Energy Efficient Feedback-based Scheduler for Delay Guarantees in IEEE 802.11e Networks ⋆

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Abstract

Energy saving algorithms for 802.11 Wireless LAN (WLAN) are basically based on keeping in a low-power state the Wireless Network Interface Card (WNIC) whenever a wireless station does not have frames to be transmitted/received. This can severely affect the QoS of the service provided to higher layers due to the transient time needed to switch from a low-power to a high-power state. Recently, the 802.11e Working Group (WG) has proposed a set of innovative functionalities in order to provide QoS in WLANs. In particular, the core of the 802.11e proposal is the Hybrid Coordination Function (HCF), which has a HCF Controlled Channel Access (HCCA) and an Enhanced Distributed Coordination Access (EDCA). In this paper, an innovative HCCA-based algorithm, which will be referred to as Power Save Feedback Based Dynamic Scheduler (PS FBDS), has been proposed to provide bounded delays while ensuring energy saving. Using ns-2 simulations, it has been shown that PS FBDS is able to provide a good trade-off between QoS and power saving at both low and high network loads.

Key words: WLAN, Power Saving, QoS, Dynamic Bandwidth Allocation, Feedback control

1 Introduction

The IEEE 802.11 WLAN is a well assessed solution for providing ubiquitous wireless networking [1,2]. In the architecture of such networks, the building block is the Basic Service Set (BSS), which consists of an Access Point (AP)

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and a set of Wireless Stations (WSTAs). The traffic from/to the WSTAs is channeled through the AP, which may be connected to the wired part of the network. WSTAs are usually devices, such as laptops or PDAs (Personal Digital Assistants), with limited battery supply lifetime [3]. For example, it has been shown that a Wireless Network Interface Card (WNIC) can reduce the battery lifetime of a laptop up to the 60 percent [3,4]. As a consequence, power-saving is a critical issue for a broader diffusion of WLAN equipped hot-spots [5]. To this aim, the 802.11 standard proposes a power saving (PS) mechanism in the Distributed Coordination Function (DCF), which is based on turning off the WNIC whenever a wireless station does not have frames to send/receive [1]. However, several works [6–8] have highlighted that 802.11 PS presents several inefficiencies and can severely affect the frame delivering delay, thus, making the 802.11 WLANs useless for real-time applications. The works [9–12] propose some energy optimizations of the 802.11 MAC, but when the PS is not used.

The 802.11e Working Group (WG) has recently proposed a set of innovative functionalities in order to provide QoS in WLANs [13]. In particular, the core of the 802.11e proposal is the Hybrid Coordination Function (HCF), which has a HCF Controlled Channel Access (HCCA) and an Enhanced Distributed Coordination Access (EDCA). Previous works have shown that HCCA can be fruitfully exploited to provide a bounded-delay service to real-time applications [14–16]. However, these works did not consider any requirements on energy consumption, which are fundamental when we have to deal with portable devices such as laptops or PDAs. In order to bridge this gap, this paper proposes an innovative HCCA-based algorithm, which will be referred to as Power Save Feedback Based Dynamic Scheduler (PS FBDS), providing bounded delays while ensuring energy saving. The performance of PS FBDS has been investigated using *ns*-2 simulations [17].

The rest of the paper is organized as follows: Section 2 gives an overview of the 802.11 MAC protocol and of QoS enhancements; Section 3 describes the the PS FBDS algorithm; Section 4 reports *ns*-2 simulation results. Finally, the last section draws the conclusions.

2 The IEEE 802.11 MAC

2.1 The DCF access method

The basic 802.11 MAC protocol is the Distributed Coordination Function (DCF), which is based on the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism: for each frame a station listens the channel before transmitting; if a station detects an idle channel for a minimum interval time called DCF Interframe Space (DIFS), then it transmits immediately a MAC Protocol Data Unit (MPDU). Otherwise, if the medium is sensed busy, transmission is deferred until the channel is sensed idle for a DIFS period plus an additional random backoff time [1]. The backoff time is a multiple of a *slot time*, where the slot time depends on the physical layer implementation, and the multiple is an integer taken from a uniform distribution in the interval from 0 to the *Contention Window* (CW) [1,2], which is set according to the number of consecutive retransmissions.

2.2 The PCF access method

In order to support time-sensitive services, the 802.11 standard defines the Point Coordination Function (PCF) as an optional access method which provides a contention-free medium access. The Point Coordinator (PC) polls the stations asking for time-sensitive service and allows them to transmit a data frame without channel contention. With PCF, the time is divided into repeated periods, called *SuperFrames* (SFs), which consist of a Contention Period (CP) and a Contention Free Period (CFP). During the CP, the channel is accessed using DCF whereas, during the CFP, is accessed using the the PCF. Although PCF has been designed to support time-bounded multimedia applications, this mode leads to poor QoS performance. In fact, it is hard for the AP to predict the transmission time of a polled WSTA [18,19].

2.3 IEEE 802.11e QoS enhancements

In order to obtain service differentiation in 802.11 WLANs, the 802.11e Working Group has introduced an improved access method, known as the Hybrid Coordination Function (HCF) [13]. This access scheme extends the basic 802.11 DCF method.

Stations operating under 802.11e specifications are usually known as enhanced stations or QoS Stations (QSTAs). Using the same priority values of the IEEE 802.1D standard [20], 802.11e defines 8 Traffic Categories (TCs) characterized by traffic specifications (TSPECs) similar to those introduced in [21] for *IP FlowSPecs* definition and adopted in IntServ [22] and DiffServ [23] architectures. In particular, four Access Categories (ACs) have been introduced in order to support the mentioned eight TCs. To satisfy the QoS requirements of each AC, the concept of TXOP (Transmission Opportunity) is introduced, which is defined as the time interval during which a station has the right to transmit and is characterized by a starting time and a maximum duration. The contiguous time during which TXOPs are granted to the same QSTA is called Service Period (SP). The interval T_{SI} between two successive SPs is called Service Interval [18,13].

The Hybrid Coordination Function (HCF) is made of a contention-based channel access, known as the Enhanced Distributed Coordination Access (EDCA), and of a HCF Controlled Channel Access (HCCA). The use of the HCF requires a centralized controller, which is called the Hybrid Coordinator (HC) and is generally located at the AP.

The EDCA method operates as the basic DCF access method [1,2], but using different contention parameters per access category. In this way, a service differentiation among ACs is statistically pursued [24]. A queue is associated to each AC at any QSTA, which acts as a virtual station with its own QoS parameters. Each queue within a station contends for a TXOP and defers its transmission until the channel is sensed idle for a time interval, known as Arbitration Interframe Space (AIFS), plus an additional random backoff time, which is given by the product between a slot time and an integer drawn from a uniform distribution over the interval [0,CW(i)]. Note that, for each class AC(i), a contention window CW(i) and an AIFS(i) are defined as shown in Table 1 [25]. If several backoff timers reach zero within the same station at the same time slot, then the highest priority frame will be transmitted and any other frames will be deferred with a retry procedure and modifying the backoff timer [18,13]. Tuning EDCA parameters in order to meet a specific QoS need is a current research topic [19,26].

Table 1

Typical values of EDCA contention parameters

AC	CW_{min}	CW_{max}	AIFS
AC_BK	CW_{min}	CW_{max}	7
AC_BE	CW_{min}	CW_{max}	3
AC_VI	$(CW_{min}+1)/2-1$	CW_{min}	2
AC_VO	$(CW_{min}+1)/4-1$	$(CW_{min}+1)/2-1$	2

The HCCA method combines some of the EDCA characteristics with some feature of the Point Coordination Function (PCF) scheme.

The time is still divided into SuperFrames, each one starts with a beacon frame after which, for legacy purpose, there could be a contention free period (CFP) for PCF access. The remaining part of the superframe forms the Contention Period (CP), during which the QSTAs contend to access the radio channel using the EDCA mechanism (see Fig. 1).

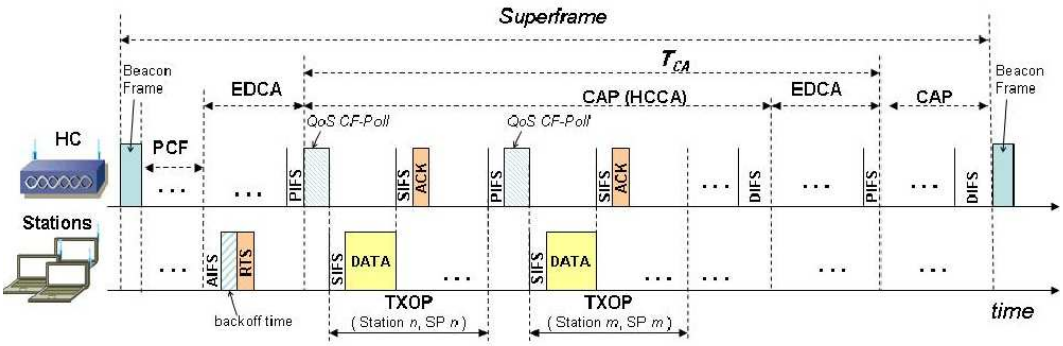

Fig. 1. Scheme of a superframe using the HCF controlled access method.

During the CP, the HC can start a Contention Access Phase (CAP) [1]. During the CAP, only QSTAs, polled and granted with the *QoS CF-Poll frame*, are allowed to transmit during their TXOPs. Thus, the HC implements a prioritized medium access control. The number of CAPs and their locations in each superframe are chosen by the HC in order to satisfy QoS needs of each station. Moreover, at least one CP interval, long enough to transmit a maximum size data frame at the minimum rate, must be contained in a superframe; this CP interval can be used for management tasks, such as associations of new stations, new traffic negotiations, and so on. CAP length cannot exceed the value of the system variable *dot11CAPLimit*, which is advertised by the HC in the Beacon frame when each superframe starts [13].

According to IEEE 802.11e specifications, each QSTA can feed back queue length of each AC to the HC [2]. This information can be fruitfully exploited to design novel HCCA-based dynamic bandwidth allocation algorithms using feedback control theory [14]. In fact, the 802.11e draft does not specify how to schedule TXOPs in order to provide the required QoS; it only suggests a simple scheduler which assigns fixed TXOPs using the static values declared in TSPECs. This scheduler does not exploit any feedback information from mobile stations in order to dynamically assign TXOPs, i.e. it provides a CBR service, which is not well suited for VBR multimedia flows [15].

An improved bandwidth allocation algorithm has been proposed in [27], which schedules transmission opportunities by taking into account both the average and the maximum source rates declared in the TSPECs. An adaptive version of the simple scheduler, which is based on the Delay-Earliest Due-Date algorithm, has been proposed in [15]. However, this algorithm does not exploit the explicit

[1] HCCA can be also enabled during the CFP with a procedure similar to the one described in this Section.
[2] In each frame header there is the *QoS Control Field* which reports queue lengths in units of 256 octets.

queue length to assign TXOPs, but implements a trial and error procedure to discover the optimal TXOP to be assigned to each station. Finally, in [14] a control theoretic framewok along with a new bandwidth allocation algorithm have been proposed to tackle the problem of dynamic bandwidth allocation in 802.11 WLANs. The algorithm proposed in [14], which has been referred to as Feedback Basad Dynamic Scheduler (FBDS), will be considered as starting point of the present work. In particular, in the next section, the Power Save extension of FBDS will be proposed as an energy efficient dynamic bandwidth allocation algorithm to support real-time services.

2.4 Overview of the Power Saving in 802.11 infrastructure WLANs

The power saving issue has been addressed in the 802.11 standard [1], by defining for each station two different power states:

- *Awake State*: the station is fully powered (i.e., the WNIC is on and consumes the power needed to transmit/receive frames and to sense the channel);
- *Doze State*: the station is not able to transmit or receive (i.e, the WNIC consumes very low power);

Moreover, two power management modes have been introduced:

- *Active* Mode: a station may receive frames at any time, i.e., it is always in awake state;
- *Power Save* (PS) Mode: a station is normally in the *Doze State* and enters in the *Awake State* to transmit frames and to receive beacon frames, broadcast, and unicast transmissions.

In the infrastructure WLANs, a station using PS mode shall inform the AP about this, by setting the power management bits in the Control Field of the frame header.

The AP cannot transmit MSDUs to stations operating in PS mode, but it has to buffer MSDUs and to transmit them only at designated time instants, when such stations are in awake state.

In all beacon frames, the *traffic indication message* (TIM) is sent to indicate stations in PS mode (i.e., PS stations) which have buffered unicast data in the AP (see Fig. 2). In particular, the AP identifies each station with an *Association ID* code, i.e., a bit code in a field of the TIM frame. On the other hand, buffered broadcast and multicast frames are signaled through the *delivery* TIM (DTIM) element. The interval between two consecutive DTIM frames is specified by the *DTIMPeriod* field within the TIM element (e.g., see Fig. 2 in which the *DTIMPeriod* is equal to three beacon intervals).

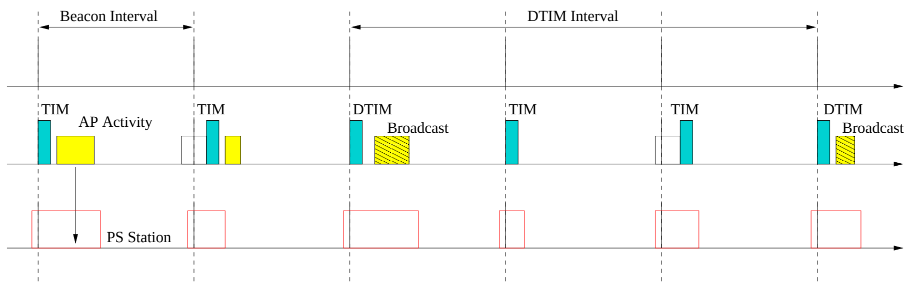

Fig. 2. Sequence of TIM and DTIM frames.

A PS Station shall wake up in order to receive the Beacon frame and to detect, by means of TIM/DTIM, if the AP has buffered MSDUs for it.

If the PS station accesses the channel with the DCF method and there are pending data in the AP, it sends to the AP a PS-Poll frame during the Contention Period (CP) in order to receive a single buffered data frame; if the AP sets the *More data field* in the sent frame, the station can request other frames until there are buffered MSDUs or can transit in doze state. Broadcast frames are sent immediately after the beacon frame that includes DTIM: a station should be active until it has received broadcast frames from the AP.

Otherwise, if the PS station accesses the channel with the PCF method and there are pending data in the AP, it remains awake during the Contention-Free Period (CFP) at least until it receives any frame from the AP (i.e., management or data frames). If the more data field is set when the CFP ends, the station can remain awake to send a PS-Poll frame to the AP during the CP or passes in doze state until the next CFP.

2.5 IEEE 802.11e power saving enhancements

The IEEE 802.11e Working Group has introduced a new power saving mechanism, known as *Automatic Power Save Delivery* (APSD) [13], which allows the delivery of downlink frames to a station according to a defined "schedule", i.e., the downlink frames are transmitted by the HC only in given service periods.

In particular, when APSD is active, the HC buffers the data frames addressed to APSD stations (i.e., stations which use the APSD mode) in doze state and it transmits them according to two different type of service periods: *Scheduled* and *Unscheduled*.

Scheduled service periods occur always at the same time instants in the superframe. These service periods are assigned by the HC to a station when a new traffic stream starts. During its scheduled service period, a station is awake to receive buffered downlink frames and/or polls the HC.

Unscheduled service periods are asynchronous in the superframe. They occur as soon as the HC knows that the APSD station wakes up by receiving any frame from the station.

When a station wants to use APSD mode, it signals this intent to the HC by setting a specific subfield in the TSPEC; during the association, the station requests the service period. If the HC could not satisfy the period request by the station, it sends a "schedule element" with its new service period proposal.

3 The PS FBDS Bandwidth Allocation Algorithm

This section summarizes the FBDS bandwidth allocation algorithm proposed in [14] and introduces its power saving extension. The algorithm, which has been designed using classical feedback control theory, distributes the WLAN bandwidth among all the multimedia flows by taking into account the queue levels fed back by the QSTAs [14]. Bandwidth allocation is pursued by exploiting the HCCA functionalities, which allows the HC to assign TXOPs to the ACs by taking into account the specific time constraints of each AC.

Mainly following [14], we will refer to a WLAN system made of an Access Point (AP) and a set of quality of service enabled mobile stations (QSTAs). Each QSTA has N queues, with $N \leq 4$, one for any AC in the 802.11e proposal. Let T_{CA} be the time interval between two successive CAPs. Every time interval T_{CA}, assumed constant, the AP must allocate the bandwidth that will drain each queue during the next CAP. We assume that at the beginning of each CAP, the AP is aware of all the queue levels $q_i,\ i = 1, \ldots, M$ at the beginning of the previous CAP, where M is the total number of traffic queues in the WLAN system. The latter is a worst case assumption, in fact, queue levels are fed back using frame headers as described in Sec. 2.3; as a consequence, if the i^{th} queue length has been fed at the beginning of the previous CAP, then the feedback signal might be delayed up to T_{CA} seconds.

The dynamics of the i^{th} queue can be described by the following discrete time linear model:

$$q_i(k+1) = q_i(k) + d_i(k) \cdot T_{CA} + u_i(k) \cdot T_{CA}, \qquad i = 1, \ldots, M, \tag{1}$$

where $q_i(k) \geq 0$ is the i^{th} queue level at the beginning of the k^{th} CAP; $u_i(k) \leq 0$ is the average depletion rate of the i^{th} queue (i.e., $|u_i|$ is the bandwidth assigned to drain the i^{th} queue); $d_i(k) = d_i^s(k) - d_i^{CP}(k)$ is the difference between $d_i^s(k) \geq 0$, which is the average input rate at the i^{th} queue during the k^{th} T_{CA}

interval, and $d_i^{CP}(k) \geq 0$, which is the amount of data transmitted by the i^{th} queue during the k^{th} CP (using EDCA) divided by T_{CA}.

The signal $d_i(k)$ is unpredictable since it depends on the behavior of the source that feeds the i^{th} queue and on the number of packets transmitted during the contention periods. Thus, from a control theoretic perspective, $d_i(k)$ can be modelled as a disturbance. Without loss of generality, the following piece-wise constant model for the disturbance $d_i(k)$ can be assumed [28]:

$$d_i(k) = \sum_{j=0}^{+\infty} d_{0j} \cdot 1(k - t_j) \tag{2}$$

where $1(k)$ is the unitary step function, $d_{0j} \in \mathbb{R}$, and t_j is a time lag.

Due to the assumption (2), the linearity of the system (1), and the superposition principle that holds for linear systems, we will design the feedback control law by considering only a step disturbance: $d_i(k) = d_0 \cdot 1(k)$.

3.1 The control law

In [14], using a proportional controller with gain k_i, the following control law has been proposed to drive the queuing delay τ_i experienced by each frame going through the i^{th} queue to a desired target value τ_i^T that represents the QoS requirement of the AC associated to the queue:

$$u_i(k+1) = -k_i \cdot q_i(k) \tag{3}$$

In order to fullfill both system stability and steady-state delay requirements, in [14], it has been shown that the gain k_i has to be chosen as follows:

$$\frac{1}{\tau_i^T} \leq k_i < \frac{1}{T_{CA}}. \tag{4}$$

Finally, from inequalities (4) the following rule to tune T_{CA} system parameter it turns out:

$$T_{CA} < \min_{i=1..M} \tau_i^T. \tag{5}$$

3.2 TXOP assignment

We have seen in Sec. 2.3 that every time interval T_{CA} the HC allocates TXOPs to mobile stations in order to meet QoS constraints. This sub-section shows how to transform the bandwidth $|u_i|$ into a $TXOP_i$ assignment. In particular, if the i^{th} queue is drained at data rate C_i, the following relation holds:

$$TXOP_i(k) = \frac{|u_i(k) \cdot T_{CA}|}{C_i} + O_H \qquad (6)$$

where $TXOP_i(k)$ is the TXOP assigned to the i^{th} queue during the k^{th} service interval and O_H is the time overhead due to ACK packets, SIFS and PIFS time intervals (see Fig. 1). The extra quota of TXOP due to the overhead O_H depends on the number of MSDUs corresponding to the amount of data $|u_i(k) \cdot T_{CA}|$ to be transmitted. O_H could be estimated by assuming that all MSDUs have the same nominal size specified into the TSPEC. Moreover, when $|u_i(k) \cdot T_{CA}|$ does not correspond to a multiple of MSDUs, the TXOP assignment will be rounded in excess in order guarantee a queuing delay always equal or smaller than the target delay τ_i^T.

3.3 Channel saturation

The above bandwidth allocation algorithm is based on the implicit assumption that the sum of the TXOPs assigned to each queue is smaller than the maximum CAP duration, which is the *dot11CAPLimit*; this value can be violated when the network is saturated.

In this case, it is necessary to reallocate the TXOPs to avoid exceeding the CAP limit. This task is performed as follows: when $\sum_{i=1}^{M} TXOP_i(k) > dot11CAPLimit$, each computed $TXOP_i(k)$ is decreased by an amount $\Delta TXOP_i(k)$, so that the capacity constraints

$$\sum_{i=1}^{M} [TXOP_i(k) - \Delta TXOP_i(k)] = dot11CAPLimit \qquad (7)$$

is satisfied.

In particular, the generic $\Delta TXOP_i(k)$ is evaluated as a fraction of the total amount $\sum_{i=1}^{M} TXOP_i(k) - dot11CAPLimit$, as follows:

$$\Delta TXOP_i(k) = \frac{TXOP_i(k)C_i}{\sum_{j=1}^{M}\left[TXOP_j(k)C_j\right]}\left(\sum_{j=1}^{M} TXOP_j(k) - dot11CAPLimit\right). \quad (8)$$

Notice that Eq. (8) provides a $\Delta TXOP_i(k)$, which is proportional to $TXOP_i(k)C_i$, in this way connections transmitting at low rates are not penalized too much.

3.4 Power Saving FBDS

In this section we will discuss the extension of FBDS to manage the power saving; in particular, we will refer to this extension of the algorithm as Power Save FBDS (PS FBDS).

The proposed extensions modify the behaviour of the QSTAs when HCCA or EDCA are used. In particular, at the beginning of each superframe, a station using PS FBDS wakes up to receive beacon frames.

Then, if the HCCA method is used to access to the channel, the QSTA does not pass in *doze state* until it has received the QoS-Poll frame and the TXOP assignment from the HC. After the station has drained its queue according to the assigned TXOP, it will transit in *doze state* if and only if its transmission queues are empty.

On the other hand, when the EDCA is used, a QSTA in *doze state* wakes up whenever any of its transmission queues is not empty. In this case, after the transition to the *awake state*, the backoff timer for that QSTA is set to zero. As a consequence, that QSTA will gain the access to the channel with a higher probability with respect to stations using classical EDCA. In the sequel, we will refer to this slightly modified version of the EDCA as Power Save EDCA (PS EDCA).

4 Performance Evaluation

To test the effectiveness of PS FBDS, we have implemented the original FBDS algorithm and its power save enhanced version in the *ns*-2 simulator [17]. We have considered a 802.11a WLAN network shared by a mix of audio flows encoded with the G.729 standard [29], video flows encoded with the MPEG-4 [30] or the H.263 standards [31], and FTP flows. From each wireless node, a single data flow is generated. For the video flows, we have used traffic traces available from the video trace library [32]. For the audio flows, we have been modelled the G.729 sources using a Markov ON/OFF source, where ON and OFF periods are exponentially distributed with mean values 350 ms and 650 ms, respectively [33]. During the ON period, the voice source sends packets of 20 bytes every 20 ms (i.e., the source data rate is 8 kbps; also we consider two G.729 frames combined into one packet [34]). By taking into account the overheads of the RTP/UDP/IP protocol stack, during the ON periods the total rate over the wireless channel is 24 kbps. During the OFF period the rate is approximated by zero because we assume the presence of a Voice Activity Detector (VAD). Main characteristics of the considered multimedia flows are summarized in Table 4.

Table 2
Main features of the considered multimedia flows.

Type of flow	*Nominal (Maximun) MSDU Size*	*Mean Data Rate*	*Target Delay*
MPEG-4 HQ	1536 (2304) byte	770 kbps	40 ms
H.263 VBR	1536 (2304) byte	450 kbps	40 ms
G.729 VAD	60 (60) byte	8.4 kbps	30 ms

In the *ns*-2 implementation the T_{CA} is expressed in Time Units (TU), which in the 802.11 standard [1] are equal to 1024 μs. We assume a T_{CA} of 29 TU. The proportional gain k_i is set equal to $1/\tau_i^T$. We have compared FBDS, PS FBDS, EDCA, and PS EDCA algorithms for different network loads. In particular, we consider an 802.11a WLAN shared by a traffic mix composed by α MPEG-4 flows, α H.263 VBR flows, 3α G.729 flows, and α FTP flows, where α will be referred to as load factor. The data rate has been assumed equal to 54 Mbps for all the mobile stations. The load factor has been varied in order to investigate the effect of different traffic conditions on the performance of the considered allocation algorithms.

Stations hosting FTP flows do not use any power saving extensions. FTP flows are used to fill in the bandwidth left unused by flows with higher priority.

Table 3 summarizes the power consumption parameters considered in our simulations.

Power Save capabilities, when used, are turned ON after 15 s of simulation time.

Table 3
Power consumption parameters (see Maxim MAX-2825 802.11g/a RF Transceiver IC [35]).

TX Power	393 mW
RX Power	357 mW
Stand-by Power	125 mW
Doze Power	33 μW
Start Energy	10 J

Figs. 3 and 4 show the average value and the standard deviation of the one-way packet delay experienced by the MPEG flows for several values of the load factor α. They show that both FBDS and PS-FBDS provide the smallest delays at high network loads (i.e., when $\alpha \geq 6$). In fact, FBDS allocates the right amount of bandwidth to each flow by taking into account the transmission queue levels of each wireless node; this allows a cautious usage of the WLAN bandwidth, so that QoS constraints are met also in the presence of a high number of competing flows. Regarding the power saving issue, Figs. 5-7 report the residual energy of a node hosting a MPEG traffic source for $\alpha = 9,\ 6,$ and 3. When $\alpha = 9$ it is straightforward to note that a great energy saving can be achieved using PS FBDS. In fact, after 50 s of activity, PS FBDS leads to a total energy consumption less than 5 J, whereas, when the other considered schemes are employed, the energy consumption is larger than 8 J. When $\alpha = 3$ (low network load) PS HCCA and PS EDCA provide the same energy saving because, in this case, almost all traffic is served using EDCA. For $\alpha = 6$ intermediate results are obtained. Thus PS FBDS allows energy saving while providing the same delay bounds of the original FBDS algorithm.

Similar conclusions can be drawn by looking at Figs. 8-12, which report analogous results obtained for a wireless node hosting a H.263 traffic source.

Results are very different when we consider G.729 flows. In fact, we have to consider that these flows are served with the maximum priority by the EDCA, and that the PS EDCA is more aggressive than standard EDCA (see Sec. III.D). Figs. 13 and 14 show that, when PS EDCA is used, the smallest delays are obtained. However, from these figures it can be noticed that delays provided by the other considered schemes are smaller than 100 ms also at high network loads, i.e., PS FBDS, FBDS, and standard EDCA provide acceptable performance.

Regarding energy consumption, Fig. 15 reports the residual energy of a node hosting a G.729 traffic source in the case $\alpha = 9$. It shows that while PS FBDS,

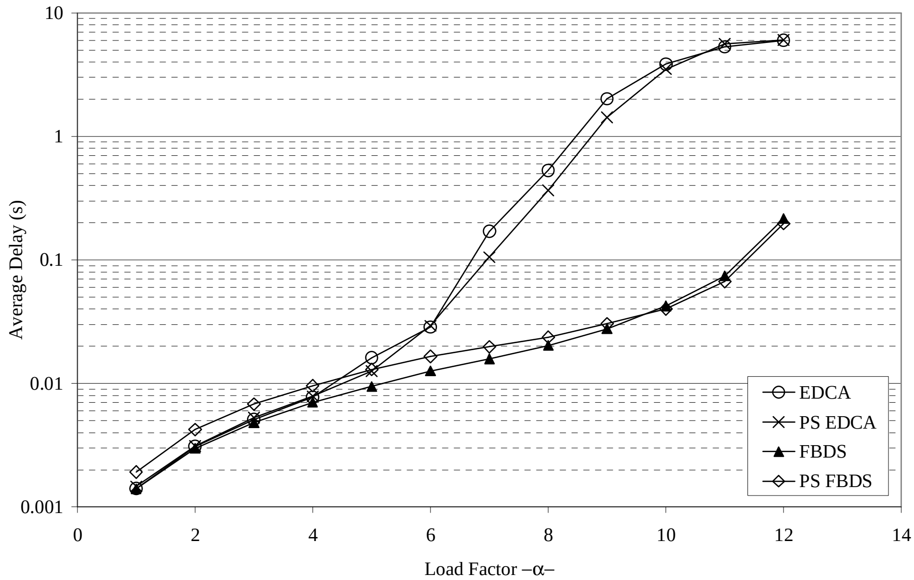

Fig. 3. Average one-way delays of MPEG4 flows as a function of the load factor α.

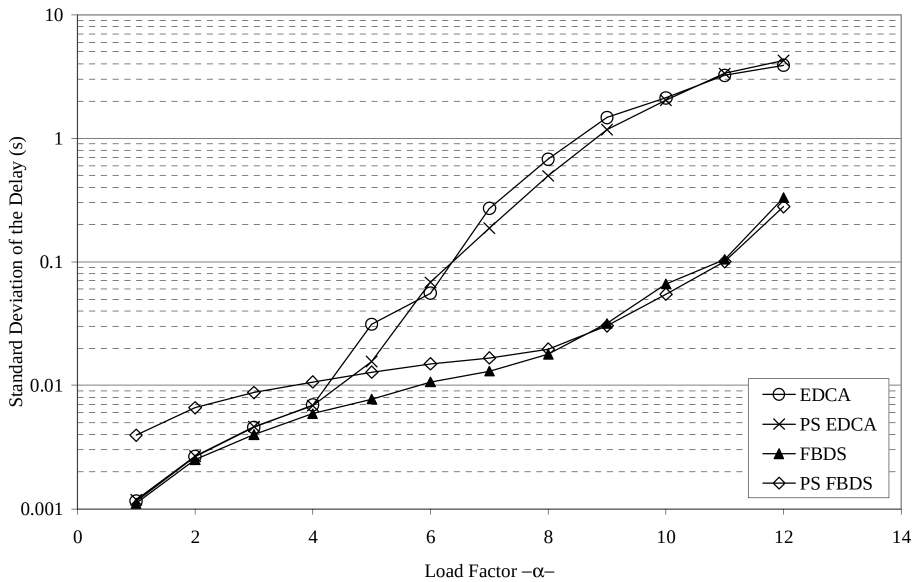

Fig. 4. Standard deviation of one-way delays of MPEG4 flows as a function of the load factor α.

FBDS and EDCA provide almost the same energy consumption observed in the previous simulations, PS EDCA provides the highest energy saving. The reason is that PS EDCA reset the backoff to zero before turning ON the WNIC and accessing the channel, which reduces the listening channel time and enables energy saving. The gap between PS FBDS and PS EDCA diminishes for smaller values of α for the same reasons discussed above (see Figs. 16 and 17).

To conclude, we have observed that PS FBDS is able to provide an acceptable trade-off between energy saving and one-way packet delay. In fact, it provides

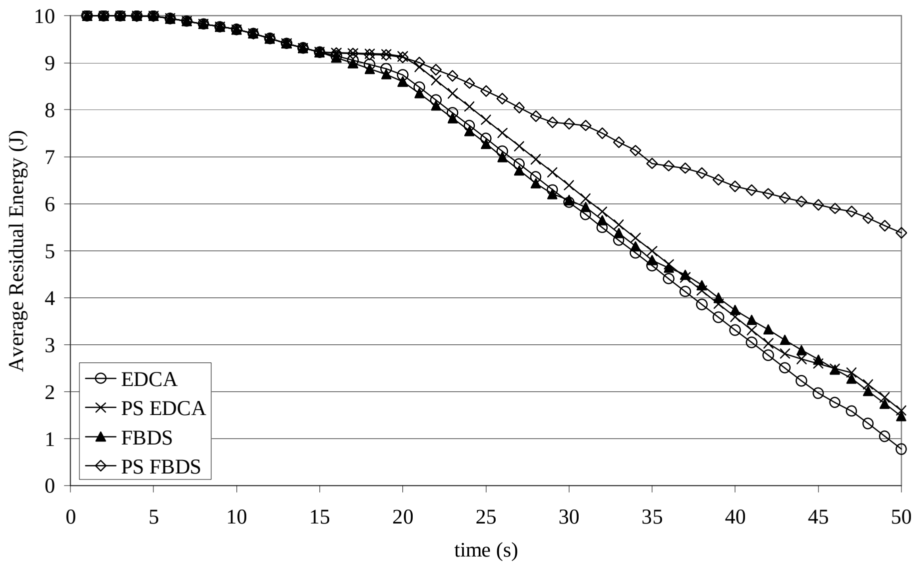

Fig. 5. Average Residual Energy for a node hosting a MPEG-4 flow when $\alpha = 9$.

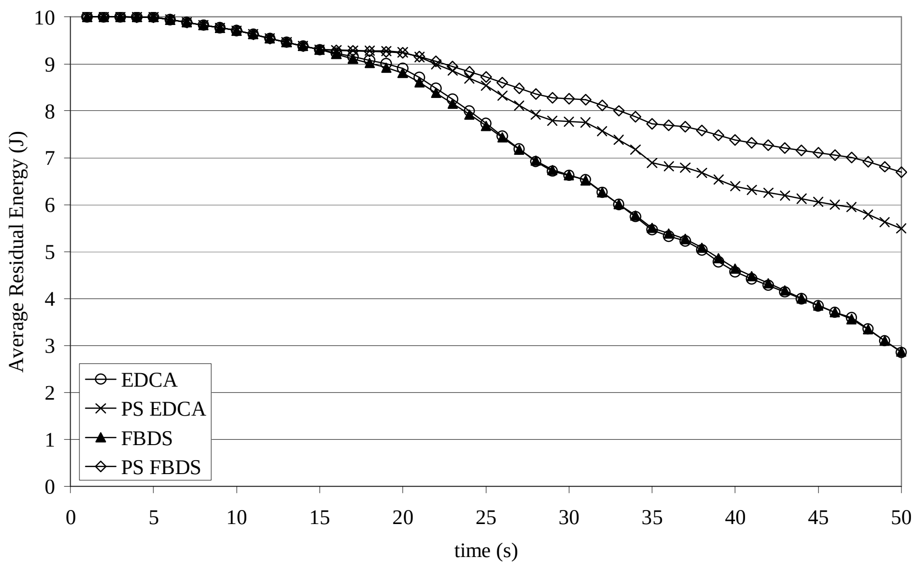

Fig. 6. Average Residual Energy for a node hosting a MPEG-4 flow when $\alpha = 6$.

a bouded-delay service to all categories of flow, under various network load conditions. On the other hand, PS EDCA is able to provide bounded delays with energy saving only to stations hosting G.729 flows, but at the expense of the service provided to video flows.

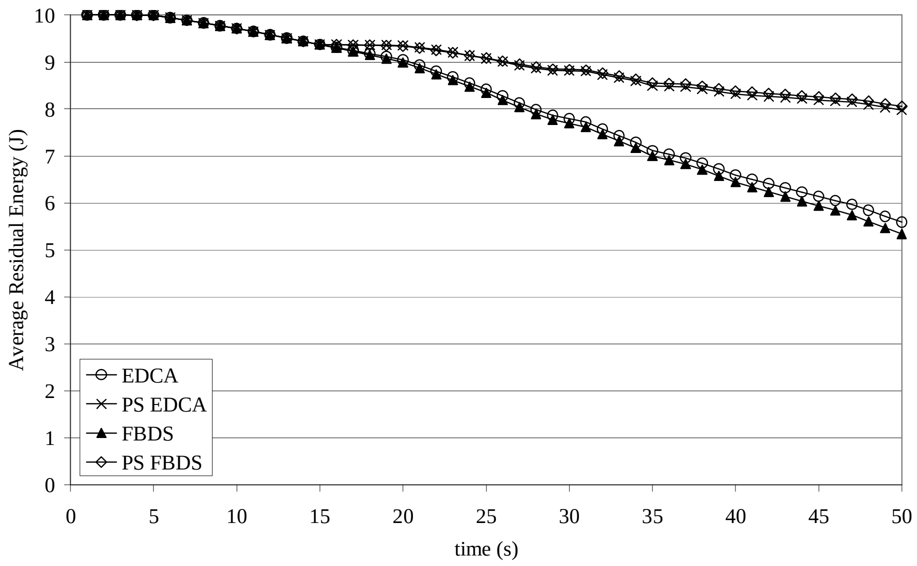

Fig. 7. Average Residual Energy for a node hosting a MPEG-4 flow when $\alpha = 3$.

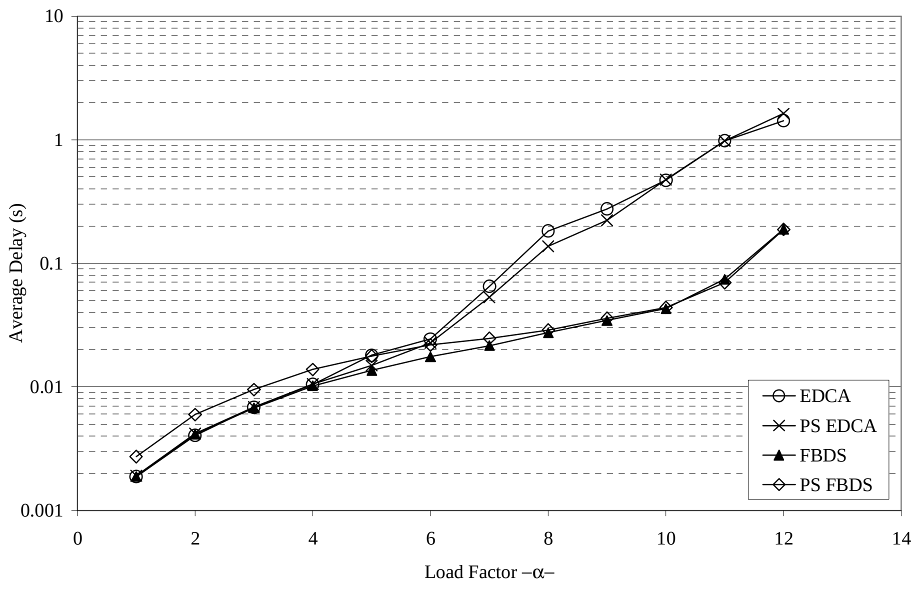

Fig. 8. Average one-way delays of H.263 flows as a function of the load factor α.

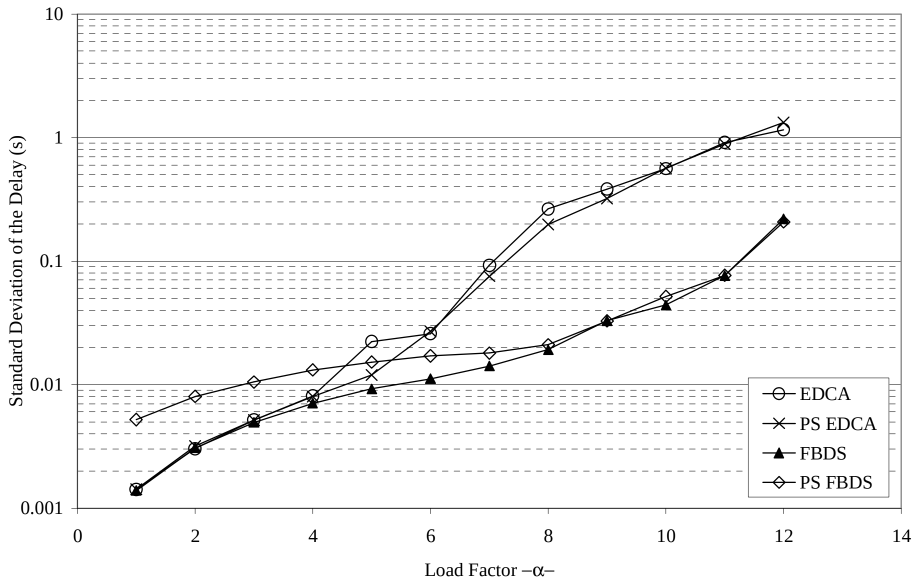

Fig. 9. Standard deviation of one-way delays of H.263 flows as a function of the load factor α.

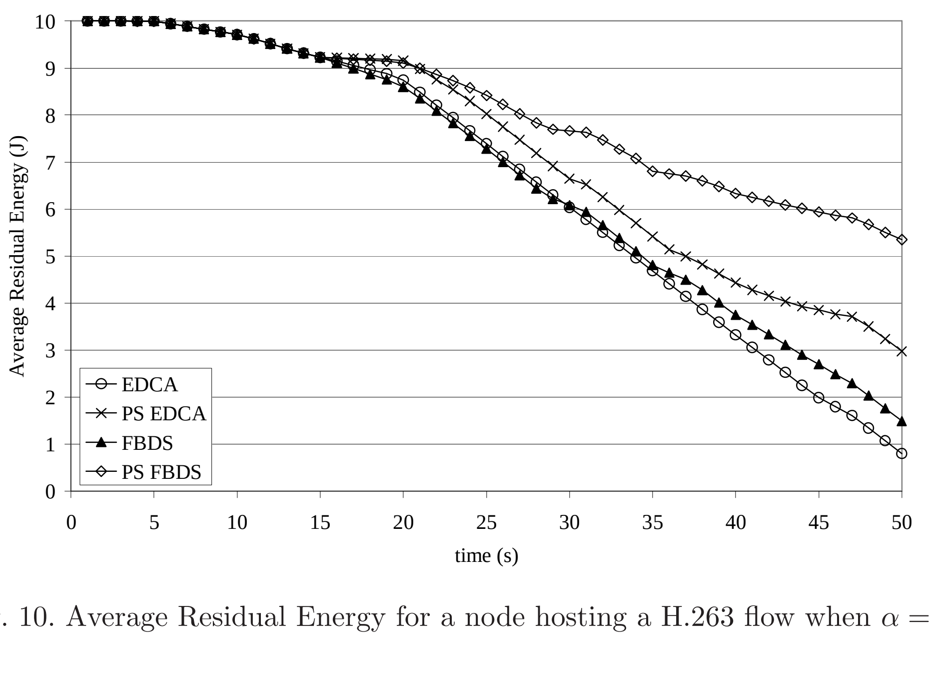

Fig. 10. Average Residual Energy for a node hosting a H.263 flow when $\alpha = 9$.

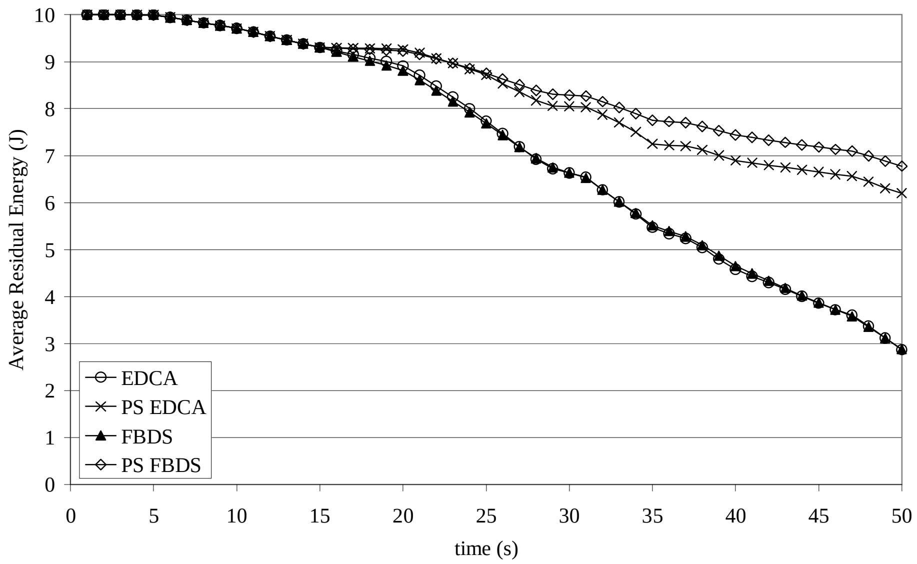

Fig. 11. Average Residual Energy for a node hosting a H.263 flow when $\alpha = 6$.

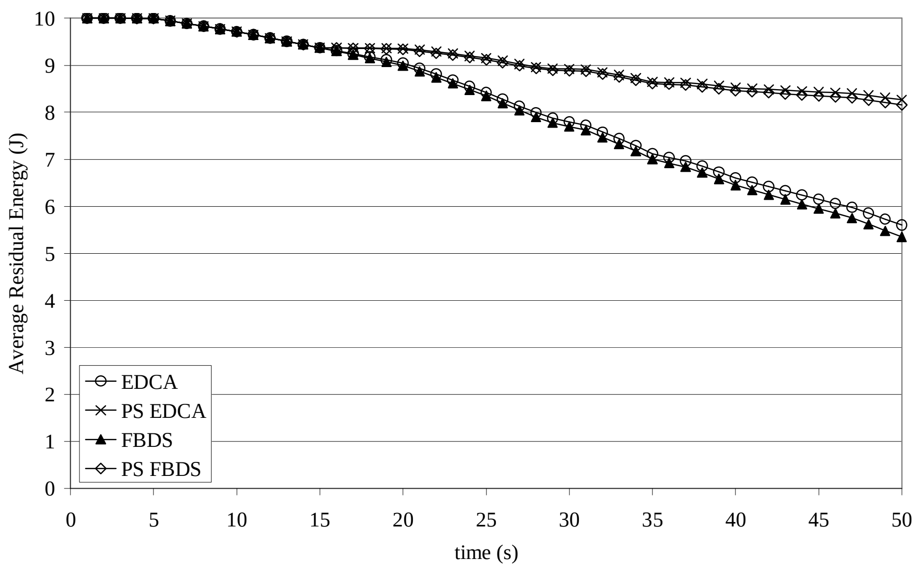

Fig. 12. Average Residual Energy for a node hosting a H.263 flow when $\alpha = 3$.

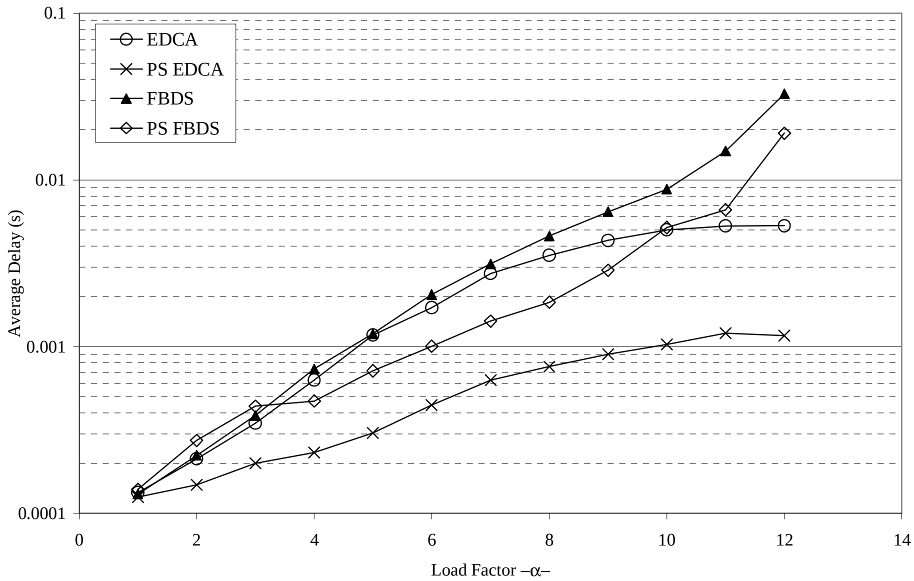

Fig. 13. Average one-way delays of G.729 flows as a function of the load factor α.

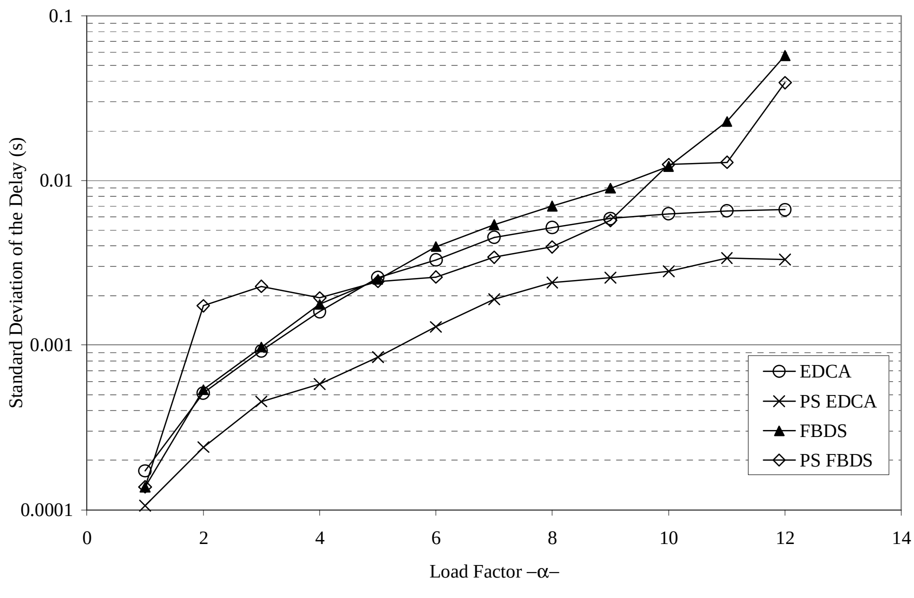

Fig. 14. Standard deviation of one-way delays of G.729 flows as a function of the load factor α.

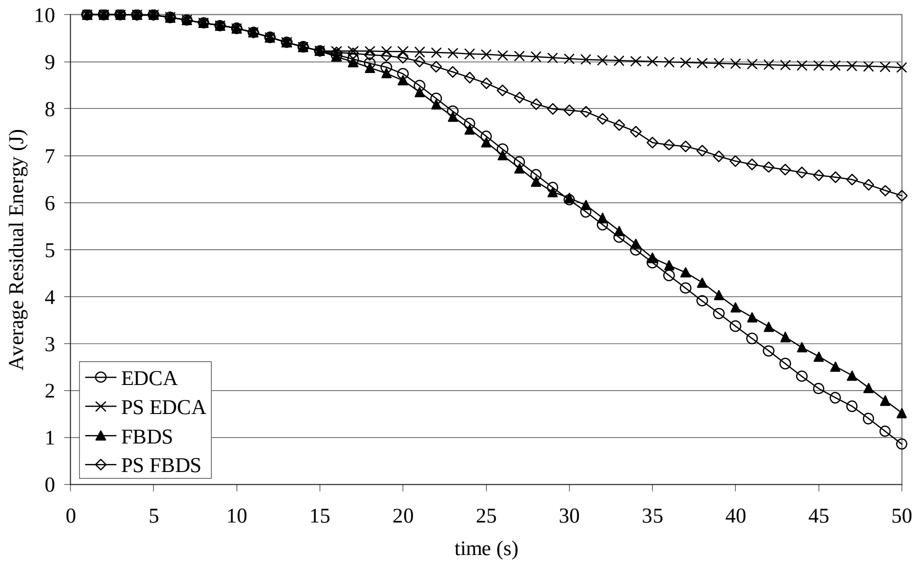

Fig. 15. Average Residual Energy for a node hosting a G.729 flow when $\alpha = 9$.

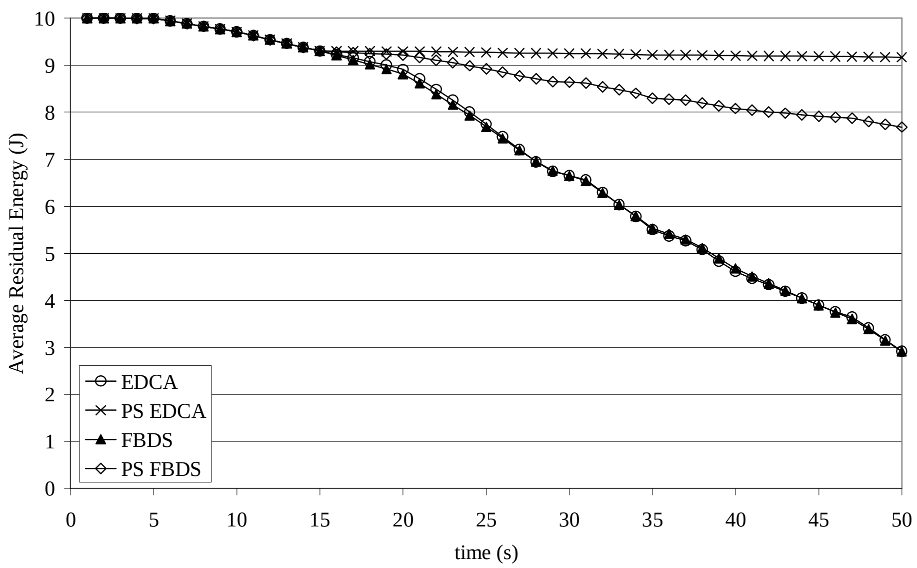

Fig. 16. Average Residual Energy for a node hosting a G.729 flow when $\alpha = 6$.

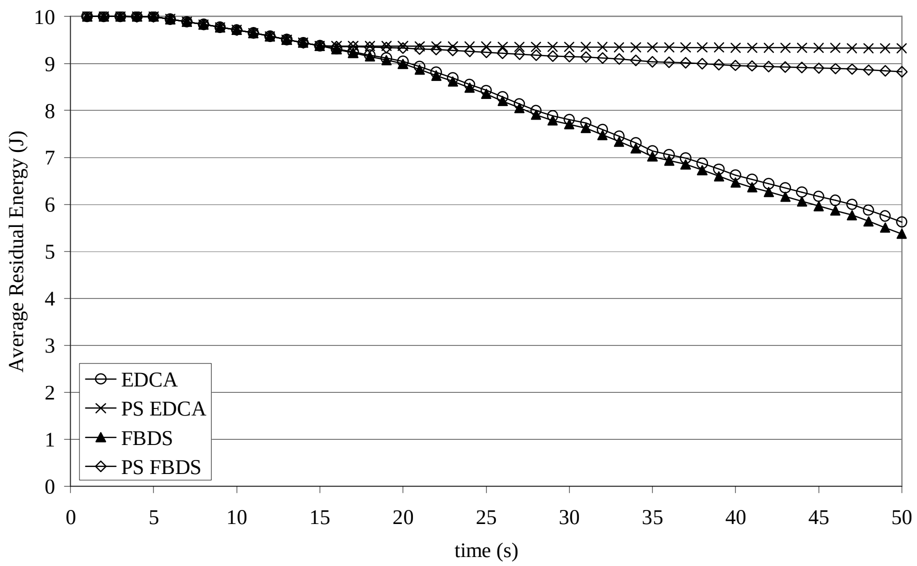

Fig. 17. Average Residual Energy for a node hosting a G.729 flow when $\alpha = 3$.

5 Conclusion

In this paper, a scheduling algorithm that addresses the trade-off between power saving and QoS using the 802.11e MAC has been proposed. It has been designed using classical feedback control theory. The performance of the proposed scheme, which has been referred to as PS FBDS, has been investigated using *ns*-2 simulations in realistic scenarios where the wireless channel is shared by heterogeneous traffic flows. The results obtained under different traffic load conditions have shown that PS FBDS is able to provide a bounded delay service to real-time flows and, at the same time, to significantly reduce energy consumption at both high and low network loads.

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