Overlapping Aware Scheduled Automatic Power Save Delivery Algorithm

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Abstract—**Mobile devices including Wireless LAN functionality are becoming increasingly popular in society. The wide range of products available in the market target different customer needs but most of them should meet two main requirements: QoS support for differentiating real-time services from non real-time and power saving functionality to achieve an operating time according to users' expectations. The devices presenting the most challenging technical issues to meet these two requirements are dual-mode handsets (Cellular/WLAN) because of their mandatory support of a strict QoS demanding application, VoIP, and their small device size which severely limits the battery size. The focus of our work in this paper is the evaluation of the capability of a specific IEEE 802.11e power saving mechanism, Scheduled Automatic Power Save Delivery (S-APSD) in combination with HCF Controlled Channel Access (HCCA) to efficiently address the challenges posed by the requirements of Wireless LAN-capable mobile devices. In order to do so, we designed an Overlapping Aware S-APSD algorithm (OAS-APSD) and evaluated its performance in combination with HCCA as compared to the basic 802.11 power save mode using EDCA.**

Keywords— **Wireless LAN, 802.11, 802.11e, QoS, Power Save Mode, APSD and S-APSD.**

I. Introduction

The wide adoption of the IEEE 802.11 wireless LAN technology by home and business users, due to its capability of providing low cost high speed wireless Internet access, is driving a strong trend toward the inclusion of this technology in mobile devices like cellular phones, personal digital assistants (PDAs) or laptops. However, several challenges need to be addressed with respect to QoS and power saving limitations to achieve a seamless integration of the Wireless LAN technology in such devices.

Regarding QoS, an enhancement of the 802.11 MAC layer was designed, the IEEE 802.11e standard [1], which defines mechanisms to provide QoS differentiation. IEEE 802.11e defines the Hybrid Coordination Function (HCF) to support QoS. Two channel access methods are defined: a contention-based method called the Enhanced Distributed Channel Access (EDCA) and a contention-free one referred to as HCF Controlled Channel Access (HCCA). Within a superframe two phases of operation are possible, 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. A thorough overview of the 802.11e QoS enhancements can be found in [2].

With respect to the battery usage efficiency, the intrinsic nature of 802.11, which is based on a shared channel access (CSMA/CA), forces wireless stations to continuously listen to the channel to determine its current status. As a result, a handheld device connected through an 802.11 wireless LAN, will drain its battery after a few hours as opposed to current mobile devices that can have a standby battery lifetime up to several days, e.g., cellular phones. Ideally, mobile devices including the wireless LAN technology should achieve a battery consumption similar to current handheld devices in order to meet users' expectations.

The IEEE 802.11 standard provides a power save mode that reduces the time required for a station to listen to the channel. Once every Beacon interval, usually 100ms, the access point (AP) sends a Beacon indicating whether or not a certain station[1] has any data buffered at the AP. Wireless stations wake up to listen to Beacons at a fixed frequency and poll the AP to receive the buffered data by sending power save polls (PS-Polls). Whenever the AP sends data to a station, it indicates whether or not there are more data frames outstanding, using the More Data bit in the data frames, and a station goes to sleep only when it has retrieved all pending data. Although this mechanism significantly alleviates the power consumption problem, a dependency between the data frames MAC downlink delay (AP to station) and the listen interval is introduced. Consequently, some listen interval values can result in downlink delays unacceptable for certain QoS-sensitive applications, e.g., VoIP. Further details about the legacy 802.11 power save mode operation can be found in [3].

In order to address some of the power saving issues that arise when a specific QoS is desired, the 802.11e standard includes an optional extension of the 802.11 power save mode defined as Automatic Power Save Delivery (APSD). Two different APSD modes have been defined depending on whether a distributed or a centralized mechanism is preferred. Unscheduled APSD (U-APSD) is a distributed mechanism where stations decide on their own when to awake to request the frames buffered at the AP while sleeping. Scheduled APSD (S-APSD) is the centralized mechanism where the AP determines a schedule for the stations to awake to receive the frames that the AP buffered.

Given the fact that for Wireless LAN-capable mobile devices the S-APSD mechanism is expected to provide the best QoS and power saving performance, we focused our work in this paper on the evaluation of the capability of the S-APSD mechanism to efficiently address the challenges posed by the aforementioned requirements. The evaluation required, as a previous step, the design of an S-APSD algorithm since none was available in the IEEE 802.11e standard or in the literature.

To the best of the authors' knowledge there is no published related work regarding S-APSD algorithms and their performance. In the area of providing QoS in a wireless LAN a lot of research has been done during the last several years, see for example [2], [4] for EDCA and [5] for HCCA. With respect to the 802.11 power save mode, the infrastructure mode has been studied for

[1] In this paper the terms AP and station refer to what in the 802.11e standard is denoted as QAP and non-AP QSTA respectively.

instance in [6] where the main focus was to improve the performance for web-like traffic. Regarding U-APSD, in [7] a modified version of the U-APSD functionality (UPSD) based on an 802.11e draft (Dec'04) was studied where the performance of three different UPSD modes was analyzed in a single scenario with 12 stations and two types of traffic, voice and FTP.

In our previous work, we studied in [3] the impact of using the 802.11 power save mode in combination with the 802.11e EDCA QoS mechanisms. In [8] we proposed a MAC power saving algorithm to adaptively control the delay introduced by the 802.11 power save mode for applications requiring QoS guarantees. In [9] we defined a static implementation of U-APSD (SU-APSD) and evaluated its QoS and power saving performance as compared to the 802.11 power save mode. Finally, we designed an adaptive algorithm for U-APSD (AU-APSD) which aims to dynamically configure the SU-APSD algorithm based on the information available at the MAC layer [10]. The paper at hand extends our previous results by analyzing for the first time the S-APSD mechanism.

The rest of the paper is structured as follows. In Section II-A a general overview of the S-APSD functionality is given. Section III describes our proposed Overlapping Aware S-APSD algorithm (OAS-APSD) providing the logic used for its design. The performance results obtained with the OAS-APSD algorithm, compared to the currently most wide spread wireless LAN power saving mechanism, legacy 802.11 power save mode, are provided in Section IV. Finally, Section V summarizes the results and concludes the paper.

II. Scheduled Automatic Power Save Delivery (S-APSD)

Automatic Power Save Delivery is the proposed 802.11e extension of the 802.11 power save mode in order to be able to provide QoS for unicast traffic even in the case of making use of a power saving mechanism. Inline with the 802.11e QoS mechanisms, which define the *distributed* EDCA access to provide *prioritized* QoS guarantees and the *centralized* HCCA access to provide *parameterized* QoS guarantees, APSD defines also a distributed power saving scheme, *Unscheduled APSD* (U-APSD), and a centralized one, *Scheduled APSD* (S-APSD). The frames buffered at the AP can be then delivered to the power saving stations either by using the EDCA access method if U-APSD is selected or by using EDCA or HCCA if S-APSD is chosen. The period of time where a station is awake receiving frames delivered by the AP is defined in APSD as *Service Period* (SP). A SP is started by a station or an AP depending on the considered APSD mechanism and is always finished by the reception at the station of a frame with the End Of Service Period Flag set (EOSP).

In the following we provide an overview of the S-APSD functionality indicating the main enhancements introduced with respect to legacy 802.11 power save mode.

A. Scheduled Automatic Power Save Delivery (S-APSD)

Scheduled Automatic Power Save Delivery (S-APSD) is the *centralized* APSD method defined in 802.11e to improve the QoS provided to stations accessing the channel using the EDCA or HCCA mechanism. The main idea behind the S-APSD design is the *scheduling* by the AP of the instants where each different station using S-APSD should awake to receive the frames buffered at the AP. The usage by a station of the S-APSD delivery mechanism for a traffic stream, in the case where the access policy is HCCA, or for an AC, in the case where the access policy is EDCA, is configured by the transmission of an ADDTS request frame to the AP with the APSD and Schedule Subfields of the TS Info field element both set to 1. In case the AP can satisfy the requested service, it will indicate so in the Schedule Element of the response which will include the *Service Start Time* (SST) and the *Service Interval* (SI).

The AP is responsible for defining for each traffic stream or AC of a station using S-APSD the SST and the SI necessary for the periodical scheduling of the delivery of frames to the stations. If a station has set up S-APSD for a traffic stream or an AC, it shall automatically wake up at the scheduled time of each SP defined by

$$SST + N \times SI \tag{1}$$

where $N \geq 0$.

The AP may update the service schedule at any time by sending a Schedule Element in a Schedule frame which will be used once the Acknowledgement to the Schedule frame has been received. The new Service Start Time though shall not exceed the beginning of the previous SP by more than a defined maximum service interval and shall not precede the beginning of the immediately previous SP by more than the defined minimum service interval. A station can also modify the S-APSD service schedule by modifying or deleting its existing traffic specification through ADDTS or DELTS messages.

A station shall remain awake until it receives a frame with the EOSP subfield set to 1. If necessary the AP may generate an extra QoS Null frame with the EOSP set to 1.

A.1 Advantages of S-APSD

Three main advantages are introduced with S-APSD with respect to the current most popular wireless LAN power saving mechanism, legacy 802.11 power save mode. These advantages will be evaluated in Section IV.

- The first advantage is the reduction in the signaling load required by the S-APSD power saving mechanism as compared to 802.11 power save mode because a station does not need to send any signaling frame (PS-Poll or QoS Null) to receive its downlink frames while in the 802.11 power save mode case a PS-Poll is required for each buffered frame at the AP.
- The second advantage, a consequence of the previous one, is the reduction in the number of collisions in the wireless channel due to signaling frames (PS-Polls or QoS Nulls) generated by the power saving stations to retrieve their frames buffered at the AP.
- The third advantage is a larger power saving due to the fact that stations do no need to spend energy contending for the wireless channel to send signaling frames to inform the AP of its awake state.

Moreover, if HCCA is used instead of EDCA, there are two additional advantages:

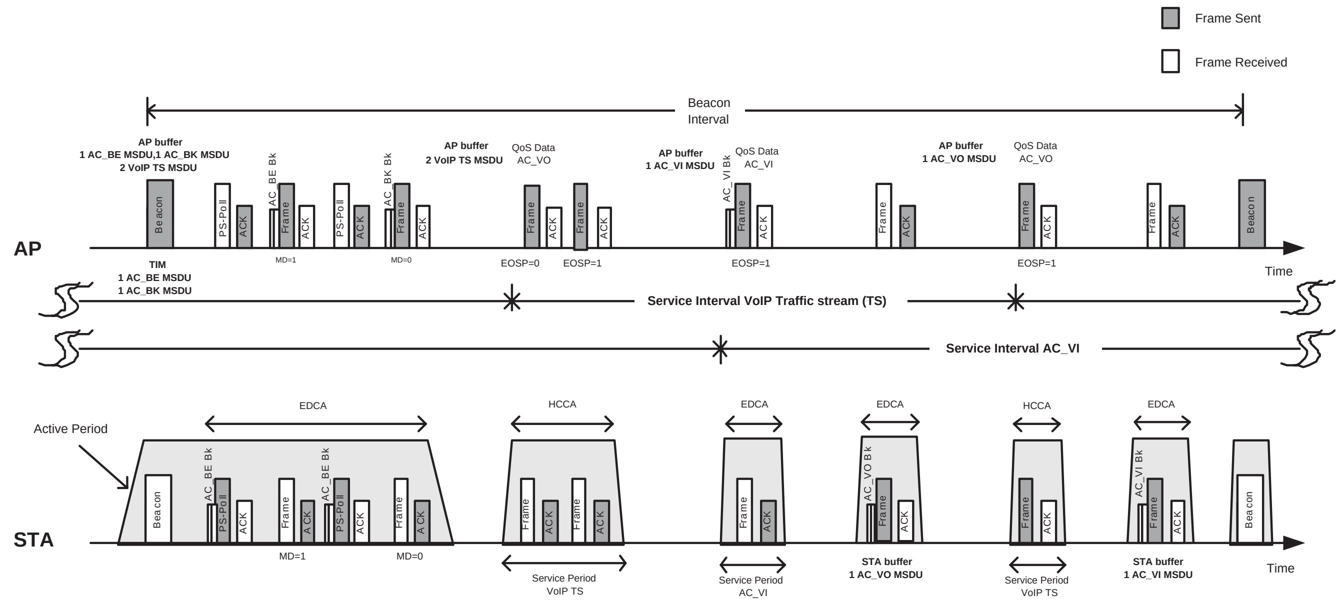

Fig. 1. S-APSD example of operation. S-APSD configuration: VoIP traffic stream in the downlink configured to use S-APSD with HCCA access mode, AC_VI traffic in the downlink uses S-APSD with EDCA access mode, AC_BE and AC_BK are configured to use legacy 802.11 power save mode. 1) First active period of the station: usage of the 802.11 power save mode mechanism to retrieve frames of AC_BE and AC_BK categories as indicated in the TIM. 2) Second active period: the station wakes up at the scheduled time for the VoIP traffic stream service period and receives the frames from the AP which assigned itself a TXOP using the HCCA mechanism. 3) Third active period: the station wakes up at the scheduled time for the AC_VI service period and receives the frame from the AP which obtained a TXOP using the EDCA mechanism. 4) Fourth active period: usage of the EDCA mechanism by the station to transmit an AC_VO frame in the uplink. 5) Fifth active period: the station wakes up again at the scheduled time for the VoIP traffic stream service period and receives one frame from the AP. 6) Sixth active period: usage of the EDCA mechanism by the station to transmit an AC_VI frame in the uplink.

- First, larger power saving improvements can be achieved because the frame delivery schedule can be kept tighter.
- Second, an improved QoS experience since congestion in the EDCA access has a limited effect on HCCA transmissions.

III. OAS-APSD Algorithm

The IEEE 802.11e S-APSD specification introduces different mechanisms to control the QoS and power saving provided to a station for each different AC or traffic stream. The specific implementation of these mechanisms to actually deliver the desired QoS and power saving is though, as usual, left open to allow differentiation between vendors. In the following, we describe our proposed Overlapping Aware S-APSD algorithm for an AP.

The main input required by the S-APSD algorithm from the AP QoS algorithm is the Service Interval (SI) to be used for a traffic stream or an AC of a station requesting this service. The SI might be determined by the AP QoS algorithm in two different ways depending on whether EDCA or HCCA is used to deliver the frames. In the case where the access policy is contention-free channel access (HCCA), the Service Interval would be determined by an HCCA QoS algorithm based on the information provided in the TSPEC. On the other hand, in the case where the access policy is contention-based channel access (EDCA), the Service Interval would be assigned based on the expected QoS requirements of the traffic corresponding to a certain AC.

The first clear objective of an S-APSD algorithm is to make sure that different Service Periods do not overlap in order to guarantee that stations have to be awake to receive their frames the minimum possible amount of time. The information available at the AP to be used by the S-APSD algorithm is full knowledge of all the events that have a fixed schedule: Beacon transmission time and period (BI), already scheduled SPs and period (SIs), already scheduled TXOPs and period (SIs) and contention-free period schedule. In the rest of the paper we will refer to these events as Scheduled Events (SEs).

Two different approaches could be used to schedule the starting time of service periods: contiguous scheduling of SPs within a period of time or non-contiguous. The contiguous scheduling of SPs would have the advantage of the simplicity of the algorithm required to determine the service start time for the schedule of a new S-APSD service. This approach, however, would present the problem that, since the Service Intervals are not easily changed and can be different for each traffic stream or AC using S-APSD, no contiguous scheduling of SPs could be achieved unless specific requirements/limitations would be set for the assignation of service intervals values. See Figure 2 for a graphical representation. Moreover, if HCCA would be chosen as the S-APSD frame delivery mechanism, an inefficient use of the wireless channel could occur when a SP had been scheduled but no frames happen to be buffered at the AP to be delivered to the station. In this case, the TXOP would end earlier than planned but, because the starting time for the next SP would be very close, the probability for an EDCA station to get access to the channel would be very low resulting in wasted capacity of the channel.

If the schedule for the service periods is not done contiguously though, the algorithm to determine the service starting times gets more complex. The higher degree of freedom, however, allows to avoid the above mentioned problems without

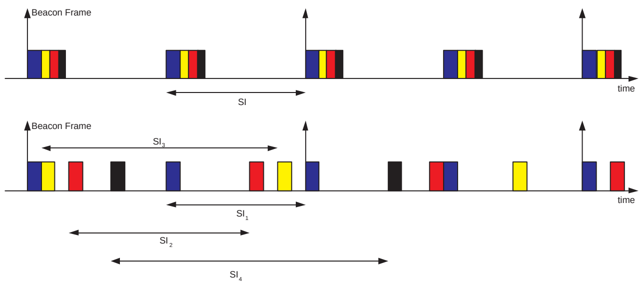

Fig. 2. S-APSD Service Period Allocation Possibilities, Contiguous versus Non-Contiguous

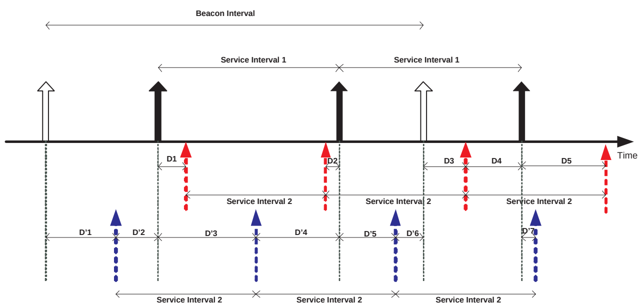

Fig. 3. S-APSD Service Period Scheduling Example

having to set any requirement on service intervals values. Once the non-contiguous approach has been chosen based on the aforementioned issues, the question is which criteria should be used in the algorithm in order to determine the service starting time for a new scheduled service period. Taking into account that the closer the scheduled SPs are, the higher the probability of wasting channel resources if HCCA is used (empty slots) or of being awake longer than necessary if EDCA is chosen (SP overlap), we propose to schedule the service starting time for a new scheduled service period such that the relative distances with respect to the previous and next scheduled events are maximized.

Figure 3 graphically shows the operation to be performed by the S-APSD algorithm. In the example, the schedule for two scheduled events is shown: the beacon transmission with its corresponding Beacon Interval and the schedule for service periods for a station with Service Interval 1. Then, when a new schedule for service period has to be added with Service Interval 2, the different Service Starting Times possibilities are checked (dashed arrows) and the relative distances computed (D1, D1', D2, etc.). Based on these relative distances the algorithm can determine a Service Starting Time that maximizes the distances between the scheduled events and thus, minimize the overlapping probability of Scheduled Events.

Algorithm 1 is our proposed implementation of the method depicted in Figure 3 to determine a service start time for a new S-APSD service taking into account the previously explained considerations. The proposed method, in principle, would require to check all possible overlappings of scheduled events in the future depending on the considered service starting time. Obviously, this would lead to an infinite number of operations to determine the desired service start time resulting in being impossible to implement the method in practice. Fortunately, when

Algorithm 1 OAS-APSD algorithm that determines the Service Starting Time (SST) for a new traffic stream taking into account the already Scheduled Events (SE) to avoid their overlapping.

SST **to be determined given a specific** SI_{new}
$N, SST, SST_{temp}, dist_{avg}, temp\_dist_{avg}, max\_dist_{min} \leftarrow 0$
$temp\_dist_{min} \leftarrow BI$

Create empty list of $SEs \rightarrow List_{SE}$
Compute LCM **considering** *All* SIs **plus** $BI \rightarrow LCM$

for $\forall\ SEs \in [t_{current}, t_{current} + LCM]$ **do**
  Insertion in $List_{SE}$ **of** SEs
end for

while $SST_{temp} < SI_{new}$ **do**
  while $SST_{temp} + SI_{new} \times N < LCM$ **do**
    Find $prev\_SE$ **and** $next\_SE$ **in** $List_{SE}$
    $dist_{next\_SE} \leftarrow next\_SE - (SST_{temp} + SI_{new} \times N)$
    $dist_{prev\_SE} \leftarrow SST_{temp} + SI_{new} \times N - prev\_SE$
    Insertion in $distances\_SST_{temp}$ **of** $dist_{next\_SE}$ **and** $dist_{prev\_SE}$
    $N \leftarrow N + 1$
  end while
  $temp\_dist_{min} \leftarrow$ **Minimum of** $distances\_SST_{temp}$
  $temp\_dist_{avg} \leftarrow$ **Average of** $distances\_SST_{temp}$

  if $temp\_dist_{min} > max\_dist_{min}$ **then**
    $max\_dist_{min} \leftarrow temp\_dist_{min}$
    $dist_{avg} \leftarrow temp\_dist_{avg}$
    $SST \leftarrow SST_{temp}$
  else if $temp\_dist_{min} = max\_dist_{min}$ **then**
    if $temp\_dist_{avg} > dist_{avg}$ **then**
      $dist_{avg} \leftarrow temp\_dist_{avg}$
      $SST \leftarrow SST_{temp}$
    else if $temp\_dist_{avg} = dist_{avg}$ **then**
      $SST \leftarrow random(SST, SST_{temp})$
    end if
  end if
  $SST_{temp} \leftarrow SST_{temp} + precision$
end while

a limited number of scheduled events is considered, defined by their SST and SI, it can be realized that a repetition pattern occurs with a period corresponding to the least common multiple (LCM) of the different SIs. As a result, the period of time to be considered by the algorithm to find the service start time that minimizes the overlapping is not infinite but limited to the LCM of the SIs. Regarding the possible service starting times, the number of possibilities is again not infinite but restricted first by the 802.11e specification, the maximum precision is a microsecond, and second by the SI length since after that the pattern is repeated periodically. Based on the aforementioned observations we can conclude that the proposed method is implementable in practice and the required computational load bounded.

IV. Performance Evaluation & Discussion

In this section we evaluate the performance of our proposed OAS-APSD algorithm as described in Section III as compared to the current most widely spread wireless LAN power saving mechanism, legacy 802.11 power save mode. The objective of the study is to i) to validate the OAS-APSD algorithm design and ii) evaluate whether the QoS and power saving performance improvements justify the additional complexity of the system as compared to simply using 802.11 power save mode. The analysis is performed via simulation. We extended the 802.11b libraries provided by OPNET 10.5 [11] to include 802.11 legacy power save mode, the HCCA QoS mechanisms of 802.11e required and our proposed OAS-APSD algorithm.

Two different scenarios are considered in the study. The first scenario, *Legacy PSM*, corresponds to currently available mobile devices where all stations use legacy 802.11 power save mode in combination with EDCA. The second scenario, *OAS-APSD*, corresponds to future mobile devices where some devices might include S-APSD and HCCA functionality while others still use 802.11 power save mode and EDCA. In order to evaluate the full differentiation potential of OAS-APSD compared to 802.11 power save mode, the HCCA access method has been chosen to deliver the data frames buffered at the AP for S-APSD stations. In the uplink though, we have opted for EDCA to try to minimize the changes required at the mobile devices to be able to support S-APSD.

In the evaluation we study the impact of increasing the number of stations on the MAC throughput and delay, the power saving efficiency and the resulting power saving costs. The experiment starts with a scenario of one AP and four wireless LAN stations where each station is configured to send and receive traffic from their corresponding pair in the wired domain of its type of application, i.e., one station sends and receives Voice traffic, a second one sends and receives Video traffic, a third one sends and receives Web traffic and a fourth one sends and receives E-mail traffic. The number of stations increases in multiples of four stations always keeping the relation of $1/4$ of stations of each aplication type. All stations operate at a data rate of 11Mbps.

The configuration of the applications used is detailed below:

- Voice: G.711 Voice codec with silence suppression. Data rate: 64kbps. Frame length: 20ms. Talk spurt exponential with mean 0.35s and silence spurt exponential with mean 0.65s.
- Video: MPEG-4 real traces of the movie 'Star Trek: First Contact' obtained from [12]. Target rate: 64kbps. Frame generation interval: 40ms.
- Web: Page interarrival time exponentially distributed with mean 60s. Page size 10KB plus 1 to 5 images of a size uniformly distributed between 10KB and 100KB.
- E-mail: Send interarrival time exponentially distributed with mean 120s. Receive interarrival time exponentially distributed with mean 60s. Size exponentially distributed with mean 100KB.

The *Legacy PSM* scenario is configured such that all stations use 802.11 power save mode and the EDCA settings used are the ones corresponding to the type of traffic generated. In the *OAS-APSD* scenario case, the Voice and Video stations are configured to use S-APSD with service intervals of 40 and 60 ms, respectively, while Web and E-mail stations use 802.11 power save mode. We have chosen the Service Interval for Voice and Video stations 20ms above the frame generation interval of the traffic sources (20 and 40 ms respectively) to model the fact that, in general, to meet the QoS requirements of the applications it is not necessary to perfectly match their frame generation interval and thus, due to power saving and channel usage efficiency reasons, a larger one is preferable. The precision used in the evaluation to find the Service Starting Times with our proposed OAS-APSD algorithm is 1ms.

Since our focus is on the differences in the performance between the two power saving mechanisms considered and not on the EDCA parameters configuration, we assume a fixed configuration of the 802.11e EDCA QoS parameters based on the 802.11e standard recommendation [1]. The parameters used are detailed in Table I.

	AIFS	**CWmin**	**CWmax**
AC_VO	2	31	63
AC_VI	2	63	127
AC_BE	3	127	1023
AC_BK	7	127	1023

TABLE I

EDCA CONFIGURATION FOR THE DIFFERENT ACS

EDCA-TXOP durations are configured to allow the transmission of one data frame after gaining access to the medium (TXOPlimit=0). The RTS/CTS mechanism has not been enabled to avoid its influence over the mechanisms being studied. The Beacon interval used is 100 ms and the listen interval configured for the 802.11 power save mode stations is 1.

The length of the simulations performed is 300 seconds with a warm-up phase of 30 seconds. The number of seeds used to obtain each value in the graphs has been chosen such that the 95% confidence interval of a value in a certain point does not overlap with the 95% confidence interval of any other value.

QoS Differentiation

Figures 4 and 5 illustrate the impact of increasing the number of stations on the MAC downlink delay and throughput respectively. As expected, the OAS-APSD method (dot-dashed line) clearly outperforms the 802.11 power save mode one (Legacy PSM, solid line) in the number of Voice and Video stations that can be accepted in the system. This is mainly because the access method used with OAS-APSD to deliver the frames from the AP to the stations is HCCA instead of EDCA. Given the strict priority to access the channel that HCCA has over EDCA, the delay and throughput requirements of Voice and Video in the S-APSD case can be met as long as enough resources are available in the channel. With respect to Web and E-mail stations, a priori it could be expected that the S-APSD scheme would result in a worse performance than the legacy 802.11 power save mode one since strict priority is given to Voice and Video traffic. However, the S-APSD approach presents a better performance than 802.11 power save mode in the downlink both in delay and throughput terms because of the lower collision rate experienced by these categories since they do not compete with Voice and Video traffic.

The corresponding uplink delay and throughput results are shown in Figures 6 and 7. *OAS-APSD*, as opposed to the downlink case, is outperformed by 802.11 power save mode in the maximum number of Voice and Video stations that can be accepted in the network. However, the system performance is determined by the combination of the uplink and downlink performance which is best in the *OAS-APSD* case. The main difference of the S-APSD uplink case for Voice and Video with respect to the downlink one is that, when a frame has to be sent in the uplink, stations awake and directly transmit using EDCA instead

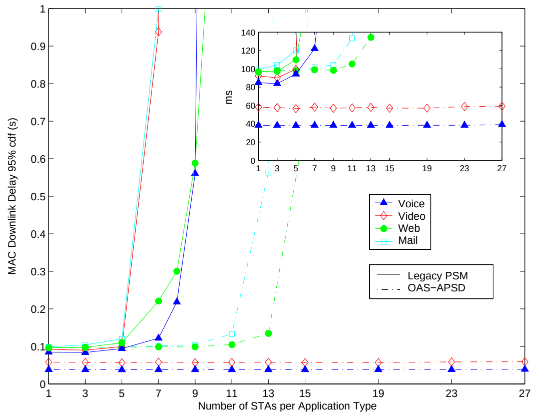

Fig. 4. Impact of the number of stations on the MAC downlink delay

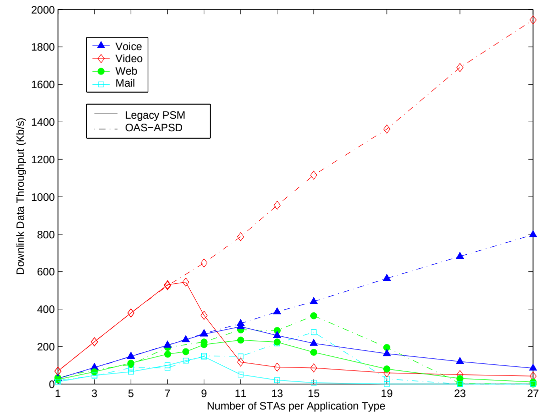

Fig. 5. Impact of the number of stations on the MAC downlink throughput

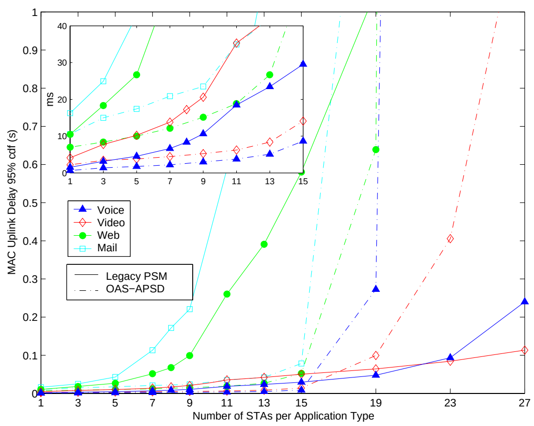

Fig. 6. Impact of the number of stations on the MAC uplink delay

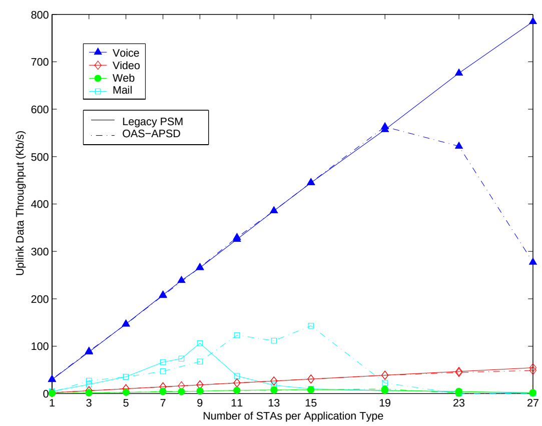

Fig. 7. Impact of the number of stations on the MAC uplink throughput

of waiting for a service period and receive frames delivered using HCCA. Therefore, the uplink delay increases progressively according to the congestion load in the wireless channel while in the downlink it is independent of the congestion as long as enough resources are available for HCCA [2].

A. Power Saving Efficiency

The main objective of the OAS-APSD mechanism is to reduce the power consumption of the stations while providing the necessary QoS. In the previous section we have studied the QoS differentiation achieved by OAS-APSD as compared to 802.11 power save mode. In this section we study the differences in power consumption between both methods and whether the QoS differentiation advantages obtained with the OAS-APSD configuration have a cost in power saving efficiency terms.

The power saving model used for the evaluation has been derived based on current WLAN cards/chipsets available on the market and consists of four states: Sleep, Listen, Reception and Transmission. The *Clear Channel Assessment* (CCA) function used in our analysis is CCA mode 1, or energy threshold.

Based on this model, we compute the percentage of time spent during an active session in each state by the stations and particularize the results by translating these percentages into *mA* based on the information provided in the product datasheet of a common PCMCIA WLAN card [13]. The power consumption values used are shown in Table II[3].

Cisco Aironet^{TM}	**Sleep**	**Listen**	**Reception**	**Transmission**
Power (mA)	15	203	327	539

TABLE II
POWER CONSUMPTION OF A POPULAR PCMCIA CARD

Figure 8 shows the power spent by the stations for the two power saving methods under study. As expected, *OAS-APSD* clearly outperforms *Legacy PSM* since the S-APSD stations only awake according to the agreed schedule and receive their data frames directly. Legacy stations have to compete to access the channel to inform the AP that they are awake plus have to wait until their frames become the next to be delivered. Thus, *OAS-APSD* results in a clearly larger capacity of the network. For instance, in the *OAS-APSD* case, up to 60 stations can be accepted in the network before any reach the same power consumption as in active mode while, in the *Legacy PSM* case, 28 stations can be accepted, i.e., 114% increase. The differences between the power consumption of each application type station

[2]Note that in this experiment the uplink is the bottleneck direction for OAS-APSD because EDCA is used instead of HCCA. We have chosen this option in order to minimize the changes required at the mobile devices to support the S-APSD functionality.

[3]For the sleep mode we used the value of a previous model of a Cisco PCMCIA card (Cisco Aironet 350) since no information was available for the current one

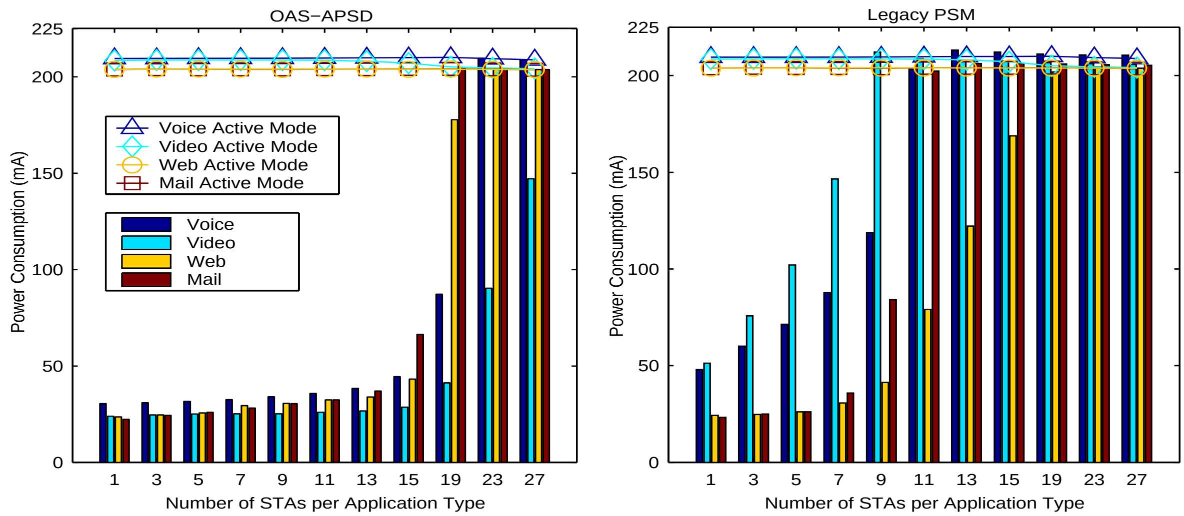

Fig. 8. Impact of the number of stations on the power consumption for *OAS-APSD* and *Legacy PSM*

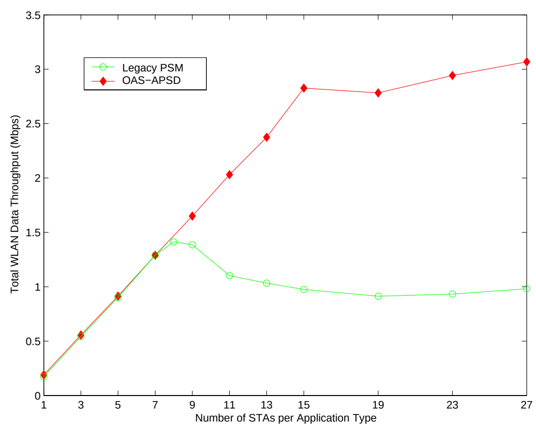

Fig. 9. Impact of the number of stations on the total channel capacity

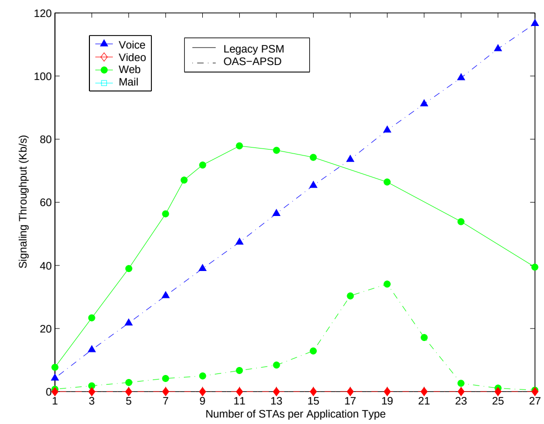

Fig. 10. Impact of the number of stations on the signaling load

depends mainly of two factors. First, it depends on the amount of traffic sent and received. Second, it depends on the priority that this traffic has when accessing the channel. In the *OAS-APSD* downlink case, the strict priority of the HCCA traffic as compared to the EDCA traffic manages to keep the power consumption of the VoIP and Video stations below the Web and E-mail one even though the VoIP and Video applications generate much more traffic. On the other hand, in the *Legacy PSM* case, even though the EDCA settings for the VoIP and Video stations provide them with priority to access the channel, it is not enough to compensate the larger amount of traffic to be sent.

Finally, the results obtained indicate that, while the power consumption of the power saving methods is highly dependent on the QoS settings and congestion in the network, it is fairly independent of these factors in the active mode case. The reason for this difference is that, in the power saving methods case, the power consumption in the sleep state is one order of magnitude below the one of any of the other states while, in the active mode case, the power consumption in all possible states is of the same order of magnitude (no sleep state).

These results clearly demonstrate that it is worth to use a power saving method during an active session instead of directly switching to active mode but the power saving that can be achieved strongly depends on the priority to access the channel and the congestion of the network.

Power Saving Cost

In this section we evaluate which are the costs of the enhanced power saving scheme under study in terms of Wireless LAN channel usage efficiency and signaling load. In the previous sections we have clearly seen that the congestion in the channel is reached significantly later with *OAS-APSD* than with *Legacy PSM*. Therefore, as expected, the maximum usage of the channel achieved with *OAS-APSD* is much larger (about 100% increase) than the one obtained with *Legacy PSM* as shown in Figure 9. The main reason for such a significant difference is the lower number of collisions that occur in the channel in congestion conditions thanks to the HCCA mechanism usage. In this case, the applications generating most of the traffic, Voice and Video, do not need to compete to access the channel in the downlink. Thus, less channel capacity is wasted for contention that can be used for data transmission.

The corresponding signaling load results are depicted in Figure 10. At first glance, one of the main differences between the signaling load introduced by the two power saving mechanisms is that, while *Legacy PSM* generates signaling load of a single QoS type (Web), *OAS-APSD* generates signaling load of two QoS types (Voice and Web). This is because while the signaling load of *Legacy PSM* is only due to PS-Polls, IEEE 802.11e recommends to use AC_BE for PS-Polls, the signaling load of *OAS-APSD* is QoS-Nulls in the downlink for Voice and Video stations and PS-Polls in the uplink for Web and E-mail stations. The reason why the *OAS-APSD* mechanism generates signaling only for Voice and not for Video is that, in the Voice case, the silence periods might result in a service period for a Voice station where the AP has no data to deliver and thus, a QoS Null is generated to end the service period. This never happens in the Video case since the AP always has data to transmit during a service period. Note that the Video application generates a data frame always every 40ms and the service interval is 60 ms.

Regarding the decrease in signaling load introduced by *Legacy PSM* from 13 stations on, it is a consequence of the large uplink delay (see Figure 6) suffered by frames using the EDCA AC_BE settings due to congestion in the channel. This congestion does not happen in the *OAS-APSD* case for Voice signaling since, as shown in Figures 4 and 6, congestion appears in the uplink but not in the downlink. Finally, an unexpected behavior can be observed in the *OAS-APSD* case in the PS-Poll signaling load introduced by Web and E-mail stations where the slope increases before reaching congestion. The reason for that is the triggering of the TCP retransmission process due to the large delay introduced by the Wireless LAN network. This results in a larger number of frames buffered at the AP and thus, more PS-Polls are required.

V. SUMMARY & CONCLUSIONS

Mobile devices including Wireless LAN capabilities are expected to meet two main requirements in order to fulfill users' expectations: QoS support for differentiating real-time services from non real-time and power saving functionality to achieve a reasonable operating time. We have identified the IEEE 802.11e power saving mechanism Scheduled Automatic Power Save Delivery (S-APSD) as the most promising solution to efficiently address both requirements. Therefore, we focused our work in this paper on the evaluation of the potential improvements obtained with S-APSD as compared to simply using the currently most wide spread wireless LAN power saving mechanism, legacy 802.11 power save mode.

Our contributions are as follows. First, we provided a description of the S-APSD functionality. Second, we designed an Overlapping Aware S-APSD algorithm (OAS-APSD) that uses information available at the AP regarding the already scheduled transmissions in order to minimize the overlapping of service periods. Third, we provided quantitative results of the performance differences to be expected when OAS-APSD in combination with HCCA is used as compared to 802.11 power save mode in combination with EDCA with respect to: QoS perceived by the users, power saving efficiency, channel usage efficiency and signaling load. Finally, we provided the reasoning behind the performance differences pointing out the elements to be taken into account when deciding which power saving mechanism is more appropriate for a certain use case. The study required to implement HCCA, legacy 802.11 power save mode and our proposed OAS-APSD algorithm in OPNET.

The main conclusions that can be drawn from our results are i) OAS-APSD in combination with HCCA clearly outperforms 802.11 power save mode combined with EDCA in QoS differentiation, power saving efficiency and power saving cost, e.g., the delay degradation of voice users starts at 15 stations per application type instead of at 7, ii) the distribution by the OAS-APSD mechanism of the service periods results in a less congested channel and thus higher power saving as compared to 802.11 power save mode, e.g., in the voice case the power saving improvement ranges between the 36% to 82% and iii) OAS-APSD in combination with HCCA improves not only the overall performance of the real-time traffic but also of the non real-time one yielding an overall better channel usage efficiency, i.e., more users/applications can be accepted in the system.

As future work we consider the reduction of the computational load of our proposed algorithm, analysis of pros and cons of dynamic changes of the schedule of S-APSD stations and a performance comparison with the U-APSD mechanism.

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