameterized traffic similar to IntServ.

The basic concept of HCF is the transmission opportunity (TXOP), that is the time interval in which a station (also called quality enhanced station in 802.11e) is allowed to transmit. In HCCA, the TXOP is decided by the AP according to the QoS request. Specifically, the Hybrid Coordinator (HC) is responsible for the central control and it is co-located with the AP. However, here, we never refer particularly to the HC, but generally to the AP.

The superframe of HCF is defined as the beacon interval. It is composed of alternated modes of Contention Period (CP) and optional Contention-Free Period (CFP), as it can be seen in Figure 1. EDCA operates only in CP while HCCA can operate both during CP and CFP. HCCA mode can be started by the AP several times during a CP and these periods are called Controlled Access Periods (CAPs). The beacon transmitted by the AP at the start of every superframe contains control information, such as the maximum duration of CFP, the maximum duration of TXOP et al. The end of CFP is signaled by the AP using a CFP-End message. When the AP wants to initiate a CAP, it occupies the channel and uses a CF-Poll message to grant a HCCA-TXOP to a station.

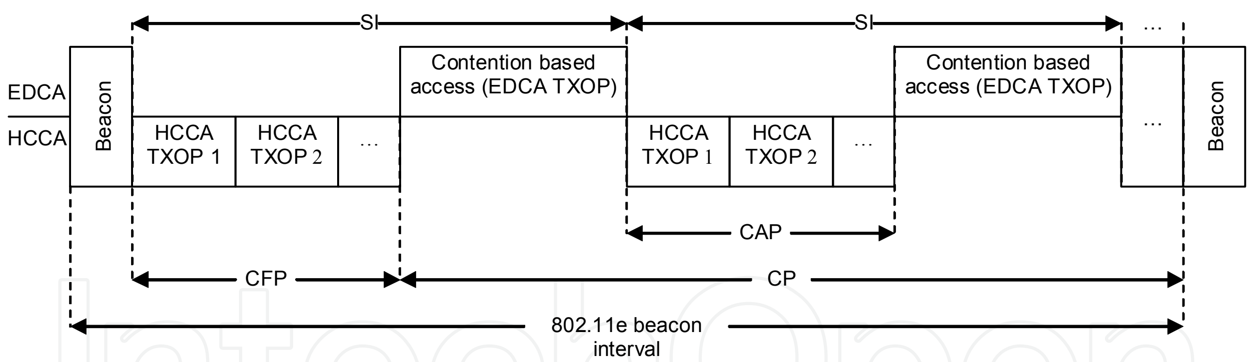

Figure 1. The HCF superframe of the IEEE 802.11e standard

In HCCA, every TS has its own packet buffer. The traffic specification (TSPEC) is responsible for the TS management. It provides the management link between higher layer QoS protocols such as IntServ or DiffServ with the 802.11e channel access functions (HCCA or EDCA, respectively). TSPEC describes characteristics of TSs, such as the mean data rate, the MAC Service Data Unit (MSDU) size and the maximum Required Service Interval (RSI). Each TS first sends a QoS request to the AP containing these characteristics. The scheduling algorithm calculates first the minimum value of all the RSIs, and then chooses the highest submultiple value of the beacon interval duration as the selected Service Interval (SI), which is less than the minimum of all the maximum RSIs. SI is the time interval between any two successive TXOPs allocated to a station.

3.2 Scheduling in HCCA

The simple scheduling algorithm used in HCCA calculates the TXOPs allocated to the different TSs as follows. The TXOP corresponds to the duration required to transmit all packets generated during a SI in a TS buffer. The mean number of packets (N_{ij}) generated in the TS buffer (j) for a station (i) during a SI is:

$$N_{ij} = \left\lceil \frac{\bar{r}_{ij} SI}{M_{ij}} \right\rceil \tag{1}$$

where $\bar{r}_{ij}$ is the application mean data rate and M_{ij} is the nominal MSDU size. The TXOP (T_{ij}) is finally as follows:

$$T_{ij} = max(\frac{N_{ij} M_{ij}}{R} + 2SIFS + T_{ACK}, \frac{M_{max}}{R} + 2SIFS + T_{ACK}) \tag{2}$$

where R is the transmission rate supported by the physical layer and M_{max} is the maximum MSDU size. The time interval corresponds to the overhead during a TXOP. Equation (2) guarantees that the TXOP will be long enough for the transmission of at least one packet with maximum size. The total TXOP assigned to a station is the sum of the TXOPs assigned to the different TSs of this station, that is:

$$TXOP_i = \sum_{j=1}^{Fi} T_{ij} \tag{3}$$

where F_i is the number of TSs in station i. The admission control algorithm checks for available bandwidth before assigning TXOP to a new TS. The fraction of total time assigned to a station i is: $TXOP_i / SI$. If the total number of QoS stations that are assigned TXOPs is K, then the scheduler needs to check if the new request of $TXOP_{K+1}$ will keep the fraction of time allocated for TXOPs lower than the maximum fraction of time that can be used by HCCA:

$$\frac{TXOP_{K+1}}{SI} + \sum_{i=1}^{K} \frac{TXOPi}{SI} \leq \frac{T_{CAPLimit}}{T_{Beacon}} \tag{4}$$

where $T_{CAPLimit}$ is the maximum duration of HCCA in a beacon interval (T_{Beacon}).
There are some drawbacks concerning the operation of HCCA. Regarding the polling mechanism, some valuable bandwidth is spent because of the polling packets sent to the stations. The use of acknowledgements is bandwidth costly, too. Since, the target is to attain high throughput rather than reliability, acknowledging the real-time traffic packets seems useless. Also, all the stations have to stay constantly fully awake waiting for data packets or polls, so there is increased power consumption. Concerning the scheduling algorithm, a major drawback is the fact that the allocated TXOPs are fixed. Thus, VBR traffic cannot be supported efficiently, because possible sudden increases in the bit generation rates would cause increased delays and packet drops. Furthermore, the scheduling algorithm does not take into account prioritized TSs. It just uses the quality requirements in order to assign TXOPs. This means that the traffic is not efficiently differentiated according to the demands

for QoS support. These issues and the solutions given by the proposed POAC-QG protocol are detailed in the next sections.

4. Priority Oriented Adaptive Control with QoS Guarantee

The new protocol introduced in this chapter is POAC-QG. The specific access scheme is able to operate in infrastructure wireless local area networks and can be used in a 802.11e network in place of HCCA. The need that has led to the development of this protocol is the necessity for bandwidth saving, strict QoS with efficient VBR traffic support, and traffic type distinction. POAC-QG is presented analytically in this section.

4.1 POAC-QG Overview

POAC-QG adopts a superframe structure, according to which there are consecutive Real-time Traffic (RT) periods and Background Traffic (BT) periods. The POAC-QG protocol operates during the RT periods, which are contention free. During the BT periods a contention based access mechanism can be used. The 802.11e superframe is suitable for adapting POAC-QG into it. The CFPs and CAPs correspond to the RT periods, and the CPs during which EDCA takes place correspond to the BT periods.

The POAC-QG access mechanism is not based on polling, but on a TDMA scheme. The concept is to reduce the bandwidth waste due to the polling model, keep the stations synchronized by dividing the RT period into time slots, and keep them informed of the time interval, source and destination of the coming transmissions. Thus, a potential power saving model could be used, since stations can stay in “sleep” mode during the RT period and “wake” only to transmit or receive data. The AP uses the beacon signal to inform the stations of the assigned slots for real-time traffic transmissions and the SI duration for the current superframe. In the beginning of every SI, except from the first one in the superframe, the AP broadcasts a SI_Start message which carries the same information with the initial beacon signal. If a station fails to receive the beacon signal, it defers, until it successfully receives a SI_Start (or a new beacon signal).

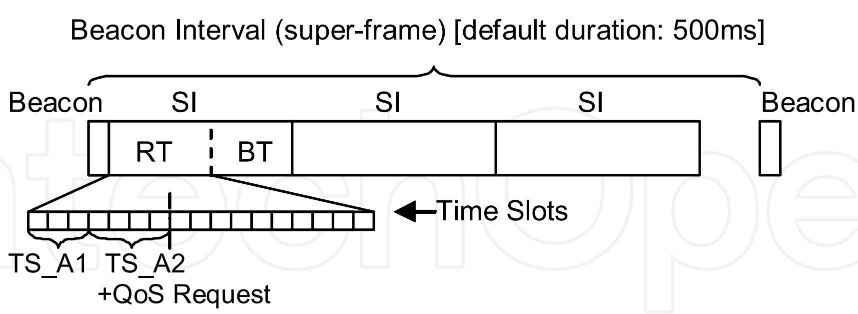

Figure 2. The superframe structure adopted by POAC-QG

When a station becomes aware of the beacon information, it ignores all subsequent SI_Start messages in the current superframe. We assume that the stations send their QoS requests for every TS during the BT periods or the last RT slots assigned to them. An overview of the superframe is shown in Figure 2.

It is known that a multimedia application can be carried out with different quality levels (depending on the codec, the audio-video quality etc). The admission control negotiates instantly multiple quality levels that can be supported by the requesting TS. The corresponding algorithm tries to serve the higher priority TSs with maximum quality level, but it can lower the provided quality levels in order to allocate slots for lower priority TSs, as well. It is of course assumed that the higher the quality level is, the higher are the resource requirements (bandwidth, delay). The main purpose of the protocol is to serve as many TSs as possible, favor the higher priority TSs, and provide the higher possible quality levels. When a station sends a QoS request to ask for slots for its TSs, it includes the traffic specifications of the different quality levels (traffic rate, maximum inter-transmission interval, maximum and nominal packet size).

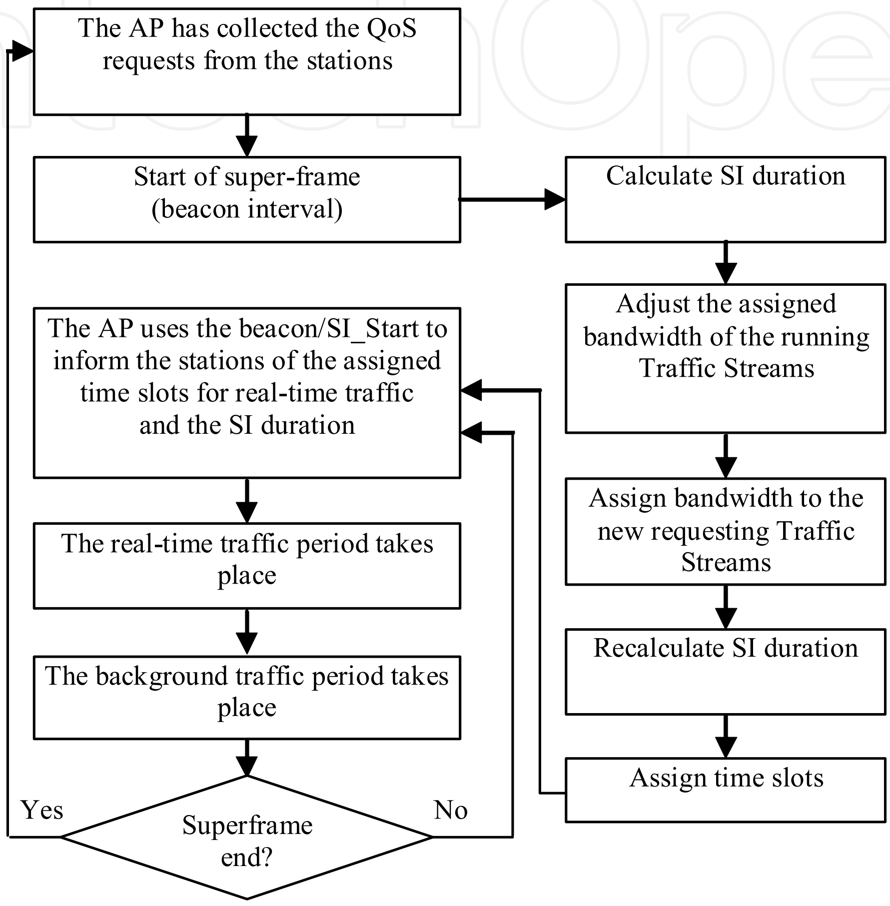

Figure 3. Operation overview of the POAC-QG protocol

Every running TS can ask for a different number of RT slots, according to its current traffic rate and the total size of its buffered packets. So, the QoS request frame that can be sent at the end of the assigned slots or during the BT periods, includes traffic specifications for both running and new TSs. This way VBR traffic can be efficiently supported. The algorithm calculates first the minimum value of all the maximum inter-transmission intervals required by the running and the new TSs, and then chooses the highest submultiple value of the beacon interval duration as the selected SI, which is less than the minimum of all the maximum inter-transmission intervals. Then, the AP allocates slots for the running TSs according to their latest requests. The reason why the running TSs are examined first is the effort of the protocol to keep the quality of the existing communications steady. After all, a new requested voice call can wait for admission, but it is unacceptable for a running call to be suddenly terminated or experience increased delays. The rest of the bandwidth is then assigned to the new TSs, according to the admission control mechanism. The new SI duration is calculated, based on the requests of the accepted TSs and finally the time slots are assigned to the running and the new accepted TSs. In Figure 3, an overview of the processes that take place according to POAC-QG is presented.

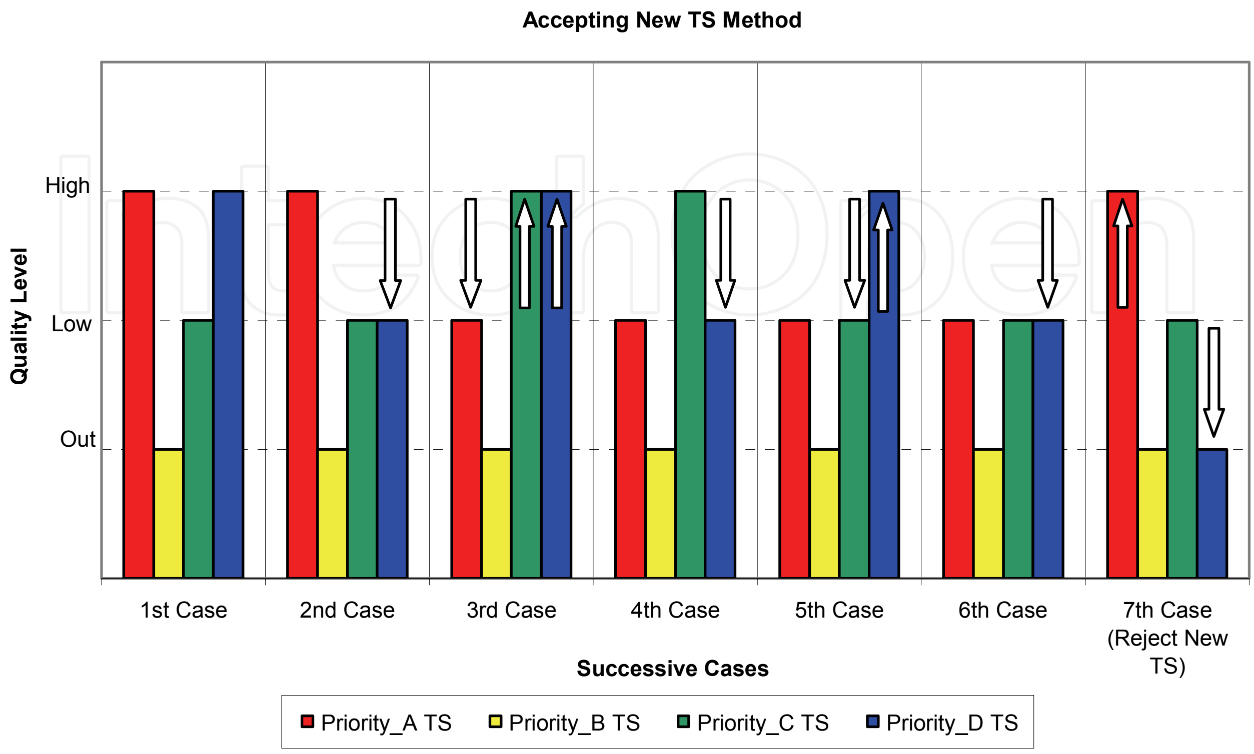

Figure 4. Example of the quality levels negotiation when examining the admission of new traffic streams

4.2 Traffic Streams Admission Control

The new TSs that request bandwidth allocation are sorted according to their priorities (highest priority first). The corresponding algorithm starts with the highest priority TS and checks if there is enough available bandwidth in order to serve the specific TS with maximum quality level. Otherwise, the QoS requirements of the lower quality level are checked. If neither the minimum quality level can be supported, then the TS is rejected and the next priority TS is examined. When there is no bandwidth left to serve a TS with minimum quality, then the quality levels of the previously examined higher priority TSs are lowered in order to save some bandwidth for the new TS. When the quality levels of the high priority TSs are lowered, then we also check if it becomes possible to increase the quality of the low priority TSs. This way, the best combination of supported quality levels is provided. An example of this process is described in Figure 4, where we assume two available Quality Levels (High QL, Low QL) and four new TSs with different priorities (Piority_A is the highest, while Priority_D is the lowest). The first three TSs are already examined. Let us assume that, so far, Priority_A TS has been accepted with High QL, Priority_B TS has been rejected, Priority_C TS has been accepted with Low QL, and Priority_D TS is now examined for admission. This means that we are looking for the best quality levels combination of these four TSs, which can be served using the current available bandwidth. In this example there are seven possible cases. Each time, the algorithm checks if there is enough available bandwidth in order to serve the TSs providing the corresponding quality levels combination. If there is not, then we proceed to the next best quality levels combination (case). The final case is the rejection of the examined TS (quality level: OUT). A simple form of the code is presented in Figure 5.

```
for i=0 To NumberOfNewTSs-1 //Each new TS is examined
 {
  GetNextTS=false //A flag to proceed to the next TS
  do //Searching for the best combination of quality levels of the TSs examined so
   { //far that requires bandwidth not more than the available bandwidth
    Calculate NewBandwidthAssigned //Calculate bandwidth assigned so far
    if NewBandwidthAssigned+BandwidthTS[i]>AvailableBandwidth
     { //If the current combination of quality levels requires more bandwidth than
       //the available, then we check the next "best" combination.
      j=i//Starting from the last examined TS,we search back for the first TS that
      do // has higher quality level than MIN, so we can lower it.
       {
        if QualityLevelTS[j]!=OUT //If a TS has been rejected, then it is not
         {                        //further considered.
          if QualityLevelTS[j]==MIN //When the examined TS is assigned the min
           QualityLevelTS[j] = MAX  //quality level, then it gets the max level to
                                    //ensure best combination and we proceed.
          Else
           QualityLevelTS[j]-- //The quality level of the specific TS is lowered
          j-- //Proceed to the next TS, that is the previously examined while it
         }   //also carries a higher priority (lower TS index -> higher TS priority
       }while (QualityLevelTS[j+1]==MAX OR QualityLevelTS[j+1]==OUT) AND j>-1
      if j==-1 AND (QualityLevelTS[0]==MAX OR QualityLevelTS[0]==OUT)
       QualityLevelTS[i]=OUT // All combinations have been examined. The current TS
     }                       // i is rejected, because there is no way to get the
                             // bandwidth requested by any of the quality levels
    else // The quality levels of the TSs 0 to i have been decided
     {
      Assign the decided quality qevels for the TSs 0 to i
      GetNextTS=true // Proceed to the next (lower priority) TS (i+1)
     }
    if QualityLevelTS[i]==OUT //If the examined TS is rejected, then the quality
     GetNextTS=true           //levels of all the previous TSs do not change and we
                              //proceed to the next (lower priority) TS (i+1)
   }while GetNextTS==false //Examine the next (lower priority) TS (i+1)
 }
```

Figure 5. The code form of the TS admission control algorithm

4.3 Dynamic Control Adapted to Resource Requirements

POAC-QG implements a dynamic control mechanism which efficiently supports VBR real-time traffic by adapting to the changing requirements of the running TSs. When the AP assigns RT slots to a station, it provides some extra slots allocated for its QoS request frame transmission. The station uses this frame to send the TSPECs both of the new requesting and the running TSs. Before sending a QoS request, the station calculates the current traffic rate of all the running TSs by counting the generated bits for a short time interval (default value is 2 sec). It also includes in the QoS request the size of the corresponding packet buffer. At the start of every superframe, the AP assigns slots to the running TSs according to their new QoS requests. The rest of the RT bandwidth is then assigned to the new TSs as we have already discussed. The quality level initially provided to a TS remains static, because our aim is to have steady and reliable transmissions.

The algorithm that assigns time slots to the running TSs tries to adapt to the variable traffic rate without sudden alterations of the allocated bandwidth. When there is not enough RT bandwidth, it assigns a proportion of the requested bandwidth to each TS according to its priority. It is considered that all the generated and buffered packets of a TS can be transmitted during a SI, if the allocated bandwidth corresponds to the theoretical traffic rate:

$$TheoreticalTR = CurrentTR + BufferedBits / SI \tag{5}$$

where *CurrentTR* is the current traffic rate defined in the QoS request. Since we try to avert sudden and continuous alterations of the allocated bandwidth, a proportion of the requested bandwidth accession or reduction is considered to be the target. Specifically, the considered target traffic rate is:

$$TargetTR = PreviousTR + BW\_DifPercent \times (TheoreticalTR - PreviousTR) \tag{6}$$

where *PreviousTR* is the traffic rate corresponding to the bandwidth assigned during the previous superframe, and *BW_DifPercent* (default value is 0.8) is the percentage of the requested bandwidth accession or reduction which is considered to be the target. We also use a down limit for the target traffic rate related to the initial traffic rate requested, in order to avoid packet drops in cases of sharp increase of the generated packets after a long silent interval.

Obviously, when a TS requests to give back some of its assigned bandwidth because it doesn't need it anymore, this is done with no further consideration. An issue arises when there is not enough bandwidth to cover all the extra requests of the running TSs. For this reason, an algorithm that distributes the available bandwidth taking into account the traffic priorities has been developed. It initially calculates the percentage of the available bandwidth that each requesting TS deserves (eligible bandwidth). The available bandwidth corresponds to the slots left in the maximum RT period, after assigning to all the running TSs the slots that already occupied in the previous beacon interval and freeing the returned slots. The eligible bandwidth percentage depends on the traffic priority and the amount of extra bandwidth requested by the TS. Specifically, we use the weights *W_PR* (default value is 5) and *W_BW* (default value is 1) to control the contribution of the traffic priority and the extra bandwidth requested, respectively, to the eligible extra bandwidth. It is obviously assumed that the traffic priority is clearly the most significant factor. The equation that gives the non-normalized eligible bandwidth percentage for the TS *i* is:

$$Per[i] = W\_PR \times PerPR[i] + W\_BW \times PerBW[i] \tag{7}$$

where *PerPR* is the normalized traffic priority:

$$PerPR[i] = \frac{PriorityWeight[i]}{\sum_{j=0}^{NumberOfRequestingTSs-1} PriorityWeight[j]} \tag{8}$$

and *PerBW* is the normalized extra bandwidth requested:

$$PerBW[i] = \frac{ExtraBW\_Requested[i]}{\sum_{j=0}^{NumberOfRequestingTSs-1} ExtraBW\_Requested[j]} \tag{9}$$

We use the term "priority weight" instead of just "priority", because the weight of a traffic priority might be considered to be different than the index of the specific priority. We assume that it holds:

$$PriorityWeight = Priority + 1 \tag{10}$$

(e.g. priority: 0 → weight: 1). Since the AP is the "heart" of the WLAN and it often interconnects the WLAN with the backbone wired network, any traffic coming from the AP should be served with definitely higher priority. In order to favor the AP TSs, we use the *W_AP* (default value is 5) factor to calculate the non-normalized eligible bandwidth percentage. So, for every TS *i* transmitted by the AP it stands:

$$Per[i] = W\_AP \times (W\_PR \times PerPR[i] + W\_BW \times PerBW[i]) \tag{11}$$

We finally normalize:

$$nPer[i] = \frac{Per[i]}{\sum_{j=0}^{NumberOfRequestingTS-1} Per[j]} \tag{12}$$

Step	TS	Priority	Requested Bandwidth	Available Bandwidth	Eligible Bandwidth	Assigned Bandwidth
1	A	6	5 Mbps	10 Mbps	5.6 Mbps	5 Mbps
	B	3	3 Mbps		2.9 Mbps	-
	C	1	4 Mbps		1.5 Mbps	-
2	B	3	3 Mbps	5 Mbps	3.3 Mbps	3 Mbps
	C	1	4 Mbps		1.7 Mbps	-
3	C	1	4 Mbps	2 Mbps	2 Mbps	2 Mbps

Table 3. Example of dynamic control adapted to requirements: Assigning extra requested bandwidth to three running traffic streams

At each step, if the eligible bandwidth of a TS is higher than its requested bandwidth, then the latter is immediately granted to this TS. Finally, a proportion of the requested bandwidth is assigned to the TSs that cannot be fully served. The algorithm that calculates the extra bandwidth that would be assigned to every requesting TS is presented in pseudo-code form in Figure 6. An example is given in Table 3. This method of continuous and dynamic bandwidth assignment completes the support provided by POAC-QG to VBR traffic.

```
//Examine each running TS requesting extra bandwidth
for i=0 to NumberOfRequestingTSs-1
 {
  SumPR+=PriorityWeight[i]
  SumBW+=ExtraBW_Requested[i]
 }
for i=0 to NumberOfRequestingTSs-1
 {
  PerPR[i]=PriorityWeight[i]/SumPR //Normalize priority
  PerBW[i]= ExtraBW_Requested[i]/SumBW //Normalize extra bandwidth requested
  Per[i]=W_PR*PerPR[i]+W_BW*PerBW[i] //Non-normalized eligible bandwidth percentage
  if i belongs to the AP
   Per[i]=W_AP*Per[i]
  IsExtraBW_Decided[i]=false //Initialization of the flag
 }
IsAnyExtraBW_Decided=true //Initialize the loop termination flag to enter the loop
While IsAnyExtraBW_Decided==true //The loop terminates at that step that no new
 {                               //extra bandwidth is decided. This means that
                                 //all requests have been examined.
  IsAnyExtraBW_Decided=false //Initialize the flag in the loop
  SumPer=0;
  for i=0 to NumberOfRequestingTSs-1
   if IsExtraBW_Decided[i]==false
    SumPer+=Per[i]
  for i=0 to NumberOfRequestingTSs-1
   if IsExtraBW_Decided[i]==false //Normalize the eligible bandwidth percentage for
    {                             //the TSs that are not examined yet and calculate
     nPer[i]=Per[i]/SumPer        //the eligible bandwidth
     ExtraBW_Eligible[i]=AvailableBandwidth*nPer[i]
    }
  for i=0 to NumberOfRequestingTSs-1
   if IsExtraBW_Decided[i]==false               //Check all the unexamined TSs and
    if ExtraBW_Requested[i]<=ExtraBW_Eligible[i]//if the bandwidth requested is not
     {                                          //higher than the eligible bandwidth
      ExtraBW_Assigned[i]=ExtraBW_Requested[i]  //then assign the requested
      IsExtraBW_Decided[i]=true                 //bandwidth to the specific TS,
      AvailableBandwidth-=ExtraBW_Assigned[i]   //update the flag which shows that
      IsAnyExtraBW_Decided=true                 //the TS is examined and lower the
     }                                          //available bandwidth.
 }
//The TSs that are not assigned extra bandwidth while being in the loop are those
//that cannot get the whole extra bandwidth requested. So, finally, we assign
//these TSs the eligible extra bandwidth.
for i=0 to NumberOfRequestingTSs-1
 if IsExtraBW_Decided[i]==false
  ExtraBW_Assigned[i]=ExtraBW_Eligible[i]
```

Figure 6. The code form of the dynamic resource allocation algorithm

5. Evaluating Performance Using Simulation

It must be clarified at this point that it is not feasible to model channel access in POAC-QG based on the concept of the classical Bianchi two-state Markov chain (Bianchi, 2000). The access scheme of POAC-QG is deterministic, since the AP is informed of the stations' transmission needs by the QoS request frames. POAC-QG, does not actually involve any idle time during the RT slots. However, we do use a three-state Markov process to simulate the link status between each pair of stations, as it is explained later. Regarding the proposed mechanism for TS admission control and dynamic adjustment of the allocated resources, the algorithmic complexity and heuristic nature makes further theoretical analysis impossible and actually unnecessary. In related work, it can be seen that this is a common concept. In (Grilo et al., 2003), the proposed SETT-EDD scheduling algorithm for HCCA is evaluated via simulation and no theoretical analysis is performed. The authors state that the typical two-state Markov chain used to model the channel does not accurately represent a WLAN with link adaptation. In (Larcheri & Cigno, 2006), there is no theoretical analysis of the open-loop and closed-loop scheduling proposals for HCCA. It is stated that the authors are not particularly concerned in finding a theoretical optimal scheduler, since it could turn out to be computationally complex or lose its optimality properties due to implementation impairments. In (Ni et al., 2003), no Markov modeling is used for the analysis of the proposed FHCF scheduling scheme for HCCA. Similarly to our approach, the authors propose a formula for resource allocation based on the queue length. Lastly, in (Chou et al., 2005), a TS admission control is proposed for HCCA, employing a sequence of computations and checks which involve the traffic specifications and the available resources. However, no asymptotic analysis is performed to validate the efficiency of the mechanism, instead, simulation comparison is used.

5.1 Simulation Features

In order to evaluate the examined protocols, a specialized simulator was developed, which models the condition of any wireless link using a finite-state machine with three states. These are the following (Gilbert, 1960; Zorzi et al., 1995):

- State G denotes that the wireless link is in a relatively "clean" condition and is characterized by a small BER, which is given by the parameter *G_BER*.
- State B denotes that the wireless link is in a condition characterized by increased BER, which is given by the parameter *B_BER*.
- State H denotes that the pair of communication stations is out of range (hidden stations).

We assume that the background noise is the same for all stations, and thus, the principle of reciprocity stands for the condition of any wireless link. Therefore, for any two stations A and B, the BER of the link from A to B and the BER of the link from B to A are the same. The time spent by a link in states G, B and H is exponentially distributed, but with different average values, given by the parameters *TG*, *TB*, *TH*, respectively. The status of a link probabilistically changes between the three states. When a link is in state G and its status is about to change, the link transits either to state H, with probability given by the parameter P_h, or to state B, with transition probability $1 - P_h$. When a link is in state B and its status is about to change, the link transits either to state H, with probability given by the parameter P_h, or to state G, with transition probability $1 - P_h$. Finally, when a link spent its time in state H, it transits either to state G or B, with the same probability (0.5). It can be easily seen that by setting the parameter P_h to zero, a fully connected network topology can be assumed, whereas for values of P_h greater than zero, the effect of the well-known "hidden station" problem on protocol performance can be studied.

In a "clean" network, it stands for the inter-station links: *TG*=3 sec, *TB*=1 sec, *TH*=0.5 sec, *G_BER*=0, *B_BER*=0, P_h=0. Similarly, for the AP-station links it stands: *TG_AP*=6 sec, *TB_AP*=0.5 sec, *TH_AP*=0.25 sec, *G_BER_AP*=0, *B_BER_AP*=0, P_h*_AP*=0. The links among the AP and the stations are considered to be more reliable than the inter-station links, because the range of the AP is usually greater than the stations' range, its emitted signal is usually stronger, and its default position is the center of the cell. In a rather not "clean" wireless environment, it stands for the inter-station links: *TG*=3 sec, *TB*=1 sec, *TH*=0.5 sec, *G_BER*=0, *B_BER*=0.00001, P_h=0.05. For the AP-station links it stands: *TG_AP*=6 sec, *TB_AP*=0.5 sec, *TH_AP*=0.25 sec, *G_BER_AP*=0, *B_BER_AP*=0.000001, P_h*_AP*=0.01. The BERs are assumed to be resulted after the application of the standard's predefined coding techniques.

The default values of the network parameters used in our simulation scenarios are presented here. The medium bit rate is 36 Mbps, the signal propagation delay is 0.0005 ms corresponding to distances among the stations of 150 m, the maximum percentage of the superframe reserved for RT transmissions is 0.95, and the maximum allowed packet size is 10 KB. According to the specifications of 802.11e, we consider the following total packet sizes: "POLL"=34 bytes, "BEACON"=124 bytes, and "QoS_Request"=44 bytes. The total overhead of every traffic packet is 106 bytes, including physical, MAC, RTP, UDP, IP, and SNAP headers.

Regarding the simulation engine, the random number generator used by our simulator is a classic multiplicative congruential random number generator with period 2^{32} provided by ANSI C. The simulation results presented in this section are produced by a statistical analysis based on the "sequential simulation" method [35]. We perform simulations in a sequential way, until the relative statistical error of the estimated mean value falls below an acceptable threshold. When the relative statistical error is low, the confidence interval is narrow, since the relative statistical error is defined as the ratio of the half-width of the given confidence interval at the point estimate. For this statistical analysis we used 95% confidence intervals. The relative statistical error threshold varies depending on the meaning of the metric and the magnitude of its value. However, this threshold was usually assumed to be lower than 2% and never exceeded 5%.

5.2 First Simulation Scenario

In order to compare the performance and the general behavior of the HCCA and the POAC-QG protocols, two simulation scenarios were used. We consider only real-time traffic streams, because the background traffic access mechanism (EDCA) is the same for the two cases. In the first scenario, we have live voice and video communications (bidirectional transmissions) between the adjacent wireless stations (station 1 communicates with station 2, station 3 communicates with station 4 and so on), and a video on demand traffic stream transmitted by the AP to each station. In Figure 7, we have a representation of the transmissions taking place in the first simulation scenario. Our aim is to compare the QoS provided by the two protocols, when there is just one quality level, that is there is no QoS negotiation. So, in this case, the proposed QoS negotiation mechanism of POAC-QG does not affect the simulation results. The characteristics of the network traffic can be found in Table 4. The simulation duration is 30 sec, every communication lasts for 20 sec, a new set of transmissions (voice, live video, video on demand) are generated every second, and the simulated WLAN consists of 10 wireless stations (that is 30 traffic streams). Also, we consider "clean" links, so we used the respective network parameters' values mentioned earlier. It should be noticed that in both scenarios, we do not drop the packets that exceed their delay bound, so as to get results from all transmissions.

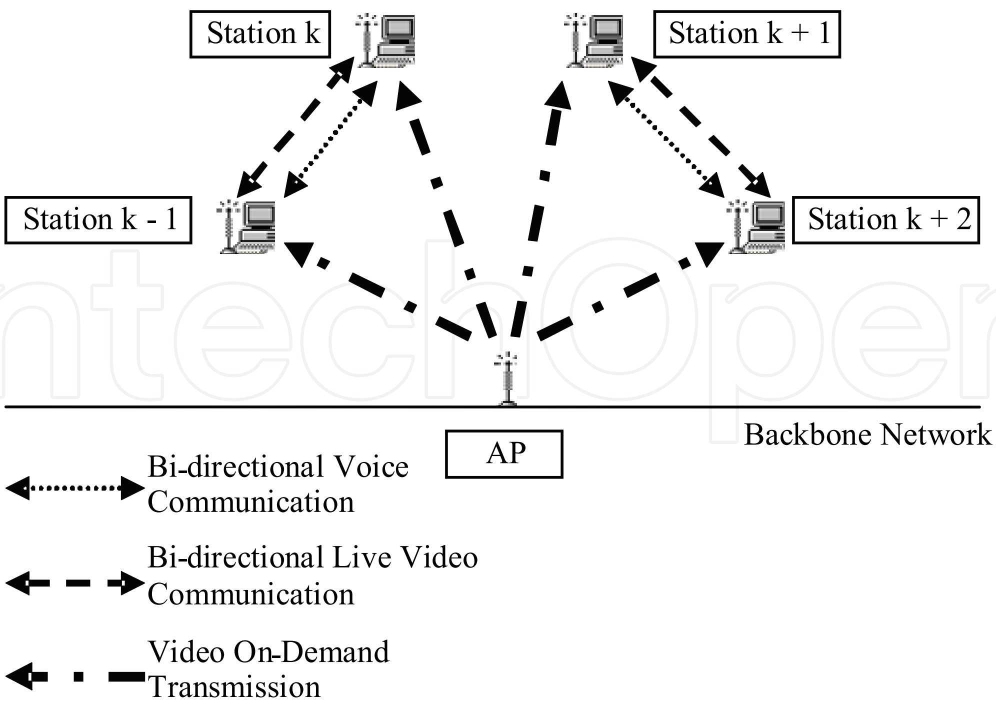

Figure 7. Traffic transmissions according to the first simulation scenario

Application	***Coding***	**Packet Data Size (bytes)**	**Packet Interarrival Time (ms)**	**Data Bit Rate**	**Packet Delay Bound (ms)**
Voice (Priority: 6)	G.711 (PCM)	160	20	64 Kbps (CBR)	50
Live Video (Priority: 5)	H.261 [QCIF]	Exponential [20-1024] Mean: 660	Exponential Mean: 26	~200 Kbps (VBR)	100
Video on Demand (Priority: 4)	MPEG-4 [4CIF]	800	2	3.2 Mbps (CBR)	200

Table 4. Traffic characteristics of the communications in the first simulation scenario

In the first simulation scenario, we get measurements of the packet jitter and the TS buffer size. These two metrics are representative of the capability of the MAC protocol to efficiently provide QoS. In Figure 8, we have plotted the results regarding packet jitter. It is obvious that in all cases POAC-QG exhibits much lower jitter than HCCA. The jitter of the voice packets is always kept below 50 ms. The graph that concerns live video, shows that POAC-QG can efficiently support VBR traffic by providing significantly low jitter values. Furthermore, it is capable of successfully serving high bit-rate CBR traffic streams, like video on demand. This superior performance of POAC-QG is partially owed in its ability to adapt to the special requirements of every TS and continuously provide the bandwidth actually needed.

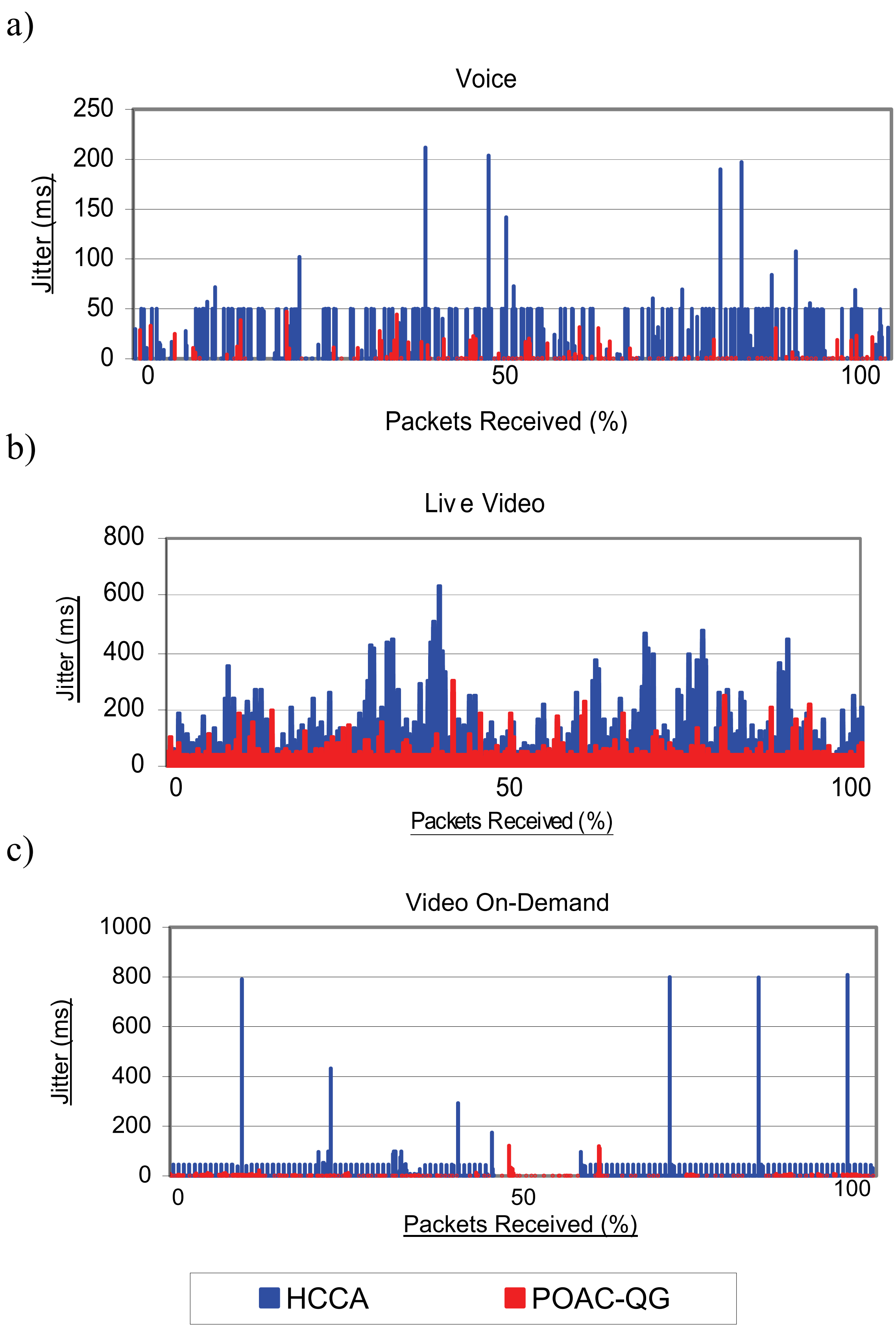

Figure 8. Packet jitter measurements concerning a) voice, b) live video, and c) video on demand traffic

The buffer size of the source station was also measured when a packet was transmitted. It is important for the source to be able to transmit on time the RT packets that arrive at the TS buffer. The ideal case would be the constant counterbalance of the transmission rate and the packet generation rate. However, in a real situation, it is quite difficult to adapt the transmission rate to the packet generation rate. This is particularly true when dealing with VBR traffic, where the packet generation rate changes continuously. In such cases, when a large number of packets suddenly arrive at the buffer, the station might be unable to transmit all packets on time, so there could be packet drops due to lack of buffer space or excess of packet lifetime. The results (which are relative to the jitter results) showed that in all cases POAC-QG manages to "unload" the buffers more efficiently than HCCA. This happens because of the proposed adaptive bandwidth assignment mechanism which continuously provides transmission rates according to the current packet generation rates. Also, the optimized access mechanism, which provides resources saving, significantly contributes to the superior performance of POAC-QG.

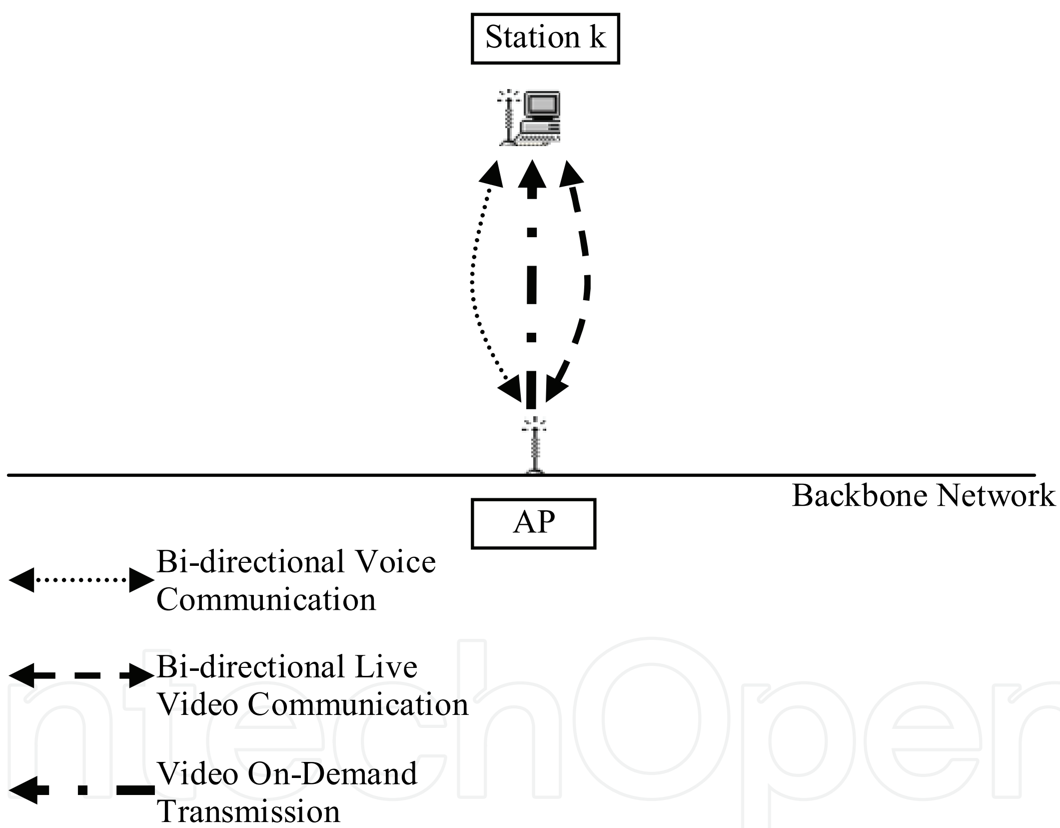

Figure 9. Traffic transmissions according to the second simulation scenario

5.3 Second Simulation Scenario

The packet delay and the QoS negotiation efficiency of POAC-QG in a rather not "clean" environment are studied in the second simulation scenario. For these reasons, we used two quality levels (MIN, MAX) and we set the network parameters to the earlier mentioned values that correspond to links of decreased reliability. The employed traffic model involves only AP-station communications. We have live voice and video communications (bidirectional transmissions) between the AP and each station, while the

AP transmits a video on demand TS to each station. In Figure 9, we have a representation of the transmissions taking place in the second simulation scenario. The traffic characteristics can be found in Table 5. We notice that voice and live video traffic support two quality levels, while video on demand traffic actually supports a single quality level. This is not a problem for the operation of POAC-QG, since it does not require that all TSs support all the provided quality levels. The simulation duration is 60 sec, every communication lasts for 30 sec, half of the transmission sets (voice, live video, video on demand) start at the beginning of the simulation and the other half start 30 sec later, and we simulated 15 WLAN topologies consisting of 2 to 30 stations (that is 10 to 150 TSs).
In Figure 10, we have plotted the average packet delay versus the number of the total offered TSs. In all cases (voice, live video, video on demand traffic), POAC-QG provides lower packet delays than HCCA, while the latter some times fails to provide delays lower than the maximum tolerable value. It should be noticed, that the total number of offered streams corresponds to the streams scheduled to take place during each simulation. However, some of them may not get permission to start at all due to limited available bandwidth. Also, the served TSs are assigned different quality levels with different bandwidth requirements, and not all of the accepted streams are served for the same time. For these reasons, we need a new metric in order to get a clear and fair view of the comparison of POAC-QG and HCCA.

Application	**QL**	**Coding**	**Packet Data Size (bytes)**	**Packet Inter-arrival Time (ms)**	**On/Off Periods (sec)**	**Data Bit Rate**	**Packet Delay Bound (ms)**
Voice (Priority: 6)	MAX	G.711 (PCM)	160	20	Expo. (mean) On: 1.5 Off: 1.8	64 Kbps (CBR)	50
	MIN	G.729_A (CS-ACELP)	20			8 Kbps (CBR)	
Live Video (Priority: 5)	MAX	H. 261 [CIF]	Expo. [40-2048] Mean: 1320	Expo. Mean: 13	Always On	~800 Kbps (VBR)	100
	MIN	H.261 [QCIF]	Expo. [20-1024] Mean: 660	Expo. Mean: 26		~200 Kbps (VBR)	
Video On-Demand (Priority: 4)	MAX	MPEG-4 [4CIF]	800	2	Always On	3.2 Mbps (CBR)	200
	MIN						

Table 5. Traffic characteristics of the communications in the second simulation scenario

We call this new metric "*Q_Score*". It depends on the priority of each served TS, its quality level, the number of served TSs, and the network's throughput. First of all, we define the factor "*Q_Factor*" which concerns the assigned quality level. *Q_Factor* is higher when a TS is assigned the MAX quality level. However, we want to get a clearly higher score when serving two MIN TSs than one MAX TS. Since it is more important to serve multiple low quality TSs than one with high quality, we decided to set *Q_Factor*=1 when the TS is assigned the MIN quality level, and *Q_Factor*=1.1 when it is assigned the MAX quality level. First, we calculate the score for each TS:

$$StreamQ\_Score = Q\_Factor \times PriorityWeight \times TimeServedRatio \tag{13}$$

where the *PriorityWeight* depends on the stream's traffic priority and the *TimeServedRatio* is the ratio of the time interval the TS was served to the total time it was scheduled to last. At this point, it should be reminded that according to our simulation settings all TSs are scheduled to last no more than the simulation duration. So, in an ideal situation, all the TSs would be completed before the simulation termination. The *IdealStreamQ_Score* is the score of a MAX quality TS that is completed before the simulation termination (*TimeServedRatio*=1). It stands:

$$IdealStreamQ\_Score = MaxQ\_Factor \times PriorityWeight \tag{14}$$

The *RatioNetQ_Score*, which concerns the total offered streams, is defined as:

$$RatioNetQ\_Score = \sum_{i=1}^{OfferedStreams} StreamQ\_Score \Big/ \sum_{i=1}^{OfferedStreams} IdealStreamQ\_Score \tag{15}$$

Finally, we calculate each simulated network's *Q_Score* in relation to the score of the same network when using a different protocol. It stands:

$$Q\_Score = RatioNetQ\_Score \times \frac{Throughput}{HigherThroughput} \tag{16}$$

for the network with the lower throughput and *Q_Score*=*RatioNetQ_Score* for the network with the higher throughput. For example, if a HCCA network has *RatioNetQ_Score*=1 and *Throughput*=0.6, and the same network using POAC-QG has *RatioNetQ_Score*=1 and *Throughput*=0.8, then the *Q_Score* for the HCCA network is 0.75 while for the POAC-QG network is 1. Thus, *Q_Score* as it is formed in equation (16), can only be used to compare the performance of two networks and not as an individual metric.

The statistical results concerning the *Q_Score* of 15 network topologies (2 to 30 mobile stations) are depicted in Figure 11. Obviously, POAC-QG always exhibits higher *Q_Score* than HCCA. This is a definite indication of the efficiency of the QoS negotiation mechanism employed by POAC-QG. In all cases, the proposed protocol ensures a better combination of MAX and MIN quality level TSs, as shown in Figure 12. It appears that POAC-QG always serves as many TSs as possible to the best quality it can achieve.

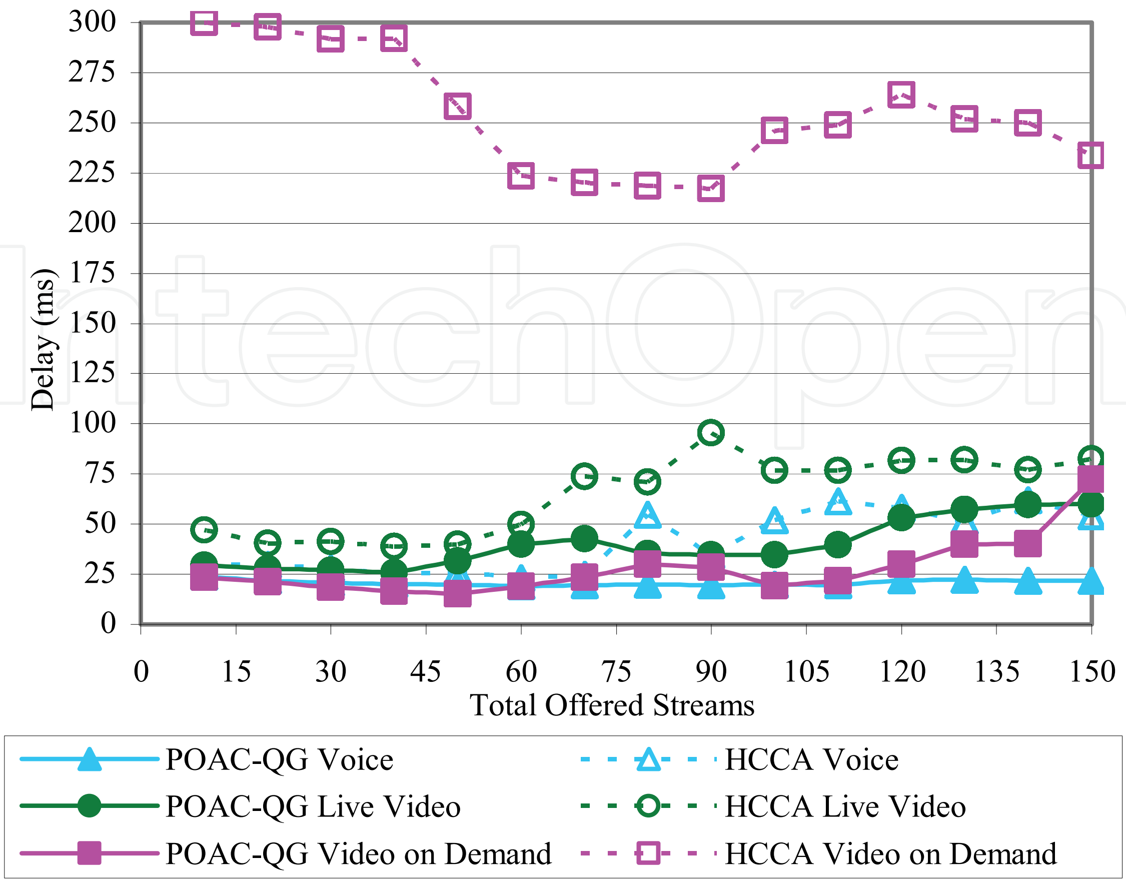

Figure 10. The average packet delay as a function of the total offered traffic streams

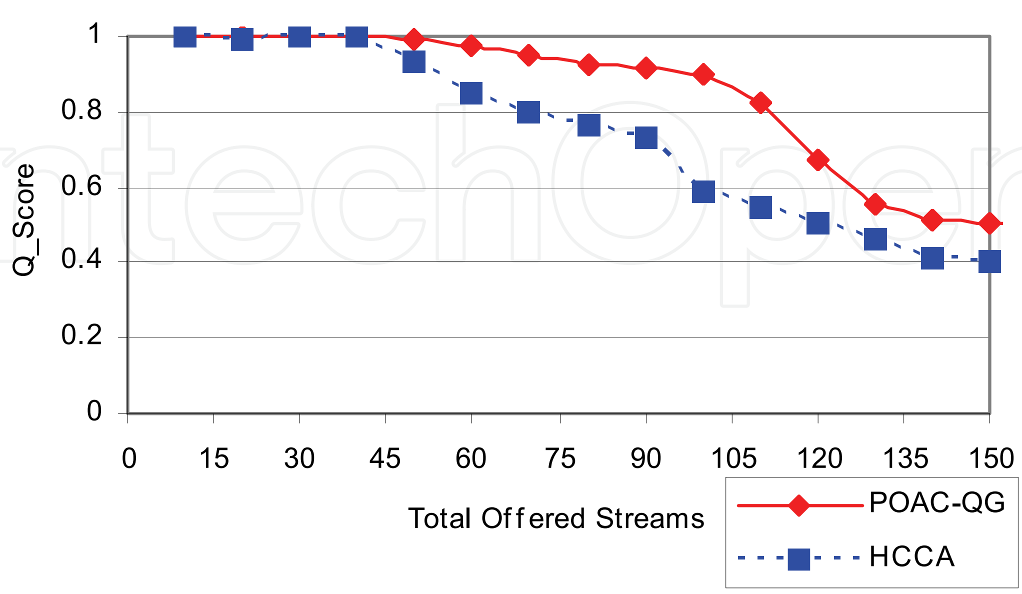

Figure 11. The Q_Score as a function of the total offered traffic streams

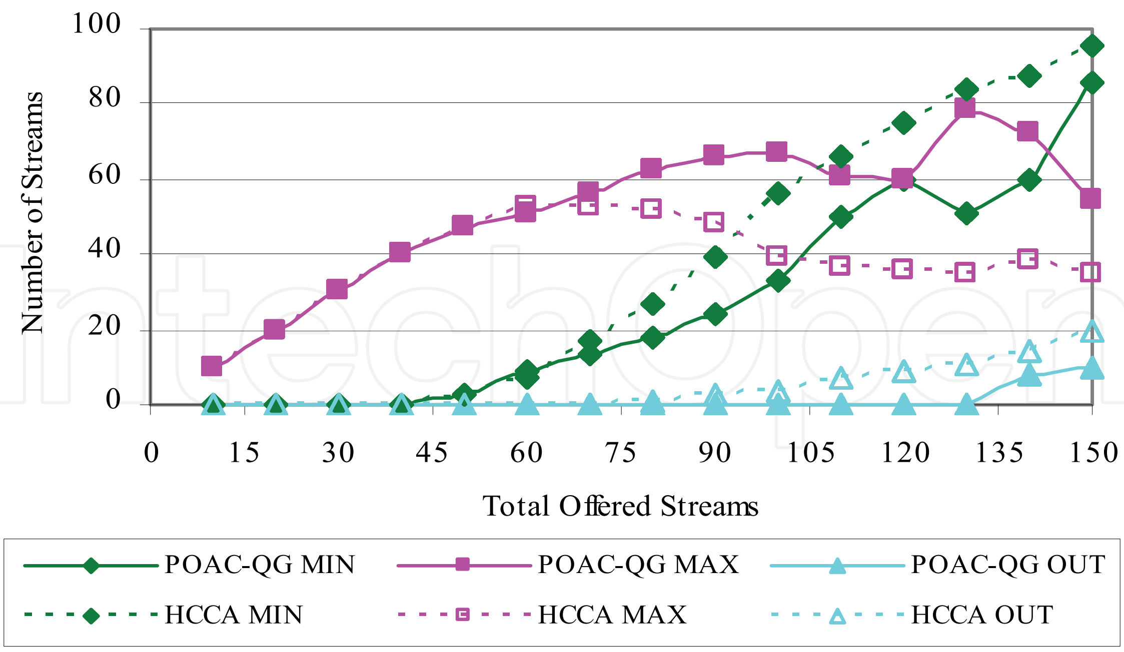

Figure 12. The number of the traffic streams assigned the minimum-maximum quality level quality level or they were rejected versus the number of the total offered traffic streams

6. Conclusion

This chapter discoursed on adaptive control for wireless local area networks introducing the Priority Oriented Adaptive Control with QoS Guarantee (POAC-QG) protocol for WLANs. It can be adapted into the HCF protocol of the IEEE 802.11e standard in place of HCCA. A TDMA scheme is adopted for the access mechanism. POAC-QG is designed to efficiently support all types of real-time traffic. It guarantees QoS both for CBR and VBR traffic, by continuously adapting to their special requirements. Since numerous network multimedia applications produce VBR traffic, it is essential to support it with high quality. HCCA, on the other hand, appears to be unable to efficiently support VBR traffic. POAC-QG makes extended use of traffic priorities in order to differentiate the TSs according to their application. The proposed superframe using slots decreases the total overhead, provides better synchronization, since every station is informed by the beacon of the exact time slots assigned to each station, and thus it potentially allows the use of an efficient power saving mechanism. POAC-QG employs a direct QoS negotiation mechanism that supports multiple quality levels for the TSs. This mechanism and the dynamic bandwidth allocation provide support to multiple TSs to the best quality the protocol can achieve. The simulation results reveal this behavior and show that POAC-QG always performs superiorly than HCCA when comparing the packet jitter, TS buffer size and packet delay. As future work, POAC-QG can be enhanced with a power saving mechanism and it can be combined with an efficient background traffic protocol in place of EDCA in order to form a complete high performance protocol for infrastructure WLANs.

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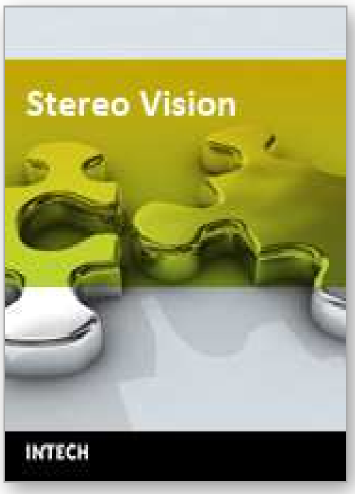

Frontiers in Adaptive Control

Edited by Shuang Cong

ISBN 978-953-7619-43-5
Hard cover, 334 pages
Publisher InTech
Published online 01, January, 2009
Published in print edition January, 2009

The objective of this book is to provide an up-to-date and state-of-the-art coverage of diverse aspects related to adaptive control theory, methodologies and applications. These include various robust techniques, performance enhancement techniques, techniques with less a-priori knowledge, nonlinear adaptive control techniques and intelligent adaptive techniques. There are several themes in this book which instance both the maturity and the novelty of the general adaptive control. Each chapter is introduced by a brief preamble providing the background and objectives of subject matter. The experiment results are presented in considerable detail in order to facilitate the comprehension of the theoretical development, as well as to increase sensitivity of applications in practical problems