Marzo 12, 2006

Colegio Oficial de Ingenieros de Telecomunicación
C/ Almagro, 2, 1^o
28010, Madrid

Estimado sr. Presidente del Colegio Oficial de Ingenieros de Telecomunicación,

Mi nombre es Daniel Camps Mur, número de colegiado en trámite, y soy Ingeniero de Telecomunicación por la Universidad Politécnica de Cataluña, desde el pasado 16 de Diciembre de 2004, fecha de lectura de mi proyecto final de carrera titulado *QoS y mecanismos de ahorro de potencia en WLANs modo infraestructura*, que obtuvo calificación de matrícula de honor.

Recientemente he recibido la carta del Colegio Oficial de Ingenieros de Telecomunicación ofreciendo la posibilidad de presentarse a la XXVI convocatoria de premios para ingenieros de telecomunicación, y este es el motivo por el que me dirijo a usted, puesto que considero ésta una iniciativa excelente de la que me gustaría formar parte.

Desarrollé mi proyecto de Febrero a Noviembre de 2004, en NEC Network Labs. en Heidelberg, Alemania, bajo la supervisión de Dr. Xavier Pérez Costa en la empresa y Dr. Xavier Hesselbach i Serra en la universidad. Mi proyecto trata sobre la problemática de introducir WLAN en terminales móviles de tercera generación, y los resultados que obtuve se aplicaron a la configuración del terminal NEC N900iL. El N900iL fue el primer terminal dual 3G/WLAN que salió al mercado, pero a fecha de hoy son ya varias las empresas que disponen de dichos terminales, poniendo de manifiesto la relevancia de la temática de este proyecto. Varias publicaciones y patentes en el área de WLAN forman parte del resultado de este trabajo.

Por todo ello me gustaría presentar mi candidatura al premio **NOKIA:** al mejor proyecto final de carrera en **Internet Móvil y Soluciones Móviles de Tercera Generación**.

Atentamente,

Daniel Camps Mur

Nombre:
Daniel Camps Mur

Tutores de Proyecto:
Dr. Xavier Pérez Costa, NEC Network Laboratories
Dr. Xavier Hesselbach i Serra, UPC

Entidad Investigadora donde que se realizó el proyecto:
NEC Network Labs Europe

Calificación:
Matrícula de Honor

Publicaciones y Méritos:

Este proyecto final de carrera fue llevado a cabo en NEC Network Laboratories como parte del desarrollo del terminal móvil dual 3G/WLAN N900iL. El trabajo aquí presentado contribuyó a la configuración del terminal N900iL, primer terminal dual 3G/WLAN, que fue lanzado al mercado japonés en Noviembre de 2004. Concretamente los parámetros de calidad de servicio de dicho terminal fueron el resultado del estudio que se detalla en el capítulo 4 del proyecto. Además, el trabajo expuesto en el capítulo 3 dio lugar a una publicación de Journal y el presentado en el capítulo 5, a un artículo de conferencia:

- Notas de Prensa de NTT DoCoMo. Disponible, bajo Noviembre 2004, en: http://www.nttdocomo.com/presscenter/pressreleases/press/pressrelease.html
- Analysis of the Integration of IEEE 802.11e Capabilities in Battery Limited Mobile Devices, Xavier Pérez Costa, Daniel Camps Mur and Toshiyuki Sashihara, *IEEE Wireless Communications Magazine*, Diciembre 2005
- APSM: Bounding the Downlink Delay for 802.11 Power Save Mode, Xavier Pérez Costa and Daniel Camps Mur, in Proceedings of *IEEE International Conference on Comunications* (ICC), Mayo 2005

También como resultado de este trabajo se obtuvieron varias patentes en el área de WLAN que actualmente están en proceso de tramitación:

- X.Pérez-Costa and D.Camps-Mur, Access Category Extension of the Access Point Power Save Mode Queue, NEC-E Invention Disclosure Nr.NLE-29-04, August 2004.
- X.Pérez-Costa, No Data Acknowledgment (NDACK), NEC-E Invention Disclosure Nr.NLE-27-04, August 2004.
- X.Pérez-Costa, Adaptive Power Save Mode: Extension of IEEE 802.11 Power Save Mode, NEC-E Invention Disclosure Nr.NLE-25-04, July 2004.

QoS AND POWER SAVING MECHANISMS IN INFRASTRUCTURE WLANs

I Introduction and Motivation

The voice service is clearly a basic need for cellular users, but recent trends show that having wide access to information via the Internet is becoming more and more important. The Internet has become part of people's lives and after all the enhancements in the Internet and on wireless technologies, users want to have it ready to use not only on their desktop computers but also in their mobile devices.

Wireless Local Area Networks (WLANs) are a direct extension of the wired LAN, that is, the fundamental piece of the global Internet and have become part of our everyday life, thanks to the development of the IEEE 802.11 standard family and the use of unlicensed spectrum. They are being extensively used in hot spot areas providing high-bandwidth Internet access at offices, airports, hotels, and conference centers. The achievement of WLAN in providing high-speed Internet access has been so impressive that it has been accepted as a co-player in provision of data services for indoor users of 3G systems.

For a seamless interworking of both technologies some requirements need to be fulfilled. One of the key requirements is that similar *Quality of Service* (QoS) guarantees should be provided in the two systems to be able to support for example a basic service as *Voice over IP* (VoIP). The IEEE 802.11 Task Group E is in the process of completing the 802.11e standard which provides means to support QoS in a Wireless LAN. The implementation of the IEEE 802.11e extension will be necessary in devices including 3G and Wireless LAN capabilities if the users want to use the inexpensive Wireless LAN access for applications which require QoS guarantees, e.g., VoIP.

However, the introduction of the Wireless LAN technology in mobile devices with severe battery limitations, e.g., cellular phones, poses new challenges. Users will expect in those devices a battery duration similar to the 3G terminals one, i.e., around 150 minutes conversing time, but this is more difficult to achieve in the 802.11 case. 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 usually WLAN devices operate at full power. Devices with battery restrictions though, can not afford to constantly operate at full power and thus, 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 be to analyzed to assess its suitability for this particular case. Specifically, three main issues require to be studied i) determine if the 802.11e QoS mechanisms are still effective in conjunction with the PSM functionality ii) detect potential functionality conflicts of the superposition of both mechanisms, iii) quantify the impact of the power save mode on the 802.11e efficiency and on the overall system performance and iv) propose better power save mechanisms in order to improve the experienced QoS.

II State of the Art

In this section we summarize the QoS mechanisms introduced in the 802.11e standard and the power save mode (PSM) defined in the 802.11 standard. We focus on these MAC layer mechanisms because the aim of this thesis is to study their interactions and propose possible enhancements.

II.A QoS extensions: 802.11e

QoS involves achieving a minimum MSDU delivery throughput and have MSDU delivery delays not exceeding a certain limit. As QoS are also understood MSDU delay variation and packet losses control.

The legacy 802.11 *Distributed Coordination Function* (DCF) is a coordination function that can not deliver MSDUs under QoS constraints. The legacy *Point Coordination Function* (PCF) is a centralized method, but has some problems in providing QoS, therefore only provides a limited QoS.

In the 802.11e standard is defined the *Hybrid Coordintion Function* (HCF), that considers two modes of operation, the *Enhanced Distributed Channel Access* (EDCA) and the *HCF Controlled Channel Access* (HCCA) that would be the enhanced version of the legacy DCF and the legacy PCF respectively. Within a superframe two phases of operation are possible in 802.11e, contention period (CP) and contention-free period (CFP). HCCA can be used in both CP and CFP while EDCA can be used only during CP.

The *Enhanced Distributed Channel Access* (EDCA) is the basis of the HCF and is used to support differentiated services with priorities, but still can not assure a deterministic QoS due to the random nature of the channel access used.

QoS is supported in EDCA by the introduction of *Access Categories* (AC) and parallel backoff instances. MSDUs are delivered by parallel backoff instances and each backoff instance is defined by its AC-specific parameters. There are four ACs, therefore there are four backoff instances in every 802.11e station, in both wireless stations and Access Point. The AC-specific parameters define the priority of the AC in the channel access by modifying the backoff procedure with different inter frame spaces, contention windows and other parameters detailed below. The four ACs are AC_VO,AC_VI,AC_BE and AC_BK. The names correspond to the applications for which they are intended, i.e., voice, video, best effort and background.

A collision between backoff entities within the same station is defined in 802.11e as a *virtual collision*. Such a collision, instead of implying that both backoff entities invoke again the backoff procedure with a doubled CW, results in the lower priority backoff instances following the normal backoff procedure and the highest priority backoff instance transmitting undisturbed. The only difference is that in a virtual collision, the collided frame is not set with the Retry bit, this bit is used in the receiver to discard possible duplicate frames.

Traffic differentiation is based on *user priority* (UP) 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.

EDCA modifies the 802.11 transmission procedure of a backoff entity by introducing a new inter frame space defined as *Arbitration Interframe Space* (AIFS). The AIFS enhances the function of the 802.11 DIFS 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. The duration of AIFS[AC] is calculated based on the *Arbitration Interframe Space Number* AIFSN[AC] as follows: $AIFS[AC] = SIFS + AIFSN[AC] \times aSlotTime$, where $aSlotTime$ refers to the duration of a slot.

A smaller AIFSN[AC] results in a higher priority when accessing the medium since the backoff counter starts decrementing after detecting the medium being idle for a duration equivalent to the AIFS[AC].

EDCA modifies the backoff procedure by requiring to the backoff instances to maintain a separate state variable for the contention window and by making the minimum (CWmin) and maximum (CWmax) size dependent on the AC. Taking into account that the CWmin value is used as the initial value to determine the random backoff period, the smaller the CWmin value is for a specific AC the higher the priority to access the medium. The same applies to the CWmax value which refers to the maximum CW value that can be reached by a certain AC, the smaller this value is the higher chances to win a contention with other stations when trying to gain access to the shared medium.

II.B Power Saving Mechanisms (PSM)

Since the focus of this thesis is to study the impact of PSM strategies over the resulting QoS guarantees, in this section is described the power saving method specified in the 802.11 standard. We assume an infrastructure network.

In 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 power management mode inform the AP of this fact using the power management bits within the frame control field of transmitted frames.

The AP buffers unicast and multicast data frames addressed to any of its associated stations that are in power save mode. If an AP has buffered frames for a station, it will indicate it in the traffic indication map (TIM) which is sent with each Beacon frame.

Stations request the delivery of their buffered frames at the AP by sending a Power Save Poll (PS-Poll). PS-Polls are sent using the normal channel access rules. A *single* buffered frame for a station in power save mode 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 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.

A station may be in one of two different power states, either *Doze*, where the station is not able to transmit nor receive and consumes very low power, or *Awake*, where the station is fully powered.

While being in power save mode a station awakes for listening 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 acknowledging (ACK) it or sending directly the data frame. 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 frames are to be transmitted. This time is indicated in the Beacon frames as the delivery traffic indication map (DTIM) interval. The broadcast/multicast frames are sent by the AP before transmitting any unicast frame following the normal transmission rules. ReceiveDTIM is true a station must awake at every DTIM.

Note that the power save mode functionality does not imply that frames sent from the station to the AP are delayed until the next beacon is received, i.e., mobile nodes wake up whenever they have data to send and follow the normal 802.11 clear channel assessment procedure.

III EDCA and PSM interaction

In this section we study how the QoS capabilities defined in the 802.11e standard and the power saving mechanisms defined in the legacy 802.11 standard perform when they are used together. Our objective is:

i Determine if the desired QoS is still provided when we use together QoS and power saving mechanisms.

ii Quantify the impact of the 802.11 Power Save Mode (PSM) on the 802.11e efficiency and on the overall system performance.

iii Detect functionality problems.

iv Quantify the power saving efficiency the stations can achieve with the standard PSM when considering applications with QoS requirements.

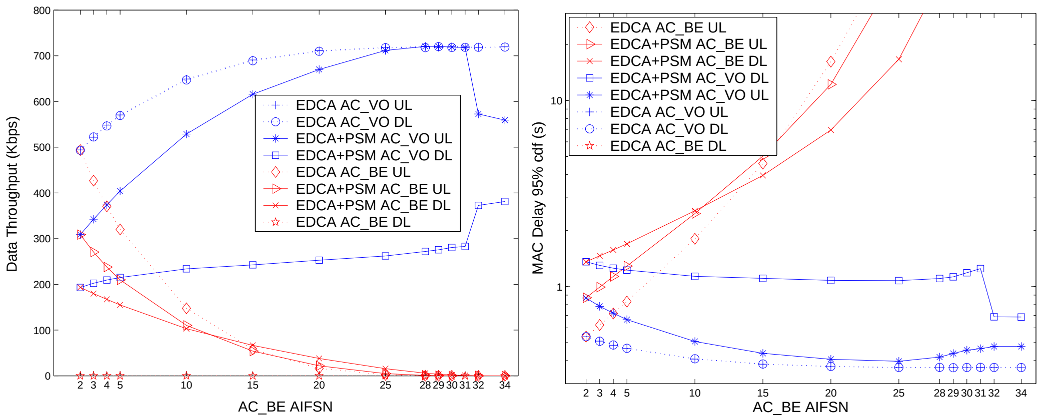
III.A QoS parameters effect

The 802.11e proposes three main configurable parameters to provide QoS, the AIFSN index, that determines the AIFS time, the CWmin and the CWmax parameters. In this section will be studied how good are these parameters in providing differentiation when using PSM and when not using PSM.

To perform this evaluation a set of experiments has been defined. We consider an infrastructure WLAN scenario with two stations and one Access Point. There is one station sending AC_VO traffic to the AP and the other one is sending AC_BE traffic. The settings used to send the PS-Polls are the same than the ones used to send the data packets. The AP is sending both kinds of traffic. The way to study the performance of the different QoS parameters is the following: the AC_VO class, in the station and the AP, will have a fixed configuration and the AC_BE class will change one of its QoS parameters in order to decrease the relative priority that it has with respect to the AC_VO station. The results for the Uplink and the Downlink when using PSM (referred as EDCA+PSM case) and when not (referred as EDCA case) will be shown. In our experiments the stations have always at least one packet to transmit.

As an illustrative example figure 1 shows the effect of tunning the most restrictive QoS parameter, the AIFS time. We consider an AIFSN value equal 2 for AC_VO and the AC_BE AIFSN is increased from 2 to 34. To avoid the effect of the CW parameters, the CWmin and CWmax have been set to 31 for both access categories. Note that because of having the same value for CWmin and CWmax the influence of the binary exponential backoff is avoided. Therefore only the AIFSN effect is observed.

The figure 1(a) shows the results of the throughput metrics for Uplink and Downlink and for the EDCA and EDCA+PSM cases. The format used in this graph is the following : In blue are presented the Uplink metrics and in red the Downlink metrics, in dotted lines are presented the EDCA metrics and in solid lines the EDCA+PSM metrics. Therefore in each graphic are depicted eight cases, Uplink and Downlink for AC_VO and AC_BE and for the EDCA and EDCA+PSM cases.



(a) Throughput

(b) PS-Poll Throughput

Figure 1: Effect of changing AC_BE AIFSN

The first thing to be noticed when looking at the mentioned graph is that in both cases, EDCA and EDCA+PSM, changing the AIFSN value is providing differentiation between the AC_VO and AC_BE classes of priority. Nevertheless very different ways to achieve this differentiation are observed in the EDCA and EDCA+PSM cases.

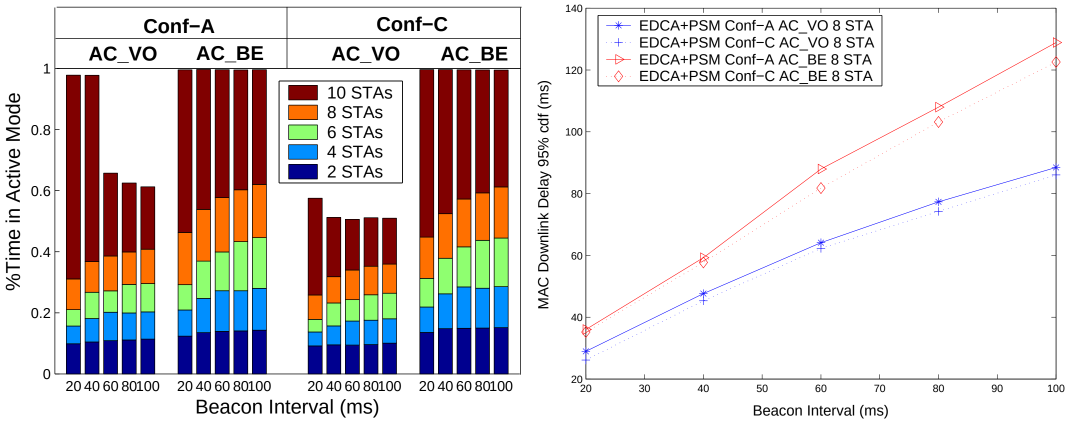
Let's focus first on the case where AC_BE AIFSN is equal 2. In this case both classes of priority AC_VO and AC_BE have the same settings, i.e. the same priority. Looking first at the EDCA case, dotted lines, is clear to observe how the AC_VO throughput and the AC_BE throughput in the Uplink are exactly the same, even the AC_VO throughput in the Downlink is the same, note that there is no AC_BE traffic sent in the Downlink because of being in a saturated scenario and having the strict priority mechanism in the AP. Therefore the available bandwidth is split in the same way between all the contending stations. Something quite different is happening in the EDCA+PSM case, at the first place the Uplink throughput is lower than in the EDCA case, this is because now the stations in addition to be sending data frames in the Uplink have to send PS-Polls to receive packets in the Downlink, and in the second place the Uplink and Downlink throughput are not the same. This asymmetry between Uplink and Downlink is an intrinsic characteristic of the PSM, since when the PSM is used the frames are buffered in the AP and only delivered when a PS-Poll is received.

The following thing to observe is how the differentiation increases when changing the AC_BE AIFSN from 2 to 34. In the EDCA case the Uplink and Downlink AC_VO throughput are increasing exactly in the same way, note that the two graphs are one over the other, and the AC_BE Uplink throughput decreases, observe that there is never AC_BE throughput in the Downlink for the reasons mentioned before. Regarding to the EDCA+PSM case the difference in Uplink AC_VO throughput with the EDCA case gets reduced when the AC_BE AIFSN increases. This is because the Uplink and Downlink AC_VO throughput increase in a very different manner when using PSM, actually the Downlink AC_VO throughput can not increase as fast as the Uplink throughput, and this is why the Uplink AC_VO station gets the most of the bandwidth, so it ends up transmitting a data throughput similar than the one in the EDCA case even when having to transmit PS-Polls. Figure 1(b) shows the delay results for the same experiment, that behave accordingly to the throughput ones.

III.B Power Saving Evaluation

In this section the effectiveness of the power save mode mechanism is studied considering two examples of EDCA configurations based on the values proposed in the 802.11e draft: aggressive (Conf-A) and conservative (Conf-C) . It is computed the percentage of time spent in active mode by the stations in power save mode for both EDCA configurations depending on the beacon interval considered and the number of wireless stations (50% of each AC).

The results in Figure 2(a) clearly show the power consumption reduction for both ACs, at least around 40%, when the channel is not congested, i.e., number of wireless stations 8 or below. AC_VO stations present a lower power consumption because they send and receive frames faster. At the first sight the behavior seems to be quite flat, because the longer the beacon interval the more the frames that the station has to download after each beacon. But there are some effects to remark, there is a bigger increase in the power consumption when the beacon interval gets bigger than the frame generation rate (30 ms in this scenario), this is because then all the stations have a frame to download after each beacon frame. From that point on the power consumption increase when increasing the beacon interval is lower, on one hand download frames with the More Data bit requires less time but on the other hand when the time required to download the packets from the AP increases is more probable to have Uplink transmissions within that time so the delivery of packets from the AP is delayed. The 10 stations case presents a percentage of time in active mode close to 1 for the AC_BE case since the channel is getting congested and a lower one for AC_VO. The aggressiveness of Conf-A that produces a longer time for resolving collisions when the channel is congested benefits from a longer beacon interval in the AC_VO case because of the randomizing effect of the More Data mechanism. To conclude Figure 2(b) shows the effect of the beacon interval on the downlink delay. It is clearly observed how the downlink delay increases with the beacon interval, and this can lead to some configurations where the stringent QoS requirements of applications like VoIP are not going to be fulfilled.



(a) % Time awake

(b) Downlink Delay

Figure 2: PSM Evaluation

IV PSM enhancements proposal

Several problems when using standard power save mode have been detected so far:

- An important impact is observed on the Downlink delay, where special attention has to be paid to the beacon interval configuration. Some beacon interval configurations might harm the QoS required by applications like VoIP.
- There is an effect that decreases the standard PSM efficiency and is the fact that all the PS-Poll and Downlink data transmissions are synchronized just after the beacon frame.

A power saving mechanism is desired whose performance does not depend in such a strong way on the AP's configuration. We would like a power saving scheme able to bound the downlink delay to a value suitable to assure the QoS of any application, while breaking the synchronization that all the stations see after the beacon frame in standard power save mode.

For the sake of simplicity no QoS extensions will be considered, at this point the stations will be working according to the legacy DCF defined in the 802.11 standard. The interactions of the new power saving mechanisms when using QoS mechanisms are left as possible future work.

Our main goal is to design a mechanism that reduces the Downlink delay dependency with the beacon interval observed when using standard PSM. This must be done keeping a power saving efficiency at least as good as when using standard PSM. The reference application to design these new mechanisms will be VoIP.

Using VoIP, the standard PSM, if configured with a large beacon interval, might not fulfill the application QoS requirements. Imagine that we have a VoIP application using a codec with a frame size of 20 ms, typical value for G.711, this means that every 20 ms, new frames are arriving at the AP. The beacon interval configured in the AP is 100 ms, therefore between two consecutive beacons this station receives five frames that are buffered in the AP. The different frames see different delays distributed between 0 and 100 ms until the beacon time arrives. After the beacon, the WLAN station realizes that it has frames buffered in the AP and starts sending PS-Polls to download these frames. Here it is very clear the synchronization effect of the standard PSM, if instead of having only one station running a VoIP application there are five stations, after every beacon all the stations will have five frames buffered in the AP and will try to recover them by sending PS-Polls. This synchronization leads to a higher probability of collision right after the beacon, and this means more time to download the frames, that of course turns into less power saving.

A possible solution to the delay and the synchronization problems is the following: If the stations' MAC layer would know that every 20 ms there is a frame addressed to them arriving to the AP, then it would be better to send a PS-Poll every 20 ms. By doing this the Downlink delay that a frame, when arriving to the AP, can see, is bounded to 20 ms, not to 100 ms (because of the beacon interval) like before. Therefore the dependency with the beacon interval is broken and the synchronization after the beacon is also broken, because now each station sends the PS-Polls in a distributed way.

In order to overcome the above mentioned issues an adaptive power save mode algorithm (APSM) for the stations is proposed in this thesis. Using the information available at the MAC layer, APSM provides a soft upper bound of the MAC Downlink delay by estimating the data frame interarrival time and generating PS-Polls at the same rate.

Adaptive PSM

The adaptive power save algorithm proposed has been designed to fulfill the following objectives:

1. Provide a soft upper bound of the MAC Downlink delay according to common application requirements independently of the beacon interval value.
2. Keep the bound guarantee even in the case of more than one application per station (traffic mixed).
3. Guarantee a power saving efficiency similar or better than the one of standard power save mode.
4. Minimize the signaling load introduced in the channel.
5. Minimize the impact on the standard power save mode.

The algorithm designed is based on the estimation of the current Downlink data frame interarrival time to adapt the PS-Poll interval accordingly and in this way upper bound the MAC Downlink delay to the frame arrival interval. This approach is considered because in general applications can cope with an end-to-end delay well above their frame generation interval, e.g., a delay sensitive application as VoIP which codecs usually generate frames every 10-30 ms, can deal with an overall delay of 150-300 ms. Considering that in most of the networks including WLAN access the main contributor to the overall delay is usually the MAC layer, upper bounding the MAC Downlink delay to the Downlink frame interarrival time should satisfy the most stringent application requirements.

There is a preliminary issue to be solved if we want to generate PS-Poll without waiting for the Beacon frame. The problem comes because we generate PS-Polls without being totally sure that a data frame is buffered at the AP. According to the 802.11 standard Power Save mode description, PS-Polls sent by an 802.11 station to an AP can either be acknowledged by receiving the correspondent data frame or by an acknowledgment frame. In the case of receiving a PS-Poll and having no data frame buffered in the AP, the AP can not send immediately a data frame, therefore the option of sending an acknowledgment after a PS-Poll should be considered when using these mechanisms. But if the station receives an acknowledgment after the PS-Poll and no frame is buffered in the AP the station will remain awake until a successful frame in the Downlink without More Data indication will be received. As a result the power saving efficiency will suffer a significant degradation. Note that this could not happen with the standard power save mode since a PS-Poll is only sent after the indication that a frame is buffered at the AP.

A simple solution is designed for this problem that consists in using the More Data field included in the acknowledgment frames, which is currently not being used, to indicate to the station whether it should expect a data frame, i.e. remain awake, or not. By doing this a station that sent a PS-Poll but has no frame buffered at the AP can go to doze mode immediately after receiving the acknowledgment, reducing in this case the time that the station remains awake to the minimum. In the rest of the document it will be referred an acknowledgment indicating that no frame is buffered for a certain station as a *No Data Acknowledgment (NDAck)*.

The basic idea of the algorithm is the following: Two possible situations are possible when trying to estimate the Downlink interarrival time, our current PS-Poll interval estimation can be either above or below the actual value of the Downlink interarrival time. Being in one or the other case will lead to two different situations.

If our current estimation is above the actual Downlink interarrival time, what will happen is that every certain number of frames, *n_fr_rcvd*, the station will receive one frame with the More Data bit set to true. The following can be stated:

Lemma 1 *If a frame with a More Data bit indication is received the PS-Poll interval being used is above the current Downlink interarrival time.*

Let's focus now on the case where our estimation is below the actual Downlink inter arrival time. What will happen is that every certain number of frames, *n_fr_rcvd*, a PS-Poll is sent but no data addressed to that station is buffered in the AP. The station can realize about this fact because of the NDAck. The following can be stated:

Lemma 2 *If a NDAck is received the PS-Poll interval estimation being used is below the current Downlink interarrival time.*

These two events: a frame received with the More Data bit set to true or a NDAck after sending a PS-Poll will drive the algorithm. If the former happens the PS-Poll interval estimation will have to be decreased and if the latter happens the PS-Poll interval estimation will have to be increased.

But how should the PS-Poll interval estimation be modified when any of those two events occur? Note how the variable *n_fr_rcvd* behaves, this variable counts how many frames are received by the station between two consecutive frames with More Data bit indication, or between two PS-Polls acknowledged with a NDAck.

Lemma 3 *Let* $pspoll\_interval$ *be the current PS-Poll interval estimation and let* $downlink\_interarrival\_time$ *be the actual Downlink interarrival time. The number of frames received between two consecutive frames with the More Data bit indication or between two consecutive NDAcks is given by :*

$$n\_fr\_rcvd = \frac{downlink\_interarrival\_time}{|downlink\_interarrival\_time - pspoll\_interval|} \qquad (1)$$

Therefore in the situation described before the APSM algorithm should update the PS-Poll interval estimation in a way according to the inverse of the value *n_fr_rcvd*. If the value of *n_fr_rcvd* is big and one of the two events that drive the algorithm occur, either a frame with More Data bit indication or a NDAck, the estimation should be slightly modified as the current PS-Poll interval being used is close to the actual value to be estimated.

The following way to update the PS-Poll interval estimation, depending on whether the station receives MD bit or NDAck, is chosen:

$$pspoll\_interval(n+1) = pspoll\_interval(n)\left(1 \pm \frac{1}{k\left(n\_fr\_rcvd(n)+1\right)}\right) \qquad (2)$$

It can be proved that by updating the PS-Poll interval estimation in this way the estimation will converge to the actual Downlink inter arrival time. Note that by achieving this our objectives are fulfilled: The Downlink delay dependency with the Beacon interval is broken, the Downlink delay is bound to the Downlink inter arrival time, and the stations send the PS-Poll frames in a non synchronized way. In the following the performance of our algorithm when being used with realistic applications is shown, and a comparison with the Standard Power Save Mode in terms of delay and power saving is provided.

Performance Evaluation

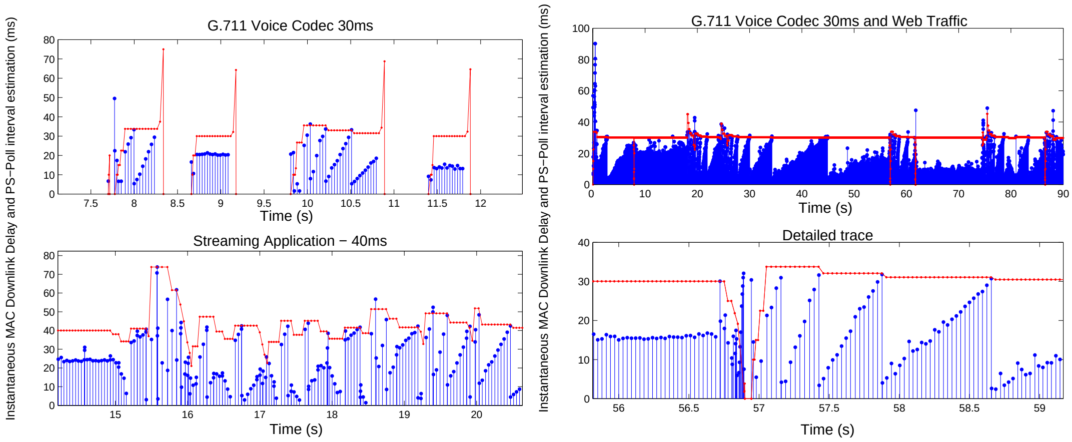
The performance of our APSM algorithm has been evaluated via simulation. The 802.11b libraries provided by OPNET 10.0 have been extended to include the 802.11 standard power save mode and the new power saving mechanisms.

In our experiments every wireless station has its corresponding pair in the wired domain. Communication occurs always between wireless-wired pairs through the AP. The length of the simulations performed is 120 seconds. The values in the graphs have been computed using the statistics obtained for each of the single wireless stations and using at least 10 different seeds.

First we focus in general scenario with realistic applications, e.g., G.711 audio codec with silence suppression (data rate 64kbps, frame rate 30ms), or do not generate traffic at a constant bit rate, e.g., MPEG-4 streaming of the movie Jurassic Park (average rate 150kbps, frames generated every 40ms).

Figure 3(a) shows the proper adaptation of the PS-Poll rate estimated by the APSM algorithm during the active periods of the VoIP source (solid line where each point represents a PS-Poll transmission) and the detection of the silence periods going back to doze mode. As a result, the soft upper bound Downlink delay guarantee is provided (amplitude of deltas).

The adaptation to the variable data rate generated by the streaming application is depicted also in Figure 3(a). In this case, the variable bit rate of the application results in a variable Downlink frame interarrival time, e.g., due to segmentation of large packets. The PS-Poll rate estimation successfully adapts to these changes while keeping around the expected average value of 40ms.



(a) Silence suppression and Streaming applications

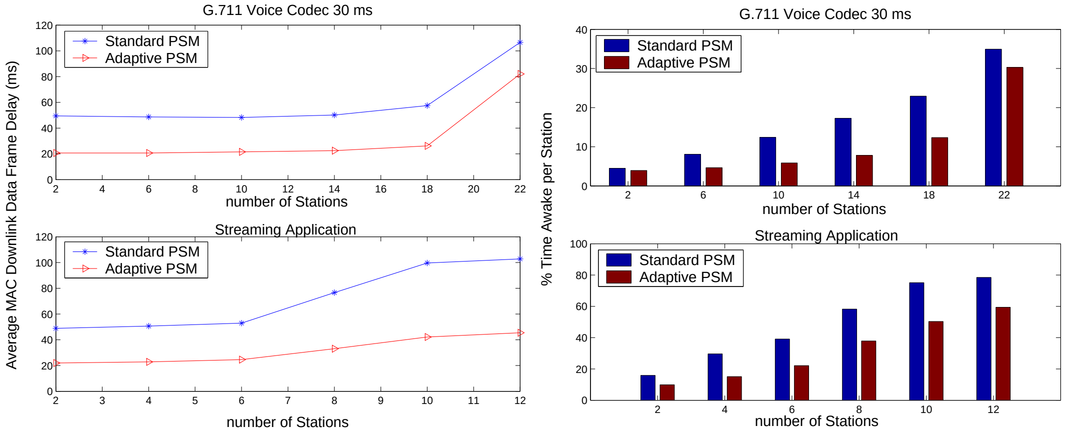
(b) Voice and Web application

Figure 3: Realistic applications

One of the main design objectives for the algorithm, is to keep the delay bound guarantee even in the case of more than one application per station (traffic mixed). We design an experiment to analyze the effect over the APSM algorithm of adding Web traffic to the VoIP application used in the previous experiment. In this case is not used silence suppression to facilitate the recognition of the web traffic burst over the voice traffic. The configuration used to emulate web traffic is page interarrival time exponentially distributed with mean 10s and page size 10 KB plus 5 images of a size uniformly distributed between 0.5 and 2 KB.

As shown in Figure 3(b), the PS-Poll interval estimation of the algorithm (solid line) reacts as desired to the additional load decreasing the PS-Poll interval and therefore keeping the soft upper bound Downlink delay guarantee of data frames (amplitude of deltas).

So far has been demonstrated that the APSM algorithm performs better than the standard power save mode when the network is in normal conditions, i.e., not saturated. Now is tested how the APSM performs in relation with the standard power save mode when the network saturates. The APSM algorithm robustness is studied by increasing the number of wireless and corresponding wired stations in our scenario. In Figure 4(a) is shown the MAC Downlink delay when the number of stations in the network increases, and in Figure 4(b) the percentage time the stations are awake, i.e., the power consumption with both the standard power save mode and the APSM algorithm. The experiments have been performed with the realistic applications considered in the former sections.



(a) MAC Delay (b) % Time awake

Figure 4: Saturation performance

Regarding to the MAC Downlink delay, Figure 4(a), shows how the APSM performs better than the standard power save mode with both applications, VoIP with silence suppression and streaming. Note that to send PS-Polls more often helps the AP to empty its queues faster so that the saturation point is achieved later. In the case of the VoIP with silence suppression application the average Downlink delay when being in the non saturated zone is slightly bigger than the half of the Downlink rate, the codec used is sending frames each 30 ms, this is because of use silence suppression, as can be seen in Figure 3(a) the first frames after a silence period have bigger delays as they are delivered using standard power save mode because the algorithm restarts during the silence periods.

Regarding the power saving efficiency Figure 4(b) shows how even in saturation the APSM performs better because avoiding the standard power save mode synchronization effect.

V Conclusions

The upcoming mobile devices including 3G and WLAN access technologies introduce new technological challenges that need to be addressed. This work identified the combination of the 802.11e QoS mechanisms with the 802.11 power save mode functionality as a key element toward the introduction of WLAN capabilities in battery limited devices as cellular phones. The performance of the superposition of both mechanisms though, requires to be studied to determine its suitability for the case considered.

The main conclusions that can be drawn from these results are i) the 802.11e mechanisms to provide different QoS are influenced by the 802.11 power save mode functionality but are still highly effective, ii) an important impact is observed on the Downlink delay, as expected, where special attention has to be paid to the beacon interval configuration and iii) in devices where power saving is a critical issue, the significant increase in the power usage efficiency in no congestion conditions justifies the power save mode costs.

The issues that arise when using the power saving method defined in the 802.11 standard with applications like VoIP that have strict delay requirements have been also explained, and some alternatives to overcome that problems described. In particular, in this thesis, an adaptive power save mode algorithm, APSM, is proposed that provides a soft upper bound of the data frames Downlink delay (statistical guarantee) according to the Downlink frame interarrival time.

Our adaptive power save mechanism is compared to 802.11 standard power save mode with respect to the resulting data frame MAC Downlink delay, power saving efficiency and required signaling load.The results show that i) as expected, the algorithm fulfills its objective of providing an upper bound of the Downlink delay according to the Downlink frame interarrival time and ii) the power saving efficiency is increased because of the desynchronization of the PS-Polls transmissions.