INTERNETWORKING WIRELESS LAN AND FUTURE CELLULAR NETWORKS

ANALYSIS OF THE INTEGRATION OF IEEE 802.11E CAPABILITIES IN BATTERY LIMITED MOBILE DEVICES

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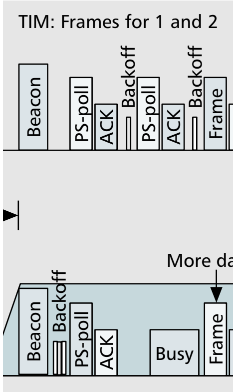


Several challenges need to be addressed in order to achieve seamless integration of WLAN and cellular systems The upcoming IEEE 802.11e standard represents a basic step toward this integration, since it provides the means to support key applications such as voice over IP.

ABSTRACT

IEEE 802.11 wireless LANs (WLANs) is widely recognized as a complementary technology to cellular access networks in hot-spot areas due to its lower cost and higher data rates. Different interworking approaches are being studied, but one common element is considered by all of them: mobile devices can include capabilities for connecting through both access technologies, allowing the best option to be chosen depending on the availability at a specific moment. However, several challenges need to be addressed in order to achieve seamless integration of WLAN and cellular systems in such a mobile device. The IEEE 802.11e standard, which defines mechanisms to provide QoS in a WLAN, represents a basic step toward this integration, since it provides the means to support key applications such as voice over IP. The IEEE 802.11 power-save mode (PSM) is another necessary element for devices with severe battery limitations (e.g., cellular phones) in order to ensure reasonable battery duration. The resulting performance when both QoS and power-saving mechanisms are used together, however, is uncertain and requires further study. We analyze the implications of the interaction of the 802.11 PSM with 802.11e QoS mechanisms by determining if the desired QoS is still provided, detecting functionality conflicts, and quantifying the impact of the PSM upon the 802.11e QoS efficiency and system performance. The evaluation is performed via simulation.

INTRODUCTION

The integration of wireless LAN (WLAN) and cellular systems is currently being designed, as can be observed, for instance, in the interworking proposal of the 3rd Generation Partnership Project (3GPP) [1]. An aspect to be taken into account in any integration approach is the use of devices with capabilities that allow connection through both access technologies. Such devices combine the worldwide coverage of cellular systems with the high bandwidth of WLAN hot spots, thus allowing a user to choose the best available network access at a certain instant.

For seamless interworking of both technologies in mobile devices, two basic requirements need to be fulfilled by WLANs. First, to allow the support of similar services in the two systems, quality of service (QoS) guarantees should be provided in WLANs. Second, users will expect battery duration in those devices that is similar to those in cellular terminals when WLANs are used.

The IEEE 802.11 Task Group E has recently completed the 802.11e standard, which provides the means to support QoS in WLAN systems. The implementation of IEEE 802.11e mechanisms will be necessary in devices with cellular and WLAN capabilities for users who want to use the inexpensive WLAN access for applications which require QoS guarantees, (e.g., VoIP).

Given the fact that transmission over a WLAN is performed through a shared medium, data packets can arrive at any time to the destination and, therefore, WLAN devices usually operate at full power. Devices with battery restrictions, however, cannot afford to constantly operate at full power and hence use power-saving mechanisms. IEEE 802.11 specifies a power-save mode (PSM) that could be used in such devices, but the effect of the interaction of this mode with the 802.11e QoS mechanisms needs to be analyzed in order to assess its suitability for this particular case. Specifically, three main issues need to be studied as follows:

- Determine if the 802.11e QoS mechanisms are still effective in conjunction with the PSM functionality
- Detect potential functionality conflicts of the superposition of both mechanisms
- Quantify the impact of the PSM on the 802.11e efficiency and on the overall system performance

To the best of our knowledge, there is no published related work regarding the interaction of 802.11e and 802.11 PSM, but both have been studied separately. In the area of providing QoS in a WLAN, a lot of research has been done during the last several years (see, for example, [2]). With respect to 802.11 PSM, the independent mode for ad hoc networks has been studied, for instance, in [3] and the infrastucture mode has been studied in [4].

The rest of this article is structured as follows. First, a description of the 802.11 PSM and the 802.11e QoS enhancements is provided. Then we describe the worst-case scenario considered for the first 802.11e-capable mobile devices and discuss the results obtained. Finally, we summarize the results and conclude the article.

802.11 POWER MANAGEMENT

The IEEE 802.11 standard defines two independent power-management mechanisms, depending on whether the infrastructure or ad hoc mode is used, that allow mobile stations to enter a power-saving mode of operation where they turn off their receiver and transmitter to conserve power. In our study, we focus on the infrastructure power-management scheme during the contention period as the most relevant case for devices, including cellular and WLAN capabilities. Note that currently most of the WLAN deployments use the infrastructure mode with the access arbitrated by the distributed coordination function (DCF).

POWER MANAGEMENT IN AN INFRASTRUCTURE NETWORK

Access Point Operation — In the infrastructure mode, the power-management mechanism is centralized in the access point (AP). APs maintain a power-management status for each currently associated station that indicates in which power-management mode the station is currently operating. Stations changing the power-management mode inform the AP of this fact by using the power-management bits within the frame control field of the transmitted frames.

The AP buffers unicast and multicast data frames destined for any of its associated stations in PSM. If an AP has buffered frames for a station, it will indicate this in the traffic indication map (TIM), which is sent with each beacon frame. During the association process, every station is assigned an Association ID code (AID) by the AP. The AID indicates with a single bit in the TIM whether frames are buffered for a specific station.

Stations request the delivery of their buffered frames at the AP by sending a power-save poll (PS-Poll). A *single* buffered frame for a station in PSM is sent after a PS-Poll has been received from a station. Further PS-Poll frames from the same station are acknowledged and *ignored* until the frame is either successfully delivered, or presumed failed due to the maximum number of retries being exceeded. This prevents a retried PS-Poll from being treated as a new request to deliver a buffered frame. Finally, APs have an aging function that deletes buffered traffic when it has been buffered for an excessive period of time.

Station Operation — A station may be in one of two different power states:
- *Awake*: station is fully powered
- *Doze*: station is not able to transmit or receive and consumes very low power

While in PSM, a station awakes to listen to a beacon once every n beacons, where n is an integer ≥ 1. The listen interval value used by a station is communicated to the AP in its association request.

Each station learns through the TIM in the beacon whether the AP buffered any frames destined to them while they were in the doze state. If a station sends a PS-Poll to retrieve a buffered frame, the AP can respond by acknowledging it (ACK) or sending the data frame directly. In the event that neither an ACK nor a data frame is received from the AP in response to a PS-Poll frame, then the station retries the sequence by transmitting another PS-Poll frame.

In the frame control field of the frame sent in response to a PS-Poll, the AP sets a bit labeled More Data if there are further frames buffered for this station. The station is required to send a PS-Poll to the AP for each data frame it receives with the More Data bit set. This ensures that stations empty the buffer of the frames held for them at the AP.

Mobile stations should also awake at times determined by the AP, when broadcast/multicast (BC/MC) frames are to be transmitted. This time is indicated in the beacon frames as the delivery traffic indication map (DTIM) interval. If ReceiveDTIM is true, a station must awake at every DTIM.

Note that the PSM functionality does not imply that frames sent from the station to the AP are delayed until the next beacon is received, that is, mobile nodes wake up whenever they have data to send and follow the regular 802.11 transmission procedure.

Figure 1 illustrates the infrastructure PSM procedure during the contention period, assuming a listen interval for station 1 (STA) and STA 2 of two beacon intervals, and a DTIM period of five beacon intervals.

For further details about the PSM operation, the reader is referred to [5].

IEEE 802.11E

The 802.11 Task Group E has recently completed the design of the 802.11 QoS MAC enhancements, which has resulted in the 802.11e extension of the standard. 802.11e defines the hybrid coordination function (HCF) to support QoS. Two channel-access methods are defined: a contention-based channel-access method called enhanced distributed channel access (EDCA) and a contention-free channel access referred to as HCF-controlled channel access (HCCA).

New mobile devices incorporating 802.11e functionality before the standard is completed are likely to include first the EDCA mechanisms and later HCCA. This can be seen, for instance, by the fact that the Wi-Fi™ Alliance [6] has started first the certification of the Wi-Fi multimedia extensions (WMM™) which include only EDCA functionality. Additionally, HCCA still requires further work to solve some detected

In the infrastructure mode, the power management mechanism is centralized in the access point (AP). APs maintain a power management status for each currently associated station that indicates in which power management mode the station is currently operating.

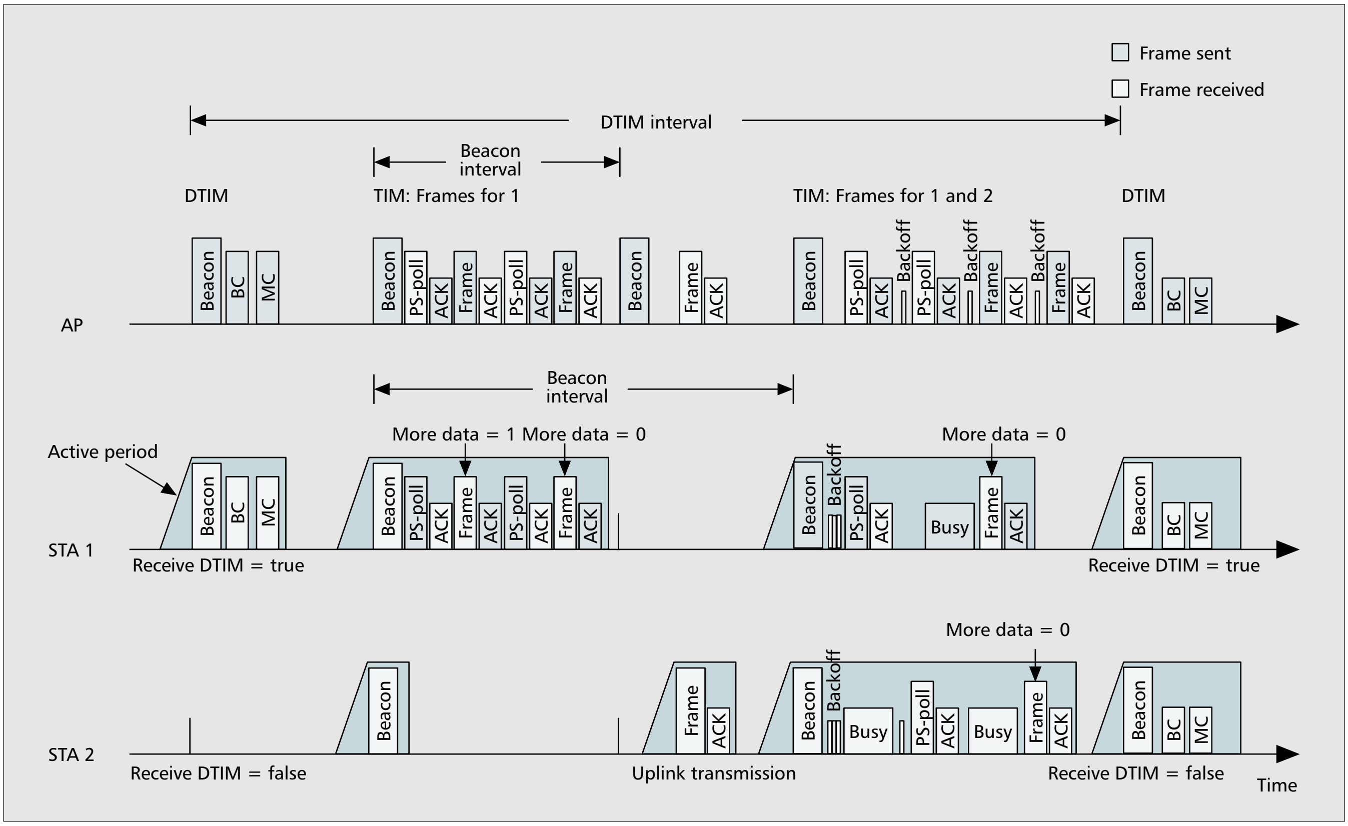


Figure 1. *Sample of infrastructure power management operation.*

problems in the case of overlapping HCs due to loss of coordination, as pointed out in [2]. Based on that, we focus our study on the interaction of EDCA with 802.11 PSM, since it is the most probable configuration to be implemented in the short term in 802.11e-capable mobile devices.

HCF CONTENTION-BASED CHANNEL ACCESS (EDCA)

802.11e introduces the concept of transmission opportunity (TXOP), which is the basic unit of allocation of the right to transmit onto the wireless medium. Each TXOP is defined by a starting time and a defined maximum duration advertised by the AP. The length of a TXOP is the duration during which the TXOP holder maintains uninterrupted control of the medium, including the time required to transmit frames sent as an immediate response to the TXOP holder's transmissions.

Two modes of EDCA TXOP have been specified, the initiation and the continuation of an EDCA TXOP. An initiation of the TXOP occurs when the EDCA rules allow access to the medium, whereas a TXOP continuation occurs when a channel-access function retains the right to access the medium following the completion of a frame exchange sequence.

Traffic differentiation is based on user priority and is achieved through varying: the amount of time a station senses the channel to be idle before backoff or transmission, the length of the contention window (CW) to be used for the backoff, and the duration a station may transmit after it acquires channel access. This is realized by the introduction of four access categories (AC) and multiple independent backoff entities. The four ACs are AC_VO, AC VI, AC_BE, and AC BK. The labels correspond to the applications for which they are intended, that is, voice, video, best effort, and background. In the following, we describe the EDCA parameters that define the priority to access the wireless medium.

Obtaining an EDCA TXOP — The EDCA parameters for each AC to be used by the backoff entities to obtain a TXOP are distributed by the HC and can be modified over time via information fields included in the beacon frames. EDCA modifies the 802.11 transmission procedure of a backoff entity by introducing a new interframe space, defined as an arbitration interframe space (AIFS). The AIFS enhances the function of the 802.11 DIFS by allowing different values for each AC with a minimum value of DIFS for the 802.11e stations and of PIFS for the 802.11e AP.

Additionally, EDCA modifies the backoff procedure by:

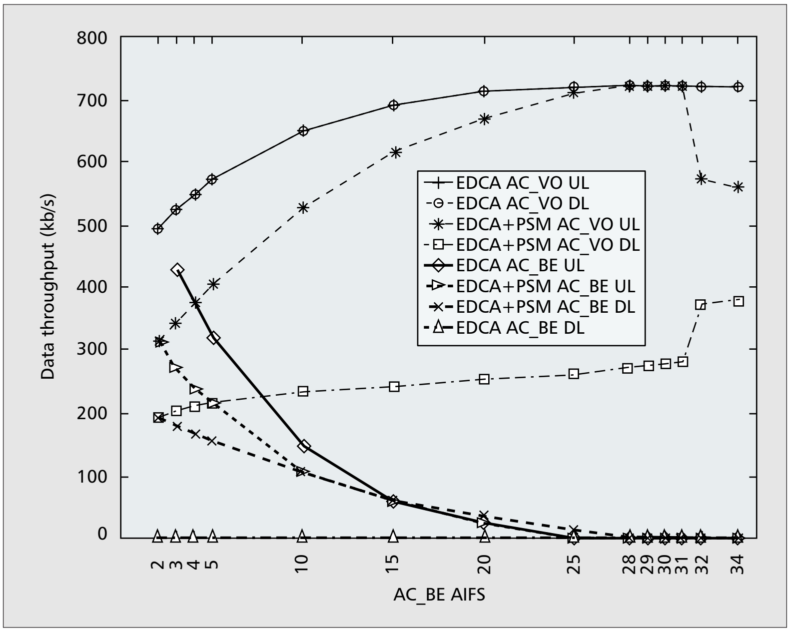
- Creating a backoff instance per AC
- Requiring the backoff instances to maintain a separate state as variable for the contention window
- Making the minimum (CWmin) and maximum (CWmax) size dependent on the AC
- Finally, the duration of a TXOP (TXOPlimit) is another AC-dependent parameter used to provide differentiation.

A brief overview of the main QoS differences introduced by EDCA, as compared to the legacy DCF, has been provided in this section. For a thorough overview of HCF, please refer to [2].

PERFORMANCE EVALUATION AND DISCUSSION

In this section, we evaluate the impact of using 802.11 PSM in combination with the EDCA QoS mechanisms (EDCA+PSM). The analysis has been performed via event-driven simulations. We extended the 802.11b libraries provided by OPNET™ [7] to include the standard 802.11 PSM described above and a subset of the EDCA QoS mechanisms described in the previous section.

EDCA-TXOP durations are configured for all ACs so as to allow the transmission of one data frame after gaining access to the medium. The RTS/CTS mechanism has not been enabled in order to avoid its influence over the interaction being studied. PS-Polls are sent following the rules of the AC of the frames intended to be received in order to guarantee a better performance in the downlink of higher priority traffic. The listen interval configured for the power-saving stations is one. The beacon interval used is 20 ms unless otherwise indicated.



■ **Figure 2**. *The impact of AIFS variation of the AC BE station on the average throughput.*

POWER-SAVE MODE IMPACT ON THE EDCA QoS MECHANISMS

We study the impact of PSM on the expected EDCA differentiation by analyzing the differences in the performance when the EDCA parameters AIFS, CWmin, and CWmax are varied. The performance metrics used are average data throughput and MAC delay at 95 percent of the empirical cumulative distribution function (cdf).

The simulation scenario that is chosen to illustrate the performance differences consists of a WLAN network composed of a high-priority WLAN station (AC_VO), a low-priority WLAN station (AC_BE), and an AP. The stations send/receive frames to/from their corresponding partners, which are located in the wired domain and directly connected to the AP. The influence of the application traffic characteristics on the results has been avoided by guaranteeing that the WLAN stations always have a frame to transmit (125 bytes) and that the AP always has frames to transmit to both WLAN stations. Additionally, by doing this, the maximum achievable differentiation between both ACs can be observed.

AIFS — Figure 2 illustrates the effect of keeping an AIFS value of two for the AC_VO and increasing the AIFS value for the AC_BE from two to 34. The CWmin and CWmax values have been set to 31 so as to avoid the influence of the binary exponential backoff on the AIFS experiment.

The results in Fig. 2 show that the variation of the AIFS parameter, used to provide a higher throughput to a certain AC, is still effective even if it is combined with PSM. However, significant differences can be observed in specific cases due to the reasons described below.

The AC_VO and AC_BE have, in the case of AIFS 2, exactly the same EDCA settings, but the throughput achieved in the uplink (UL) by each AC of EDCA and EDCA+PSM is quite different. The additional load of the EDCA+PSM stations that transmit PS-Polls in addition to the data frames is the reason for this lower throughput. However, the difference becomes reduced when the separation between the AIFS value of the AC_VO station and the AC_BE one increases. This happens because, in the EDCA+PSM case, an increase in the AC_BE AIFS value represents a reduction not only in the throughput that the AC_BE can transmit, but also in the number of AC_BE PS-Polls that are transmitted over the channel.

In the downlink (DL) case, very different behaviors are observed, as expected, because when the 802.11 PSM is used, the frames are buffered at the AP and only delivered if the corresponding PS-Poll is received. As a result, the downlink throughput achieved by the AC_VO in the downlink under saturation conditions is significantly lower in the EDCA+PSM case as compared to the EDCA one.

Finally, there is a point in the EDCA+PSM case (AC_BE AIFS 31 in this experiment) where the difference between the AIFS of the AC_VO and AC_BE is such that no PS-Polls can be transmitted by the AC_BE stations. This causes a sharp change in the slope for AC_VO in the uplink and downlink throughput since, in our implementation, in the downlink, the high-priority frames no longer need to wait for transmission of the low-priority ones. Thus, the downlink throughput increases while the higher competition to access the channel and the larger number of PS-Polls to be sent yields a decrease in the AC_VO traffic in the uplink.

The results for the delay experienced by frames at the MAC layer have been omitted here since they are as expected, that is, inversely proportional to the throughput achieved.

CWmin and CWmax — The impact of 802.11 PSM on the differentiation achieved by modifying the CWmin and CWmax values has been studied through two different experiments. In the CWmin analysis, the CWmax value of both ACs has been set to 1023, the CWmin value of the AC_VO to 31, and the CWmin value of the AC_BE has been varied from 31 to 1023. In the CWmax case, the CWmin value of both ACs has been set to 31, the CWmax value of the AC_VO to 31, and the CWmax value of the AC_BE has been varied from 31 to 1023. Both experiments have been performed with an AIFS value of two for the two ACs.

The results obtained in the CWmin experiment (Fig. 3) resemble the ones presented in the AIFS section, that is, EDCA is still effective in providing differentiation when PSM is used. A similar reasoning for the performance differences between EDCA and EDCA+PSM applies here, taking into consideration that now instead of providing a deterministic differentiation, a statistical one is obtained. This results in a major difference, as compared to the AIFS case: no sharp change in the slope is observed for the EDCA+PSM average throughput of the AC_VO in the uplink and downlink since, in contrast to the AIFS experiment, the AC_BE average throughput value in the downlink does not reach zero.

The results for the CWmax case are very similar to the CWmin ones, so they have been omitted here due to space constraints.

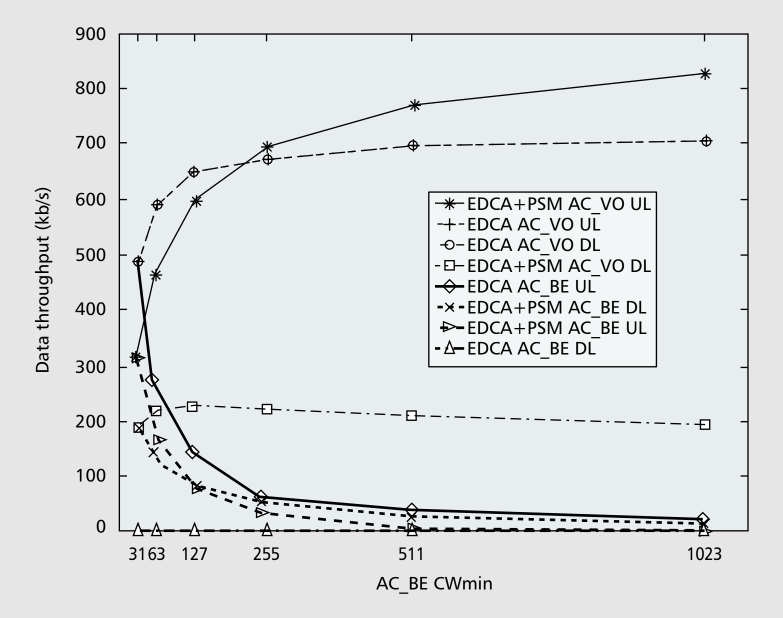


Figure 3. *The impact of CWmin variation of the AC BE station on the average throughput.*

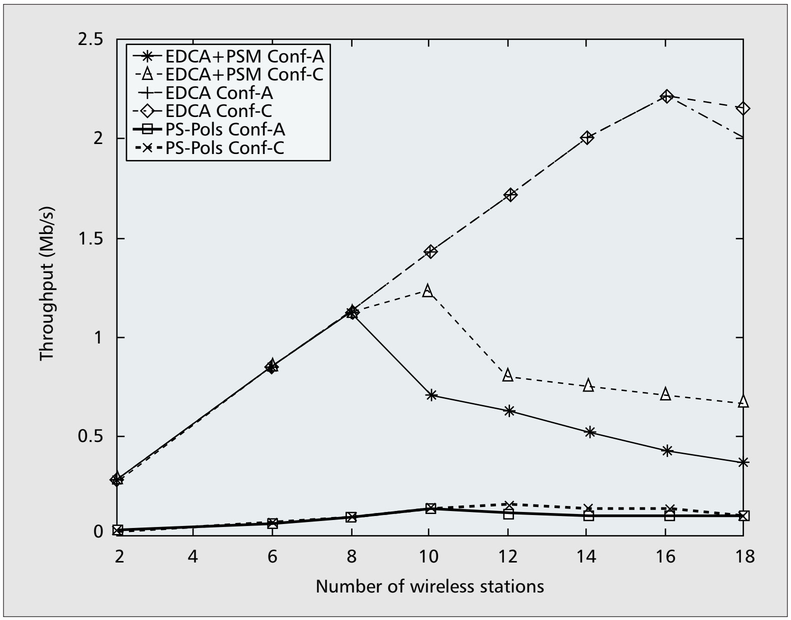


Figure 4. *The impact of the number of stations on the wireless LAN data throughput.*

COSTS OF THE POWER-SAVE MODE AND EDCA INTERACTION

The usage of the PSM mechanism implies a decrease in the WLAN bandwidth available for data transmission due to the additional signaling load and an increase in the downlink delay according to the beacon interval value. We define two different experiments to quantify the importance of this degradation. In both experiments, two examples of EDCA configurations are considered based on the values proposed in the 802.11e draft: aggressive (Conf-A) and conservative (Conf-C) (Table 1). The AIFS value chosen for both configurations (2) is the minimum needed to study the EDCA worst case.

The decrease of the effective wireless channel bandwidth and the signaling load introduced are evaluated through an experiment where we increase the number of wireless stations (50 percent of each AC) until channel saturation is reached. The beacon interval impact over the downlink delay is quantified, depending on the number of wireless stations, by increasing the beacon interval value from 20 to 100 ms. Each wireless station has its pair in the wired domain. Data traffic is generated at a constant bit rate (240 bytes every 30 ms) by the applications of the wired and wireless nodes.

Figure 4 shows the data and PS-Poll throughput sent over the wireless channel and received by its destination according to an increasing number of wireless stations. The effect of the additional overhead from PSM on the achievable effective throughput is clearly noticeable, demonstrating that it cannot be neglected. When congestion is reached, a clear difference in the behavior for Conf-A and Conf-C can be observed, in which Conf-C (because of its larger CW values for AC_BE) obtains better results with respect to the maximum achievable data throughput since the number of collisions in the channel are lower. The signaling load introduced by the PS-Polls follows a similar behavior and represents in our scenario around 8 percent of the achievable data throughput when the channel is not congested.

Based on the previous results, we have chosen the case of eight wireless stations for studying the impact of the beacon interval on the MAC delay[1] as the case where the maximum differences between the AC_VO and AC_BE will

	AIFS	CWmin	CWmax
Conf-A, AC VO	2	7	15
Conf-A, AC BE	2	15	31
Conf-C, AC VO	2	7	15
Conf-C, AC BE	2	31	1023

Table 1. *EDCA configuration for Conf-A and Conf-C.*

be observed before the wireless channel is congested. The results are depicted in Fig. 5, where an almost linear delay increment, according to an increasing beacon interval value, is observed. As expected, the longer the beacon interval is, the longer it takes the stations to be informed about buffered packets at the AP to be retrieved, hence resulting in a larger MAC delay.

POWER-SAVING EVALUATION

In this section the effectiveness of the PSM mechanism is studied in a scenario similar to the one used in the previous subsection. We computed the percentage of time spent in the active mode by the stations in PSM for both EDCA configurations, depending on the beacon interval considered and the number of wireless stations (50 percent of each AC).

The results in Fig. 6 clearly show the power saving improvement for both ACs, at least around 40 percent, when the channel is not congested, that is, number of wireless stations is eight or below. The AC_VO stations present higher power saving because they send and receive frames faster. Considering the frame generation rate of our scenario (30 ms), we can observe that when the number of frames buffered in the AP is two or above, that is, from the beacon interval case of 60 ms onward, the More Data mechanism tends to reduce the beacon interval impact, since it randomizes some of the PS-Polls transmissions. For a lower beacon interval value, the longer the beacon interval, the larger the number of PS-Polls collisions. The case of ten stations presents a percentage of time in the active mode close to one for the AC_BE case, since the channel is becoming congested and the AC_VO has higher priority to transmit.

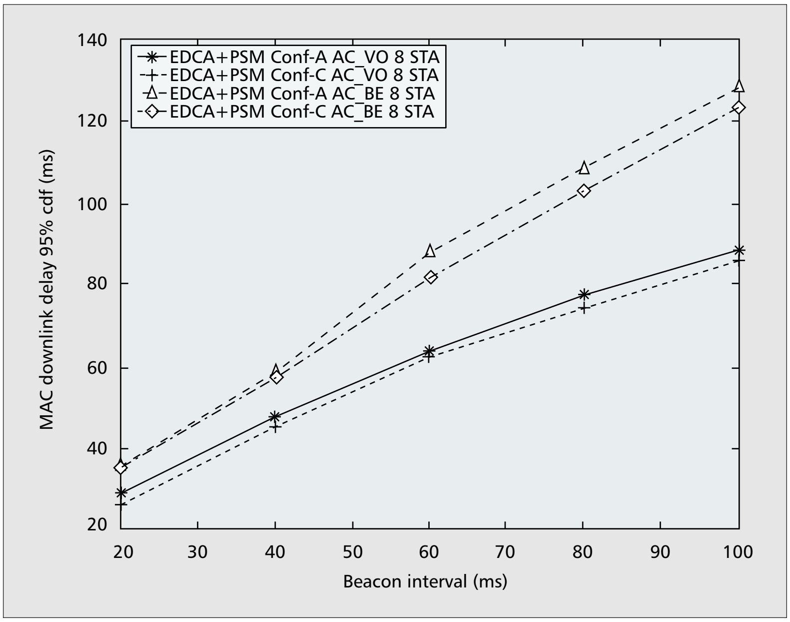


Figure 5. *The impact of the beacon interval on the downlink delay.*

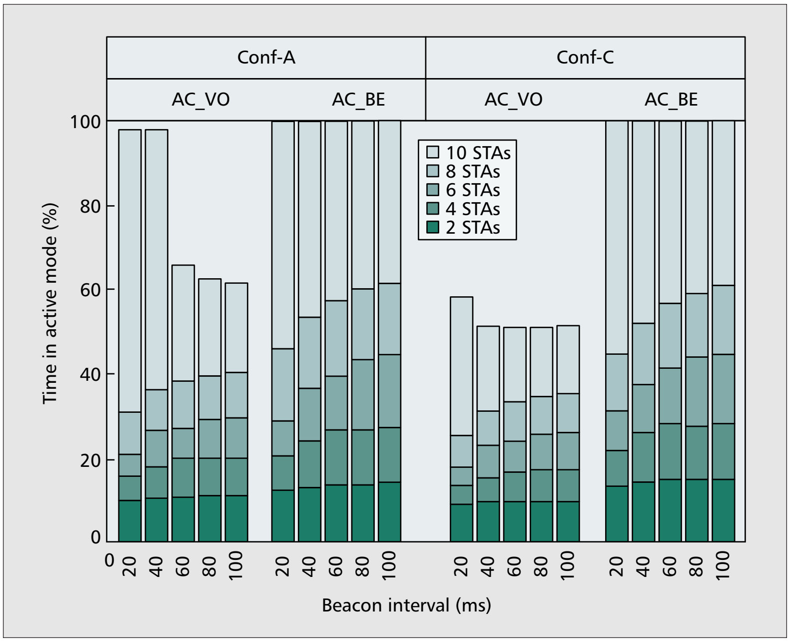


Figure 6. *The impact of the beacon interval on the power saving efficiency.*

SUMMARY AND CONCLUSIONS

The forthcoming mobile devices, including cellular and WLAN access capabilities, will introduce new technological challenges that need to be addressed. The combination of the 802.11e QoS mechanisms and the 802.11 PSM functionality has been identified as a key aspect of the introduction of WLAN capabilities in battery-limited devices such as cellular phones. However, a study of the performance of the superposition of both mechanisms is required in order to determine its suitability for the case considered.

We have evaluated the performance of the combination of the EDCA QoS mechanisms and the 802.11 PSM via simulation. Through this analysis, insight about the impact of PSM over the EDCA QoS functionality and its causes has been acquired. Therefore, the results of this study are twofold. First, we provided quantitative results of the expected performance differences when the PSM is used and the power-saving efficiency. Second, we provided the reasoning behind the impact of the different parameters, pointing out the elements to be taken into account when configuring both mechanisms to be used together.

The main conclusions that can be drawn from our results are:

- The 802.11e QoS mechanisms are influenced by the 802.11 PSM functionality, but are still effective.

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[1] *We define MAC delay as the delay experienced by a frame from the instant it arrives to the MAC layer and is placed in the PSM queue (EDCA+PSM) or AC queue (EDCA) until it is successfully transmitted.*

The combination of the 802.11e QoS mechanisms and the 802.11 PSM functionality has been identified as a key aspect of the introduction of WLAN capabilities in battery-limited devices such as cellular phones.

- An important impact is observed on the downlink delay, as expected, where special attention needs to be paid to the beacon interval configuration.
- The additional overhead introduced by the PSM considerably decreases the effective bandwidth available for data transmission in the WLAN.
- In devices where power saving is a critical issue, the significant increase in the power-usage efficiency under conditions of no congestion justifies the PSM costs.

The study presented in this article has been performed within the framework of the product development of the 3G/WLAN mobile terminal N900iL. Future work will consider the 802.11e APSD functionality.

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BIOGRAPHIES

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Daniel Camps Mur (camps@netlab.nec.de) studied telecommunications engineering at UPC. During his studies he focused on communication networks and traffic engineering. He did his diploma thesis at NEC Network Laboratories in a project related to the development of a 3G/WLAN terminal. The work focused on the analysis of the combination of the existing QoS and power saving mechanisms in WLANs, and new power saving strategies specially suited to be used with applications that require QoS were proposed. After his thesis he was hired to work as a researcher at NEC Network Laboratories. His research interests include, among others, networking simulations, traffic engineering, power saving and scheduling algorithms for WLAN.