Maximum Achievable Energy Efficiency of TXOP Power Save Mode in IEEE 802.11ac WLANs

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Abstract*—This paper provides an analysis of energy efficiency of the Transmission Opportunity Power Save Mode (TXOP PSM) in IEEE 802.11ac Wireless Local Area Networks (WLANs). This mechanism allows a device to sleep during transmissions in the channel that are addressed to other devices. This operation is also referred to as microsleep and can significantly reduce the energy consumption of devices during overhearing periods. A key contribution of the analysis presented in this paper is the awareness of the non-negligible time and energy consumption that a device incurs when it switches between awake and sleep states. If the duration of such state transitions is longer than the transmission time, microsleep operation is not possible. This becomes a critical issue as transmission rates increase, thus reducing the transmission times. In this paper, we show that the performance dependence of TXOP PSM on the awake/sleep state transitions can be overcome by using burst transmission inherent to the TXOP operation. Results obtained through theoretical analysis and computer-based simulation show gains above 400% in energy efficiency when compared to legacy mechanisms. *

I. Introduction

A new power saving mechanism called TXOP PSM was introduced in the IEEE 802.11ac amendment of the IEEE 802.11 Standard to improve the energy efficiency of IEEE 802.11 WLANs [1]. This mechanism was included in the Medium Access Control (MAC) layer as an extension of existing power saving mechanisms defined in previous amendments of the Standard. All these mechanisms allow a wireless station (STA) to dynamically switch between two power states: awake and doze (hereafter referred to as sleep). In the awake state, the STA is fully powered and its radio transceiver is ready to transmit or receive at any time. In the sleep state, the STA turns off its radio transceiver to save energy, but it is not able to transmit or receive.

The Power Save Mode (PSM) was already proposed in the first release of the Standard and is based on the mandatory contention-based channel access method called Distributed Coordination Function (DCF). The Automatic Power Save Delivery (APSD) and Power Save Multi-Poll (PSMP) were then specified in subsequent IEEE 802.11e and IEEE 802.11n amendments of the Standard, respectively. These mechanisms are enhancements of PSM to optimize the energy consumption of an STA in the awake state. Their channel access operation is based on the Enhanced Distributed Channel Access (EDCA). This channel access method is an extension of DCF to support prioritized channel access and occupancy time for different Quality of Service (QoS) traffic categories. All these mechanisms were included in a single document that merged some amendments of the Standard [2].

When PSM, APSD, or PSMP is executed in an infrastructure WLAN, an STA can sleep for a given period of time. During this time, the Access Point (AP) buffers all data packets addressed to that specific STA. The STA wakes up at a certain time to receive buffered data packets from the AP and also whenever it has data to transmit to the AP. Either the AP or the STA accesses the channel by following the rules of DCF or EDCA. In these methods, the STA that wins the contention gains access to the channel for a reserved period of time to transmit data to one arbitrary destination. This period of time is referred to as TXOP and may allow a burst transmission in which the AP or an STA may send several data packets to the intended destination.

During a TXOP, the STAs not involved in the ongoing transmission or reception consume a significant amount of energy in overhearing. To overcome this problem, TXOP PSM allows an STA to sleep whenever it listens to a TXOP in which the AP sends data to another STA. To do so, the AP indicates the duration of the ongoing TXOP in transmitted packets. Whenever an STA receives a packet destined for another STA, it can switch to the sleep state and return to the awake state at the end of the TXOP. This operation is referred to as microsleep and lets an STA sleep during short periods of time in which the channel is busy (typically, some tens, hundreds, or thousands of microseconds).

TXOP PSM has great potential to significantly improve the energy efficiency of the STAs in dense networks and when the traffic load in the network is high. In addition, this mechanism can operate alone on top of DCF or EDCA and in combination with PSM, APSD, or PSMP, hence providing the highest energy efficiency in all possible network loads. However, while extensive research work was undertaken to evaluate and improve the performance of DCF, PSM, EDCA, APSD, and PSMP (a comprehensive survey is provided in [3]), TXOP PSM has received little attention so far.

The fundamental idea behind TXOP PSM was originally proposed in [4], before TXOP PSM was included in the

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Standard. Since then, some papers [5]–[8] have introduced similar approaches to reduce the energy consumption of an STA due to packet overhearing. In [4] and [5], the authors proposed to use a low-power idle state with a very short transition time into transmit and receive states (few tens of microseconds). In [4], an STA can enter the low-power idle state while a data packet addressed to another STA is transmitted in the channel. In addition, in [5] an STA can also switch to the low-power idle state while it executes the backoff procedure specified in DCF to gain access to the channel.

On the other hand, in [6]–[8] the authors rely on the sleep state to save energy. This power state is usually available in commercial equipment, compared to the low-power idle state used in [4] and [5]. In [6], an STA can sleep during the payload duration of a data packet after it reads the MAC header and determines that the receiver address is different from its MAC address. In [7], an STA can sleep during a packet exchange between the AP and another STA. Finally, in [8] an STA can sleep during a burst of data packets destined for another STA.

In TXOP PSM, as well as in its variants [4]–[8], the microsleep operation may be feasible only if the TXOP duration is longer than the time that an STA needs to switch between awake and sleep states. Depending on the radio hardware design, such state transitions may take some hundreds of microseconds and also generate extra power consumption that cannot be neglected [9], [10]. In addition, the duration of data transmission varies depending on the data length and Physical (PHY) data transmission rate used. As PHY rates increase, the transmission time of a data packet becomes shorter. Therefore, mechanisms that exploit microsleep opportunities on a packet basis [4]–[6] may be more constrained by the awake/sleep state transitions than those that allow microsleeping during multiple packet transmissions [7], [8].

In this paper, we provide an analytical model to compute the maximum achievable energy efficiency of TXOP PSM based on the throughput analysis of DCF presented in [11] and extended in [12]. We analyze the operation of TXOP PSM on top of DCF integrating burst transmission in a WLAN composed of an AP and a finite number of STAs. A key contribution of the analysis presented in this paper is the awareness of the non-negligible delay and energy of the awake/sleep state transitions. This information is taken from experimental measurements provided in [9] and [10]. The proposed analysis validated by means of computer-based simulations allows us to determine the critical system parameters that can have a strong influence on the performance of TXOP PSM. In addition, we compare its performance to that of DCF and PSM with and without burst transmission. As a result, the comprehensive performance evaluation of TXOP PSM provided in this paper may help researchers develop advanced power saving mechanisms based on microsleep operation.

The remainder of this paper is organized as follows. An overview of TXOP PSM is provided in Section II. Section III includes the theoretical analysis of TXOP PSM. The performance evaluation of TXOP PSM is then presented in Section IV. Finally, Section V concludes this paper.

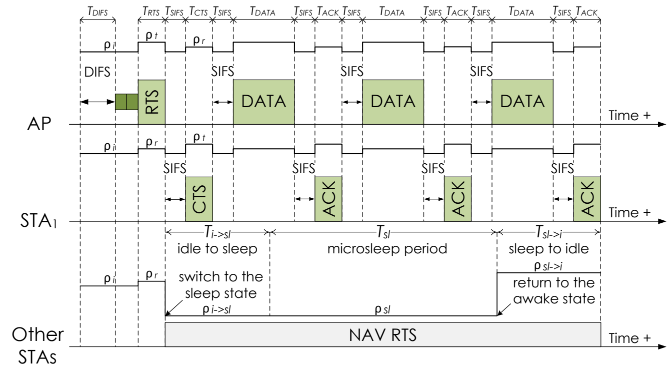

Fig. 1. Example of operation of the IEEE 802.11ac TXOP PSM mechanism. Other STAs sleep while the AP sends a burst of data packets to STA_1. The energy profiles of the AP, STA_1, and other STAs during transmission, reception (or overhearing), idle channel listening, and sleeping are shown in the figure.

II. Overview of IEEE 802.11ac TXOP PSM

The operation of TXOP PSM is exemplified in Fig. 1. In this example, the AP contends for access to the channel using the rules of DCF to transmit data to STA_1. This means that it waits until the channel is sensed idle during a DCF Interframe Space (DIFS) period, or Extended Interframe Space (EIFS) at the end of a collision. After the DIFS period, it accesses the channel following exponential backoff rules based on a Contention Window (CW) to generate random backoff times.

When the backoff period ends, the AP seizes the channel and transmits a Request-To-Send (RTS) packet to STA_1, indicating the expected transmission duration. After a Short Interframe Space (SIFS) period, STA_1 responds with a Clear-To-Send (CTS) packet addressed to the AP. After a SIFS period, the AP sends a burst of data packets with an arbitrary length (up to a maximum allowed size) to STA_1. Each successful reception of a data packet is followed by a positive Acknowledgment (ACK) response from STA_1 after a SIFS period.

Upon receiving the RTS packet addressed to STA_1, other STAs set their Network Allocation Vectors (NAVs) to the duration that the channel will remain busy. This information is retrieved from the duration field of the overheard RTS packet, and is also contained in subsequent CTS, data, and ACK packets. During the time indicated by the NAV, an STA may sleep and then awake before the NAV timer expires to attempt access to the channel after a DIFS period. In this case, the microsleep operation is possible only if the NAV duration is longer than the transition latency between awake and sleep states. If so, the awake timer of the STA is set to the time difference between the NAV value and the duration of the awake/sleep state transitions. Then, the STA sleeps until the awake timer expires. Note that we also consider the case where an STA can sleep whenever another STA sends data to the AP.

The use of burst transmission can facilitate the microsleep operation, compared to the case where a single data packet is transmitted. In order to increase the opportunities for multiple transmissions, the AP and the STAs may hold data packets for a given period of time (holding time). They may wait for a shorter time than the holding time provided that they reach the maximum allowed duration of a burst transmission before the holding time expires. In this case, they may immediately attempt access to the channel to send the burst of data packets to the intended destination.

Note that TXOP PSM may also support packet aggregation and block ACK. In addition, the multi-channel capability may allow the AP to deliver data to multiple STAs simultaneously through different channels during a TXOP. However, this is out of the scope of this paper.

III. Theoretical Analysis

The maximum achievable energy efficiency of the IEEE 802.11ac TXOP PSM mechanism is analyzed in this section. This analysis is based on the analytical model presented in [11] and its extension reported in [12] to evaluate the saturation throughput of an IEEE 802.11 DCF network.

A. System Model and Assumptions

A Basic Service Set (BSS) composed of an AP and n associated STAs in the Basic Service Area (BSA) is considered. All devices are equipped with IEEE 802.11 interfaces enabling a single antenna for communications, hence forming a Single-Input Single-Output (SISO) communications system. Wireless communication within the BSS occurs between the AP and the STAs using a shared radio channel. The size of the BSA allows all the STAs of the BSS to overhear the transmissions between each STA and the AP in both directions, thus creating a single-hop network with no hidden terminals. Note that the AP can deliver data to any STA of the BSS.

In order to compute the upper bound performance of TXOP PSM, it is assumed that the considered network operates in saturation conditions. This means that the AP and all the STAs always have data packets in their transmission queues. All data packets have constant byte length (no fragmentation needed). It is assumed that no packet error occurs due to channel variations and there exists no capture effect. In addition, no management packets, such as beacons and association requests, are considered.

B. System Parameters

The duration of the SIFS, DIFS, and EIFS periods are denoted as T_{SIFS}, T_{DIFS}, and T_{EIFS}, respectively. The minimum and maximum sizes of the CW are CW_{min} and CW_{max}, respectively. The transmission times of RTS, CTS, data, and ACK packets are expressed as T_{RTS}, T_{CTS}, T_{DATA}, and T_{ACK}, respectively. The propagation delay is referred to as δ. Let ρ_t, ρ_r, ρ_i, and ρ_{sl} be the power consumed by the radio interface of a device when transmitting, receiving or overhearing, idle channel listening, and sleeping, respectively. The radio transition time from idle (awake) to sleep are denoted as $T_{i\rightarrow sl}$ and $T_{sl\rightarrow i}$, respectively. The power consumption of each of these radio transitions is expressed as $\rho_{sl\rightarrow i}$ and $\rho_{i\rightarrow sl}$, respectively.

C. Energy Efficiency

The energy efficiency η is defined as the amount of energy consumed during the fraction of time that the channel is used to successfully transmit payload bits. Considering the saturation throughput of the network (S) expressed as (13) in [11] and (9) in [12], the network energy efficiency can be formulated as

$$\eta=\frac{\alpha P_{tr} P_s E[P]'}{(1-P_{tr})\,E_\sigma+P_{tr}P_sE_s'+P_{tr}\,(1-P_s)\,E_c'} \quad (1)$$

where

- α**:** a new variable that we add to represent the number of successful data transmissions within a given slot time.
- $P_{tr}P_s$**:** probability of successful transmission in a given slot time. These variables are defined in [11] and represent what can happen in a randomly chosen slot time, namely:
  - P_{tr}: refers to the probability that there is at least one transmission in the considered slot time, expressed as (10) in [11].
  - P_s: denotes the probability that a transmission occurring in the channel is successful. It is given by the probability that only one STA transmits in the channel, provided that at least one STA transmits, written as (11) in [11].
- $E[P]'$**:** average packet payload size considering the extension in [12] to more accurately model the backoff freezing operation, given by (10) in [12].
- $1-P_{tr}$**:** probability that a given slot time is empty.
- E_σ**:** energy consumed during an empty slot time, that is

  $$E_\sigma=\sigma\,(n+1)\,\rho_i \quad (2)$$

  where all devices consume energy for being idle for the duration of an empty slot time σ.
- $E_s^{'}$**:** energy consumed during a successful transmission based on the duration of a successful transmission considering the backoff freezing modification and the additional backoff slot σ after a DIFS period for a listening STA that will decrement its backoff counter by one unit ($T_s^{'}$), expressed as (11) in [12], thus

  $$E_s^{'}=\frac{E_s}{1-B_0}+\sigma\,(n+1)\,\rho_i \quad (3)$$

  where B_0 refers to the probability that a successfully transmitting STA may access the channel in the first slot following a DIFS period. This occurs when an STA extracts a new backoff counter value equal to zero, i.e. with probability $B_0=\frac{1}{W}$. W is defined for convenience as $W=CW_{min}+1$. The reason is that initially the backoff counter value randomly chosen by a contending STA may range from 0 to CW_{min}. This leads to a CW size of W possible values.
- $P_{tr}\,(1-P_s)$**:** probability that a collision occurs in a given slot time.

- E'_c**:** energy consumed during a collision based on the duration of a collision considering the updated model and the EIFS period (T'_c), given in [12], hence

$$E'_c = E_c + \sigma\,(n+1)\,\rho_i \tag{4}$$

where E_c is expressed as

$$E_c = E_t + E_r + E_i \begin{cases} E_t = T_{RTS} E[k] \rho_t \\ E_r = T_{RTS}\,(n+1-E[k])\,\rho_r \\ E_i = (T_{EIFS}+\delta)\,(n+1)\,\rho_i \end{cases} \tag{5}$$

where $E[k]$ is the average number of devices involved in a collision (including the AP and the n STAs). Note that in a collision $E[k]$ devices consume energy to transmit the RTS packets (E_t) whereas the rest of devices consume energy to overhear the collision of the RTS packets (E_r). All devices consume energy for being idle during an EIFS period, the propagation delay of the RTS transmission, and the additional slot time (E_i). To compute $E[k]$, the Bayesian theorem is used. The average number of devices involved in a collision is given by the summation of the probabilities that two or more (m) devices up to $n+1$ devices (considering all possible combinations) cause a collision conditioned that there is a collision in a given slot. Thus, $E[k]$ is expressed as

$$E[k] = \frac{\sum_{m=2}^{n+1} \binom{n+1}{m} \tau^m (1-\tau)^{n+1-m}}{P_{tr}\,(1-P_s)} \tag{6}$$

The energy consumption of TXOP PSM during a successful transmission (E_s) depends on the ability of those STAs that are not involved in transmission to sleep. To determine if the microsleep operation is feasible, we compute the microsleep period (T_{sl}) as the total transmission time and subtract the total switching time between awake and sleep states. As shown in Fig. 1, the transmission duration includes all what comes after the RTS transmission plus the propagation delay. This comprises the CTS transmission, β data transmissions, β ACK transmissions, $1+2{\cdot}\beta$ SIFS periods, and $1+2{\cdot}\beta$ propagation delays. Therefore, T_{sl} is computed as

$$T_{sl} = T_{CTS} + \beta\,(T_{DATA}+T_{ACK}) + (1+2{\cdot}\beta)\,(T_{SIFS}+\delta) - (T_{i\to sl}+T_{sl\to i}) \tag{7}$$

If T_{sl} is greater than zero, the STAs can sleep. In this case, the energy consumption of TXOP PSM during a successful transmission is shown in Fig. 1 and the various energy components are described as follows.

- Transmission energy consumption (E_t): The transmitter consumes energy to perform the RTS and β data transmissions to the receiver. The receiver consumes energy to perform the CTS and β ACK transmissions to the transmitter.
- Reception energy consumption (E_r): The transmitter consumes energy to receive the CTS and β ACK transmissions from the receiver. The receiver consumes energy to receive the RTS and β data transmissions from the transmitter. $n-s$ STAs only consume energy to overhear the RTS transmission as they can switch to the sleep state to save energy. s denotes the number of active STAs, which is just 1 (apart from the AP).
- Idle energy consumption (E_i): The AP and all the STAs consume energy to listen to the channel during the DIFS period and the propagation delay of the RTS transmission. After that, only the transmitter and the receiver are awake for the remaining $1+2{\cdot}\beta$ SIFS periods and $1+2{\cdot}\beta$ propagation delays of the β data and β ACK transmissions.
- Switch energy consumption (E_{sw}): The $n-s$ sleeping STAs consume energy during the transition from idle to sleep and during the transition from sleep to idle.
- Sleep energy consumption (E_{sl}): The $n-s$ STAs can sleep during the data transfer expect for when they have to switch between idle and sleep states (T_{sl}).

Based on the explanations given above, E_s for TXOP PSM when $T_{sl} > 0$ is thus formulated as

$$\begin{aligned} &E_s = E_t + E_r + E_i + E_{sw} + E_{sl} \\ &\quad E_t = (T_{RTS} + T_{CTS} + \beta\,(T_{DATA}+T_{ACK}))\,\rho_t \\ &\quad E_r = (T_{RTS} n + (T_{CTS} + \beta\,(T_{DATA}+T_{ACK}))\,s)\,\rho_r \\ &\quad E_i = ((T_{DIFS}+\delta)\,(n+1) + (1+2{\cdot}\beta)\,(T_{SIFS}+\delta)\,(s+1))\,\rho_i \\ &\quad E_{sw} = (T_{i\to sl}\rho_{i\to sl} + T_{sl\to i}\rho_{sl\to i})\,(n-s) \\ &\quad E_{sl} = T_{sl}\rho_{sl}\,(n-s) \end{aligned} \tag{8}$$

If T_{sl} is equal to or lower than zero, none of the STAs can sleep and will consume energy for overhearing the whole data transfer. In this case, the energy consumption of TXOP PSM during a successful transmission can be derived following the explanations given above to formulate (8).

Since TXOP PSM involves the transmission of β data packets, α is equal to β. Hence, the network energy efficiency of TXOP PSM in saturation conditions is given by (1) using $\alpha{=}\beta$, (10) and (11) in [11], (10) in [12], (2)–(6), and (8) when $T_{sl} > 0$ in (7).

IV. Performance Evaluation

A comprehensive performance evaluation of TXOP PSM by means of the theoretical analysis included in the previous section and computer-based simulations is presented in this section. The effects of the variable traffic load, packet length, and PHY data rate with different values of β on the performance of TXOP PSM are studied. All results are compared to the performance of DCF and PSM.

A. Simulation Scenario and Setup

The operation rules of the evaluated mechanisms were implemented in a custom-made object-oriented link-level Python simulator. The simulation scenario was implemented according to the description of the system model and assumptions presented in the previous section. In the simulator, the AP and each STA in the network constitute different entities (instances of a class) that execute the code that would be implemented in a real platform. They generate data packets of constant length following a Poisson arrival distribution, i.e. packets are generated on average at a given rate but the packet generation time is random. All the STAs generate data packets destined for the AP at an equal rate whereas the AP has as many data packets to transmit as all the STAs on average. The destination of each data packet transmitted by the AP is randomly selected among all the STAs of the network with equal probability.

All the mechanisms implemented in the simulator enable the RTS/CTS handshake, burst transmission, and a holding time. As explained in previous sections, this time is used to hold data packets ready to be transmitted in order to increase the opportunities for multiple data transmissions in each channel access opportunity. The operation rules of DCF and TXOP PSM were simulated following the specifications provided in previous sections. PSM was simulated as described next.

The AP sends a beacon packet of constant length at a period of time called beacon interval, after the channel is sensed idle during a Point Coordination Function Interframe Space (PIFS) period. All the STAs awake to receive the beacon packet. The AP informs each STA about pending data to retrieve through the Traffic Indication Map (TIM) field contained in the beacon packet or the More Data (MD) field included in delivered data packets. This occurs only if the holding time of a buffered data packet for an STA expires or the maximum allowed number of buffered data packets for an STA (i.e. β) is reached.

In order to request the delivery of buffered data packets, the STAs contend for the channel to transmit a PS-Poll packet to the AP, which responds with an ACK packet after a SIFS. Then, the AP delivers up to β buffered data packets to each STA based on the order of received PS-Poll packets, as soon as it gains access to the channel. The STAs keep sending PS-Poll packets until retrieving all buffered data packets from the AP. Likewise, when the STAs have data to transmit, they may awake at any time to transmit the data, provided that their holding time expires or the number of data packets equals the predefined value of β.

The simulation results of all the evaluated mechanisms were obtained averaging the result of 10 simulations of 15 s. Confidence intervals with a confidence level of 95% and obtained by the method of independent replication were employed. The width of the confidence intervals is 2% of the mean value at most. Therefore, they are omitted in the figures for the sake of visualization.

B. System Parameters

The IEEE 802.11 Standard defines various PHY layer techniques. Among them, the Extended Rate PHY (ERP) specification with Orthogonal Frequency Division Multiplexing (OFDM) modulation for SISO communications was selected to compute the analytical and simulation results. This PHY mode provides 8 transmission rates from 6 to 54 Mbps with Number of Data Bits Per OFDM Symbol (N_{DBPS}) from 24 to 216, respectively. Note that RTS, PS-Poll (only in PSM), and data transmissions can be performed using any of these rates. However, CTS and ACK packets must be transmitted at the basic rates 6, 12, or 24 Mbps. Also, since the beacon packets are meant for broadcast, they are transmitted at the lowest basic rate, which is 6 Mbps. All these requirements are specified by the basic rate selection rules in [2].

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Slot time (σ)	9 μs
SIFS interval (T_{SIFS})	10 μs
PIFS interval (T_{PIFS})	19 μs
DIFS interval (T_{DIFS})	28 μs
EIFS interval (T_{EIFS})	88 μs
Beacon interval	100 ms
Minimum CW size (CW_{min})	15
Maximum CW size (CW_{max})	1023
Preamble time (T_{pre})	16 μs
Signal time (T_{sig})	4 μs
OFDM symbol period (T_{sym})	4 μs
Signal extension period (T_{sigEx})	6 μs
Service bits (L_{serv})	16 b
Tail bits (L_{tail})	6 b
Length of beacon (L_B)	20 B
Length of RTS/PS-Poll (L_{RTS}=$L_{PS-Poll}$)	20 B
Length of CTS/ACK (L_{CTS}=L_{ACK})	14 B
Length of the MAC header (L_{MAChdr})	30 B
Length of FCS (L_{FCS})	4 B
Transition time from idle to sleep ($T_{i\rightarrow sl}$)	250 μs
Transition time from sleep to idle ($T_{sl\rightarrow i}$)	250 μs
Transmission power consumption (ρ_t)	1.65 W
Reception power consumption (ρ_r)	1.4 W
Idle power consumption (ρ_i)	1.15 W
Sleep power consumption (ρ_{sl})	0.045 W
Idle to sleep transition power consumption ($\rho_{i\rightarrow sl}$)	0.045 W
Sleep to idle transition power consumption ($\rho_{sl\rightarrow i}$)	1.725 W
Holding time	100 ms

The expression to compute the transmission time of each packet using the ERP-OFDM PHY mode is given in [2] by

$$T_x{=}T_{pre}{+}T_{sig}{+}T_{sym}\left\lceil\frac{L_{serv}{+}8\cdot L_x{+}L_{tail}}{N_{DBPS}}\right\rceil{+}T_{sigEx} \quad (9)$$

where x is the packet type and all the variables and their values are provided in Table I. The MAC packet length is referred to as L_x. A MAC data packet includes the frame body or MAC Service Data Unit (MSDU) together with a MAC header (L_{MAChdr}) and a Frame Check Sequence (FCS), L_{FCS}. For instance, for an MSDU of 1500 bytes and RTS/data and CTS/ACK transmission rates of 54 and 24 Mbps, respectively, T_{RTS}, T_{CTS}, T_{DATA}, and T_{ACK} are obtained by (9) as 30, 34, 254, and 34 μs, respectively. Note that the propagation delay following a packet transmission (δ) is neglected because an ideal channel was considered to evaluate the performance of the mechanisms.

Table I also includes other variables that were obtained as follows. The PIFS period was computed by [2] as $T_{PIFS}{=}T_{SIFS}{+}\sigma$ and the DIFS period as $T_{DIFS}{=}T_{SIFS}{+}2{\cdot}\sigma$. The EIFS period was calculated by [2] as $T_{EIFS}{=}T_{DIFS}{+}T_{SIFS}{+}T_{ACK}\,(6Mbps)$. A holding time of 100 ms was considered to run simulations since it produced the best performance results for all the mechanisms when multiple data transmissions were enabled. The values of power consumption in transmit, receive, idle channel listening, and sleep states were taken from [9] and [10].

Regarding the awake/sleep state transitions, the following observations were made, based on the aforementioned papers:

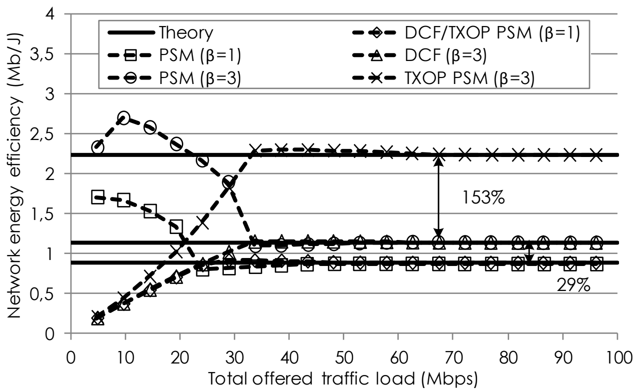

Fig. 2. Network energy efficiency of the evaluated mechanisms with β=1 and β=3 rounds of data transmissions versus the traffic load.

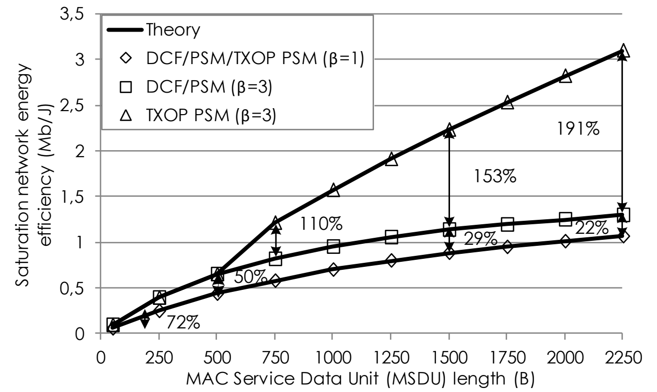

Fig. 3. Saturation network energy efficiency of the evaluated mechanisms with β=1 and β=3 rounds of data transmissions versus the MSDU length.

(i) $T_{i \to sl}$ is similar to $T_{sl \to i}$, *(ii)* $\rho_{i \to sl}$ is lower than ρ_{sl}, and *(iii)* $\rho_{sl \to i}$ is much higher than ρ_i. Therefore, as shown in Fig. 1 for the energy consumption of other STAs, the following considerations were made: *(i)* $T_{i \to sl}$ is equal to $T_{sl \to i}$ (the value was taken from [9] and [10]), *(ii)* $\rho_{i \to sl}$ is equal to ρ_{sl}, and *(iii)* $\rho_{sl \to i}$ is modeled as $\gamma \rho_i$, where γ is defined as the coefficient of power consumption during the sleep to idle state transition and $\gamma > 1$ (γ=1.5 was considered, based on [9] and [10]).

C. Results

For all the figures presented in this section, the solid lines refer to the analytical results whereas the markers are related to the simulation results. The results presented in the figures are plotted for a WLAN composed of an AP and 20 STAs, an MSDU length of 1500 bytes, and PHY control and data rates of 24 and 54 Mbps, when each parameter was fixed.

1) Effect of the Traffic Load:

In Fig. 2, we evaluate the influence of β=1 and β=3 rounds of data transmissions on the network energy efficiency of the mechanisms with increasing traffic loads. It can be seen that each mechanism shows a particular behavior in terms of energy efficiency. The energy efficiency of DCF with both β=1 and β=3 linearly increases as the traffic load increases. Then, it reaches a maximum stable value when the network enters the saturation state, where the energy efficiency is kept constant with higher traffic loads. DCF attains higher saturation energy efficiency with β=3 than with β=1, showing an improvement of up to 29%. This occurs because the AP and the STAs are able to transmit up to three data packets in each channel access attempt, thus reducing the overall channel access overhead.

The energy efficiency of PSM significantly differs from that of DCF. PSM achieves the highest energy efficiency during low traffic periods since the STAs remain in the sleep state most of the time. Its energy efficiency dramatically decreases during heavy traffic periods, up to a similar value to that of the energy efficiency of DCF. The reason is that most of the STAs are regularly awake to transmit and receive data. Note that the reduction of energy efficiency of PSM with β=3 is slower than that with β=1 because the STAs do not awake until they have at least three data packets or their holding time expires. For the same reason, the energy efficiency of PSM with β=3, which is always higher than that with β=1, slightly increases and then diminishes during low-medium traffic periods.

Within the same range of traffic loads and with β=3, it can also be seen that TXOP PSM achieves higher energy efficiency than that of DCF but lower than that of PSM. However, for high traffic loads TXOP PSM provides the highest energy efficiency with a gain of 153% compared to DCF and PSM. The reason is that the AP and the STAs usually transmit two or three data packets during channel access, thus allowing overhearing STAs to sleep and save energy. Note that TXOP PSM with β=1 provides no gain over DCF in terms of energy efficiency. The reason is that, considering the selected system parameters, the STAs cannot sleep during the transmission of a single data packet.

2) Effect of the MSDU Length:

The impact of a variable MSDU length from 50 to 2250 bytes on the saturation network energy efficiency of the evaluated mechanisms is analyzed in Fig. 3. Since the saturation energy efficiency of DCF is similar to that of PSM, their energy efficiency is shown with the same line and marker for the sake of visualization. This is also the case for TXOP PSM with β=1 because it performs the same as DCF, with the exception of its energy efficiency with β=3.

It can be seen that the saturation energy efficiency of the evaluated mechanisms increases as the MSDU length is longer since more information is contained in each transmitted data packet. However, the gain of DCF and PSM with β=3 over those with β=1 decreases from 72% to 22% as the MSDU length increases up to 2250 bytes. The reason is that longer data packets increase the data transmission time during channel access, hence reducing the influence of the channel access overhead.

Similarly, the energy efficiency of TXOP PSM with β=1 increases as that of DCF and PSM for all MSDU lengths. This occurs because the STAs cannot execute the microsleep operation during data transmission. On the contrary, its energy efficiency with β=3 increases at the same rate as that of DCF and PSM until the MSDU length is sufficiently long

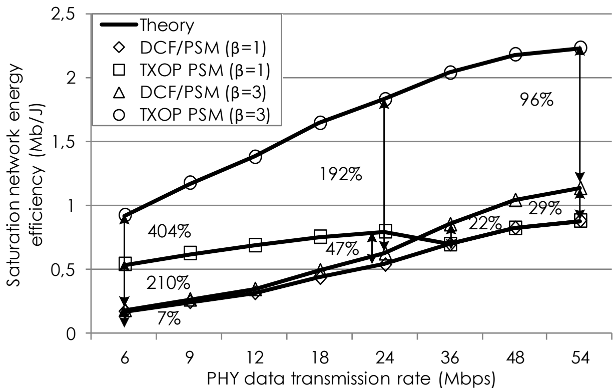

Fig. 4. Saturation network energy efficiency of the evaluated mechanisms with β=1 and β=3 rounds of data transmissions versus the PHY data transmission rate.

to facilitate the microsleep operation. This corresponds to an MSDU length that makes the microsleep period (T_{sl}) be greater than zero. In this case, the MSDU length that fulfills this requirement is above 530 bytes. For MSDU lengths above this value up to 2250 bytes, TXOP PSM significantly increases the energy efficiency of DCF and PSM with gains ranging from 110% to 191%.

3) Effect of the PHY Data Transmission Rate:

In Fig. 4, we study the influence of a variable PHY data transmission rate from 6 to 54 Mbps on the saturation energy efficiency of the evaluated mechanisms. Note that the energy efficiency of TXOP PSM is displayed with a different line and marker because its behavior significantly differs from that of DCF and PSM with both β=1 and β=3. For all the mechanisms, their energy efficiency increases as the PHY rate is higher. The reason is that the time to transmit a data packet becomes shorter, thus increasing the efficiency of data transmission. The gain of DCF and PSM with β=3 versus those with β=1 also increases with higher PHY rates from 7% to 29%.

On the contrary, the energy efficiency of TXOP PSM with β=1 is significantly higher than that of DCF and PSM for PHY rates below 36 Mbps. The highest gain is obtained for the lowest PHY rate of 6 Mbps. Then the gain decreases from 210% to 47% as the PHY rate increases up to 36 Mbps. This occurs because the transmission duration increases or decreases depending on slower or faster PHY rates, respectively. Longer transmission times increase the time that the STAs remain in the sleep state whereas shorter transmission times decrease the microsleep period. For higher PHY rates above 36 Mbps up to 54 Mbps, the energy efficiency of TXOP PSM with β=1 is the same as that of DCF and PSM. The reason is that these PHY rates do not facilitate the microsleep operation. However, TXOP PSM with β=3 provides the highest energy efficiency for all PHY rates with gains ranging from 404% to 96% when compared to DCF and PSM.

V. Conclusions

An analytical model to compute the maximum achievable energy efficiency of the IEEE 802.11ac TXOP PSM mechanism was presented in this paper. This mechanism allows a device to exploit microsleep opportunities by switching to the sleep state during packet transmissions addressed to other devices. We analyzed the operation of TXOP PSM on top of the IEEE 802.11 DCF method integrating burst transmission of up to β data packets to facilitate the execution of microsleep operation. Using the proposed model and computer-based simulations, a comprehensive performance evaluation of TXOP PSM was provided.

The results presented in this paper show that the performance of TXOP PSM strongly depends on the system parameters. The impact of the awake/sleep state transitions is particularly negative without burst transmission (β=1) and with small packets and high PHY rates. On the contrary, the use of burst transmission (β>1) reduces the performance dependence of TXOP PSM on such state transitions. Thus, the performance gain of TXOP PSM versus DCF and PSM is generally higher with burst transmission and for high traffic, large packets, and low PHY rates. For instance, with β=3 and an MSDU length of 1500 bytes, the gain decreases from 404% to 96% as the PHY rate increases from 6 to 54 Mbps.

In future work, we plan to evaluate the performance of TXOP PSM with packet aggregation and block ACK in scenarios with different traffic classes and multiple shared channels. Also, we aim at testing the mechanism in real-life environments through programmable wireless platforms.

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