Analysis of an Energy-Efficient MAC Protocol Based on Polling for IEEE 802.11 WLANs

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***Abstract*—This paper analyzes the performance of a duty-cycled polling-based access mechanism that exploits the Transmission Opportunity Power Save Mode (TXOP PSM) defined in the IEEE 802.11ac to improve the energy efficiency of Wireless Local Area Networks (WLANs) based on the IEEE 802.11. The basic idea behind the proposed approach, named GreenPoll, is to enable contention free periods, based on polling with beacons, during which wireless stations can save energy by turning off their radio transceivers after exchanging data with the access point. The closed expression of energy efficiency of GreenPoll is formulated in this paper and is used to evaluate the performance of GreenPoll considering important parameters like the traffic load, packet length, data rate, and number of stations in the network. Both analytical and simulation results show the high energy efficiency of GreenPoll with gains of up to 330% and 110% when compared to the legacy Distributed Coordination Function (DCF) and the Point Coordination Function (PCF) defined in the IEEE 802.11, respectively.*[*]**

I. INTRODUCTION

For many years, major research efforts related to the Medium Access Control (MAC) and Physical (PHY) layers of the IEEE 802.11 Standard for Wireless Local Area Networks (WLANs) [1] were focused on improving throughput, delay, fairness or achieving some degree of Quality of Service (QoS) in an otherwise best-effort technology. However, recently energy efficiency in WLANs has become a major design objective, being currently a hot research topic, due to the wide spread of portable devices equipped with WLAN interfaces, such as smartphones [2].

The IEEE 802.11 Standard specifies two modes of power management for compliant devices that operate in a WLAN, referred to as wireless stations (STAs) in the terminology of the standard. In active mode, STAs keep their radio transceivers always on (i.e., awake state), thus continuously listening to the wireless channel (being ready to either transmit or receive data) and consuming significant amounts of energy. When operating in this mode within an infrastructure WLAN, the Access Point (AP) and the STAs may execute two different methods for sharing access to the wireless channel: a distributed contention-based access method called Distributed Coordination Function (DCF) or a centralized polling-based access method called Point Coordination Function (PCF).

In Power Save (PS) mode, instead, STAs enter a low-power doze (or sleep) state wherein their radio transceivers are turned off. This yields energy savings at the cost of not being able to either transmit or receive when in this state. Typically, the STAs operating in PS mode alternate between awake and sleep states periodically to listen to selected beacons that are broadcasted periodically by the AP (every listen interval is negotiated with the AP). These beacons inform them about data buffered in the AP through a Traffic Indication Map (TIM). This TIM consists in a logical list that contains the identifiers of the STAs that must remain awake until the AP delivers all their buffered data. In the Power Save Mode (PSM) specified in the original version of the IEEE 802.11, STAs retrieve buffered data from the AP by transmitting PS-Poll frames to it using the DCF (each PS-Poll frame is used to retrieve a single data frame), or otherwise using the PCF without PS-Poll frames (i.e., waiting to be polled by the AP). In addition, STAs may wake up at any time to transmit data.

Along the various amendments of the standard, different methods backwards compatible with the PSM have been specified to optimize the amount of time that the STAs in PS mode spend in awake state for transmitting and receiving data. The Automatic Power Save Delivery (APSD) defined in the IEEE 802.11e is a mechanism for the delivery of downlink data buffered in the AP, which can be unscheduled or scheduled. In unscheduled APSD, STAs decide when to awake to transmit a trigger frame, similar to the PS-Poll but possibly combined with data, that initiates a Service Period (SP) wherein the AP delivers a burst of buffered data to them (i.e., unscheduled SP). Otherwise, in scheduled APSD STAs awake at fixed intervals determined by the AP to receive the data (i.e., scheduled SP). Furthermore, the Power Save Multi-Poll (PSMP) defined in the IEEE 802.11n extends the operation of APSD (both unscheduled and scheduled) by allowing the AP to begin an SP that includes an uplink and downlink transmission phase in order to minimize the awake time of the STAs in PS mode. Specifically, the AP transmits a PSMP frame addressed to those STAs in PS mode that are awake and containing a schedule of uplink and downlink transmissions for each of them. They only awake at their assigned transmission and reception slots.

PSM, APSD, and PSMP are all based on the same concept of periodic beacons and listen intervals. Although APSD

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improves some of the limitations of PSM and PSMP improves some of the limitations of APSD, all these PS mechanisms do not work optimally when there exist a large number of STAs with high amounts of bidirectional traffic in the network. This is due to the need to attach identifiers to the beacons, thus suffering from scalability limitations, and the dependencies on the beacon and listen intervals, which may cause performance degradation and additional energy consumption for the STAs.

On the contrary, the Transmission Opportunity Power Save Mode (TXOP PSM) defined in the IEEE 802.11ac is not based on listen intervals and beacons attaching a TIM. STAs in this PS mode opportunistically go to sleep when the AP or other STAs transmit (i.e., during a TXOP), based on the virtual carrier sense information carried in management and overheard control and data frames. TXOP PSM is able to significantly improve the energy efficiency of STAs in highly dense networks and with heavy traffic conditions, while also being able to be used in conjunction with other PS mechanisms when the number of STAs and the traffic load in the network are both low. In this case, the available time for sleeping (i.e., the total data transmission time or TXOP duration) must allow the STAs to go to sleep and wake up taking into account the duration of the on/off transitions of radio transceivers.

Unfortunately, the regular operation of the DCF may not facilitate the TXOP PSM operation. Typically, a TXOP is reserved/granted for the transmission of a single data packet. Therefore, depending on the duration of the TXOP, which depends on the data length and the data transmission rate, and the duration of on/off radio transitions, which may be in the order of hundreds of microseconds [3]–[5], it may not be possible for a third STA to go to sleep during the transaction.

In contrast, the PCF concatenates multiple bidirectional TXOPs between the AP and the STAs, thus facilitating the execution of the TXOP PSM. Motivated by this, we presented in [6] the Green Polling MAC Protocol (GreenPoll) as a new access mechanism that combines the TXOP PSM for power saving and the PCF with reservation and implicit polling. GreenPoll achieves low overhead and overcomes scalability limitations compared to beacon-based PS mechanisms. These features of GreenPoll are inherited from the Bidirectional Polling MAC Protocol (BidPoll) presented in [7].

Results presented in [6] were only based on computer-based simulations. In this paper, we extend that work by theoretically analyzing the maximum achievable energy efficiency of GreenPoll taking into account the influence of the on/off radio transitions. The analysis is validated by means of computer-based simulations, and various system parameters have been studied to analyze the performance of GreenPoll. For the purpose of comparison, the performance of GreenPoll has been compared to those of the DCF and PCF as legacy mechanisms, as well as the performance of BidPoll.

The rest of the paper is organized as follows. Section II describes related work. In Section III, we provide an overview of the protocols under consideration. The energy efficiency analysis of the protocols is then presented in Section IV. Section V includes the evaluation results. Finally, conclusions and future work are outlined in Section VI.

II. RELATED WORK

In addition to the power saving features defined in the IEEE 802.11 Standards, power saving has received much attention in recent years [2]. Particularly related to this paper are the power saving mechanisms based on polling presented in [8]–[10]. These inspiring works propose different structures for the beacons. Essentially, they refer to multi-polling packets which poll various STAs at once. These packets contain the access order, the receiver association identifier, the TXOP duration, and other relevant information for each polled STA, in a way similar to the PSMP. Based on the multi-polling packet, the STAs that are not involved in the polling process can immediately return to the sleep state while those involved in the data exchange are only awake for data transmission and reception periods. In [8], the STAs of later order may consume more energy due to overhearing, whereas in [9] this problem is effectively addressed at the cost of certain throughput degradation. The work in [10] copes with the limitations of [8] and [9] in terms of robustness and reliability.

Unfortunately, existing protocols show the following drawbacks when the number of STAs in the network increases: *(i)* scalability issues related to the multi-polling packet, i.e. the greater the number of STAs the larger the packet, and *(ii)* complexity issues in terms of TXOP scheduling. Furthermore, all the aforementioned works do not analyze the influence of the on/off radio transitions on the energy consumption of the STAs. These transitions require a certain switching time and extra power consumption that should not be neglected [3]–[5].

In its turn, GreenPoll [6] differs from the proposed schemes in [8]–[10] in the fact that STAs enable sleeping processes based only on the virtual carrier sense information attached to the transmitted beacon, control, and data packets. Therefore, GreenPoll can avoid explicit scheduling information attached to the beacons and overcome scalability limitations. To reduce the overheard of control packets, GreenPoll employs both implicit polling and acknowledgment (ACK) through uplink and downlink data packets from [7]. Also, to reduce the energy consumed by the last polled STAs, a cyclic polling order scheduling mechanism, wherein, for example, the last STA will become the first to be polled in the next round, is applied.

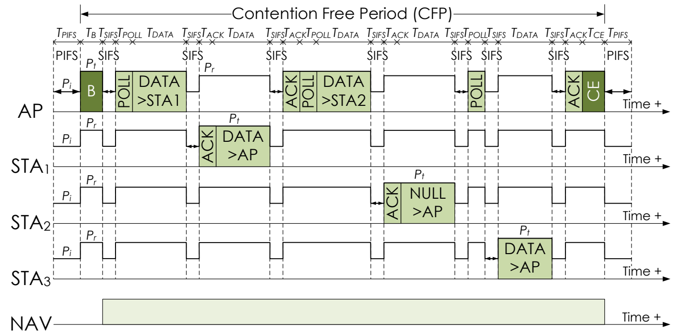
Since previous studies on GreenPoll are solely based on computer-based simulations, this paper contributes to the field with the analytical derivation and performance evaluation of GreenPoll in terms of energy efficiency, considering the delay and energy constraints of the on/off radio transitions.

III. MAC PROTOCOLS OVERVIEW

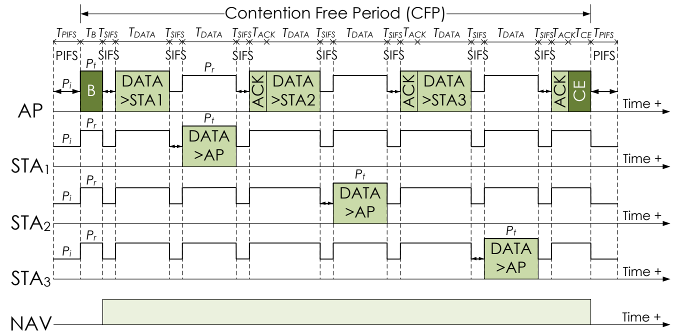
This section briefly describes the protocols under consideration in this paper. They are the DCF, PCF, BidPoll, and GreenPoll, whose operation is exemplified in Fig. 1.

A. DCF and PCF

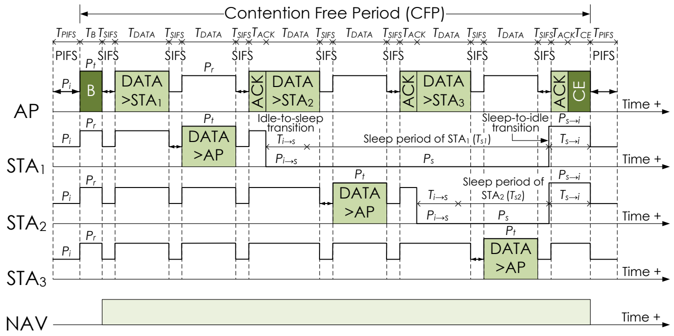
The DCF is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) in combination with a



(a) PCF: The AP begins a CFP through a beacon and sends poll and data packets to the STAs, which respond with data packets or null data packets.



(b) BidPoll: The AP can poll the STAs through data packets and the STAs can send back data packets as implicit ACK packets.



(c) GreenPoll: The AP exchanges data with the STAs, which go to sleep after being polled based on the NAV information until the end of the CFP.

Fig. 1. Examples of operation of the PCF, BidPoll, and GreenPoll protocols.

Binary Exponential Backoff (BEB) algorithm and a handshake of Request-To-Send (RTS) and Clear-To-Send (CTS) control packets. In each data transmission, the transmitting STA senses the wireless channel for a DCF Interframe Space (DIFS) and waits for a random backoff time based on a Contention Window (CW). Then, it performs an RTS/CTS exchange with the receiving STA, interleaved by a Short Interframe (SIFS), before sending its data packet. The receiving STA replies with an ACK packet after a SIFS, upon successful reception of data. Other STAs not involved in the data exchange read the duration field of overheard RTS, CTS, DATA, and ACK packets and update their Network Allocation Vectors (NAVs) with the expected occupancy time of the wireless channel. They will not attempt access to the wireless channel for the duration of the NAV.

The PCF employs a polling strategy to enable contention free data transmissions between the AP and the STAs. As shown in Fig. 1a, the AP initiates a Contention Free Period (CFP) after a PCF Interframe Space (PIFS) by transmitting a Beacon (B) that contains the duration of the CFP. All the STAs receiving the beacon update their NAVs and can only transmit when they receive a poll packet from the AP. The AP sequentially polls each STA, possibly in combination with downlink data, based on a polling list that is updated with the identifiers of the STAs registered to it during the association process. A polled STA may respond with a null data packet after a SIFS if no data packets are to be transmitted. The transmission of a CFP End (CE) packet indicates the end of a CFP, after which a new CFP may begin after a PIFS.

B. BidPoll and GreenPoll

In BidPoll, the general structure of a CFP is split into two virtual phases whose duration is determined by the AP through two NAV values attached to the beacons. The first phase is specifically reserved for uplink and downlink data transmissions with very low overhead of poll and ACK frames between the AP and the STAs that requested TXOPs in the previous CFP. The second phase is used for dynamic data exchanges between the AP and the rest of STAs that are not served in the first phase until the end of the CFP. Also, in this phase it is possible to achieve low overhead by using downlink data as implicit polls and uplink data as implicit ACKs when there are TXOPs in both directions.

GreenPoll extends the operation of BidPoll as follows. In the first phase, the STAs with no data to transmit go to sleep whereas those with data to transmit remain awake until the AP delivers downlink data to them, after which they respond with uplink data. After reception of the ACK packet in response to valid uplink data reception by the AP, these STAs go to sleep until the end of this phase according to one of the NAV values retrieved from the beacon. The STAs can return to the sleep state only if the remaining time allows them to switch between awake and sleep states before their NAV timers expire. In the second phase, all the STAs are awake and those that entered the sleep state in the first phase but were not granted transmission opportunities as well as those that remained awake during the entire phase without transmitting data are able to transmit and receive data in this phase. Depending on the traffic characteristics of the network in real-time, the AP and the STAs may execute the legacy PCF, or BidPoll for more efficient data transfer, in this phase.

To compute the duration of the first phase, the AP uses own information regarding the downlink buffer status for all the STAs and external information regarding uplink traffic provided by the STAs. Specifically, each polled STA informs the AP about more data packets ready to be transmitted and the required TXOP duration to transmit backlogged packets by using the duration and more data fields, respectively, available in the header of data packets. With this information, the AP will allocate the required time in the first phase for the STAs having both transmission and reception opportunities. When a STA receives the beacon, it returns to sleep if it has sent no request for data transmission in the previous CFP. Otherwise, the STA records the duration of the first phase and then sets a timer to monitor the time elapsed until it successfully performs a data exchange with the AP. Using these two values, a polled STA can compute the remaining polling time and determine if it can go to sleep and wake up before the end of the first phase. If so, it sets its wakeup timer and enters the sleep state.

In addition, the AP will estimate a maximum CFP duration (i.e. the other NAV value in the beacon) in case that not all the STAs have requested a transmission opportunity in the previous CFP or some of those willing to transmit do not have downlink data buffered in the AP. The time left after the end of the first phase will be allocated to those STAs in the second phase, whose nature is unpredictable and where the AP can terminate the CFP at any time (preferably after all the STAs have been served).

Note that the performances of BidPoll and GreenPoll highly depend on the intensity and symmetry of the traffic flows in the network. When the traffic load is heavy and the traffic flows are highly bidirectional, most of the STAs in the network will transmit and receive data in the first phase whereas the impact of the second phase will be marginal. In other cases, the second phase will be predominant and BidPoll and GreenPoll will mostly operate as the legacy PCF.

Figs. 1c and 1b show examples of operation of BidPoll and GreenPoll, respectively, when all the STAs of the polling list have both transmission and reception opportunities at the beginning of the CFP (i.e., illustrating a CFP that entirely operates as in the first phase).

IV. ANALYSIS

In this section, the expressions of the maximum achievable energy efficiency of the protocols considered in this paper are derived based on the system model and assumptions described as follows.

A. System Model and Assumptions

We consider a Basic Service Set (BSS) composed of an AP and N associated STAs in the Basic Service Area (BSA). All devices are equipped with IEEE 802.11n wireless interfaces enabling a single antenna for communications, i.e., 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. We assume that 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. Note that the AP can deliver downlink data to any STA of the BSS.

In order to compute the upper bound of the theoretical energy efficiency within the BSS in idealistic conditions, the following assumptions are made: *(i)* neither collisions nor channel errors occur, *(ii)* the transmit queues are never empty, *(iii)* no packets are lost because of queue overflow, and *(iv)* fragmentation is not used. In addition, we consider constant data packet length and negligible propagation delay due to the short-range transmissions.

TABLE II
SYSTEM PARAMETERS

Parameter	Value	Parameter	Value
T_{slot}	9 μs	L_{serv}	16 b
T_{SIFS}	10 μs	L_{tail}	6 b
T_{DIFS}	28 μs	L_{RTS},L_B,L_{POLL},L_{CE}	20 B
T_{PIFS}	19 μs	$L_{CTS}, L_{NULL}, L_{ACK}$	14 B
T_{EIFS}	88 μs	L_{MAChdr}	30 B
CW_{min}	15	L_{FCS}	4 B
CW_{max}	1023	$T_{i\rightarrow s}, T_{s\rightarrow i}$	250 μs
T_{BO}	67.5 μs	P_t	1.65 W
T_{pre}	16 μs	P_r	1.4 W
T_{sig}	4 μs	P_i	1.15 W
T_{sym}	4 μs	$P_s, P_{i\rightarrow s}$	0.045 W
T_{sigEx}	6 μs	$P_{s\rightarrow i}$=αP_i (α=1.5)	1.725 W

Among the possible configurations of the IEEE 802.11n at the PHY layer, we select the Extended Rate PHY-layer (ERP) Orthogonal Frequency Division Multiplexing (OFDM) specification for SISO communications. The ERP-OFDM PHY provides 8 transmission modes with different modulation schemes and coding rates. The characteristics of each mode (m) together with the data transmission rate and Number of Data Bits Per OFDM Symbol (N_{DBPS}) are reported in Table I. As specified in [1], the transmission times of management, control, and data packets using the ERP-OFDM PHY are computed as

$$T_x{=}T_{pre}{+}T_{sig}{+}T_{sym}\left\lceil\frac{L_{serv}{+}L_x 8{+}L_{tail}}{N_{DBPS}}\right\rceil{+}T_{sigEx} \quad (1)$$

where x is the packet type and may correspond to a Beacon (B), CE, POLL, NULL, RTS, CTS, ACK, or DATA. The variables T_{pre}, T_{sig}, T_{sym}, and T_{sigEx} denote the preamble time, the signal time, the OFDM symbol period, and the signal extension period, respectively. The ceiling function $\lceil . \rceil$ contains the sequences of service bits (L_{serv}) and of tail bits (L_{tail}). The MAC packet length (L_x) may correspond to the lenght of a data packet (L_{DATA}) or MAC Protocol Data Unit (MPDU) or one of the management and control packets considered. The MPDU contains a frame body or MAC Service Data Unit (MSDU) together with a MAC header (L_{MAChdr}) and a Frame Check Sequence (FCS) denoted as L_{FCS}. All the above parameters and their values are provided in Table II.

Note that control response packets like CTS, NULL, and ACK are transmitted using the mandatory rates, i.e., 6, 12, and 24 Mbps, depending on whether the transmission rate of the received packet is 6 or 9, 12 or 18, and 24, 36, 48, or 54 Mbps, respectively [1]. Also, we assume that management packets such as B and CE are transmitted at the lowest basic rate, i.e., 6 Mbps. The transmission times of all packet types for each ERP-OFDM PHY mode are also given in Table I.

B. Energy Efficiency and Energy Consumption

The energy efficiency of a given protocol x (η_x) is defined as the amount of bits contained in an MSDU divided by the energy consumption ratio (E_x) required to transmit the data packet that includes the MSDU:

$$\eta_x[\text{Mb/J}]{=}\frac{8 \cdot L_{MSDU}}{E_x} \quad (2)$$

TABLE I
ERP-OFDM PHY MODES AND TRANSMISSION TIMES FOR MANAGEMENT, CONTROL, AND DATA PACKETS (1500-BYTE PAYLOAD) IN IEEE 802.11n

m	Modulation	Code rate	PHY rate	N_{DBPS}	T_B	T_{CE}	T_{POLL}	T_{NULL}	T_{RTS}	T_{CTS}	T_{ACK}	T_{DATA}
1	BPSK	1/2	6 Mbps	24	58 μs	58 μs	58 μs	50 μs	58 μs	50 μs	50 μs	2078 μs
2	BPSK	3/4	9 Mbps	36	58 μs	58 μs	50 μs	50 μs	50 μs	50 μs	50 μs	1394 μs
3	QPSK	1/2	12 Mbps	48	58 μs	58 μs	42 μs	38 μs	42 μs	38 μs	38 μs	1054 μs
4	QPSK	3/4	18 Mbps	72	58 μs	58 μs	38 μs	38 μs	38 μs	38 μs	38 μs	710 μs
5	16-QAM	1/2	24 Mbps	96	58 μs	58 μs	34 μs	34 μs	34 μs	34 μs	34 μs	542 μs
6	16-QAM	3/4	36 Mbps	144	58 μs	58 μs	34 μs	34 μs	34 μs	34 μs	34 μs	370 μs
7	64-QAM	2/3	48 Mbps	192	58 μs	58 μs	30 μs	34 μs	30 μs	34 μs	34 μs	286 μs
8	64-QAM	3/4	54 Mbps	216	58 μs	58 μs	30 μs	34 μs	30 μs	34 μs	34 μs	254 μs

where L_{MSDU} denotes the byte-length of an MSDU and E_x is defined as the product of power consumed and time spent in transmission over the total amount of transmitted data packets.

The energy consumption ratio of each protocol under consideration is described and formulated as follows.

1) DCF: The energy consumption ratio of DCF (E_{DCF}) is split into three energy consumption components, namely, transmitting (E_t), receiving and overhearing (E_r), and idle (E_i). Let P_t, P_r, and P_i denote the variables associated with the power consumed by the radio transceiver of a STA in each of those operational states. Also, the DIFS and SIFS intervals and the slot time are denoted as T_{DIFS}, T_{SIFS} and T_{slot}, respectively, and $T_{DIFS}{=}T_{SIFS}{+}2T_{slot}$. Since we consider no collisions, T_{BO} can be assumed the average backoff time, which is calculated using the minimum CW size (CW_{min}) and T_{slot} as $T_{BO}{=}\left(\frac{CW_{min}}{2}\right)T_{slot}$. For the same reason, the maximum CW size (CW_{max}) and the EIFS interval (T_{EIFS}) do not appear in the analysis (although they will be considered in the simulation part), and $T_{EIFS}{=}T_{DIFS}{+}T_{SIFS}{+}T_{ACK}$ (6Mbps). All these variables and their values are shown in Table II.

During a transmission cycle of DCF, the transmitter, either the AP or a STA, consumes energy to transmit an RTS packet and a data packet and to receive a CTS packet and an ACK packet from the receiver. On the other hand, the receiver consumes energy to receive an RTS packet and a data packet from the transmitter and to respond with a CTS packet and an ACK packet. Meanwhile, the $N{-}1$ STAs not involved in the transmission consume energy to overhear the exchange of packets. The AP and the N STAs also consume energy for listening to the wireless channel for a DIFS interval, an average backoff period, and all the SIFS intervals. Therefore, E_{DCF} is expressed as

$$\begin{aligned} E_{DCF}&{=}E_t{+}E_r{+}E_i\\ E_t&{=}\left(T_{RTS}{+}T_{CTS}{+}T_{DATA}{+}T_{ACK}\right)P_t\\ E_r&{=}\left(T_{RTS}{+}T_{CTS}{+}T_{DATA}{+}T_{ACK}\right)NP_r\\ E_i&{=}\left(T_{DIFS}{+}T_{BO}{+}3T_{SIFS}\right)(N{+}1)\,P_i \end{aligned} \tag{3}$$

2) PCF: The energy consumption ratio of PCF (E_{PCF}) can be similarly expressed as E_{DCF}. In this case, there is no DIFS interval but a PIFS interval denoted as T_{PIFS} and calculated as $T_{PIFS}{=}T_{SIFS}{+}T_{slot}$ (see Table II for the specific value). During the polling activity, the AP and the N STAs of the polling list consume energy to transmit and receive, respectively, both the B and CE packets and a poll packet, a data packet, and an ACK packet for each polled STA. In addition, they consume energy to receive and transmit, respectively, a data packet and an ACK packet by each polled STA. When the AP communicates with a STA, or vice versa, the other $N{-}1$ STAs consume energy to overhear the exchange of packets. The AP and the N STAs also consume energy for being idle during a PIFS interval and all the SIFS intervals. As a result, $2N$ data transmissions are performed between the AP and the N STAs (in both directions). E_{PCF} is thus formulated as

$$\begin{aligned} E_{PCF}&{=}\frac{1}{2N}\left(E_t{+}E_r{+}E_i\right)\\ E_t&{=}\left(T_B{+}N\left(T_{POLL}{+}2\left(T_{DATA}{+}T_{ACK}\right)\right){+}T_{CE}\right)P_t\\ E_r&{=}\left(T_B{+}N\left(T_{POLL}{+}2\left(T_{DATA}{+}T_{ACK}\right)\right){+}T_{CE}\right)NP_r\\ E_i&{=}\left(T_{PIFS}{+}\left(2N{+}1\right)T_{SIFS}\right)(N{+}1)\,P_i \end{aligned} \tag{4}$$

3) BidPoll: The energy consumption ratio of BidPoll ($E_{BidPoll}$) contains the same as E_{PCF} but removing all poll packets and an ACK packet in each data exchange. Hence, $E_{BidPoll}$ is given as

$$\begin{aligned} E_{BidPoll}&{=}\frac{1}{2N}\left(E_t{+}E_r{+}E_i\right)\\ E_t&{=}\left(T_B{+}N\left(2T_{DATA}{+}T_{ACK}\right){+}T_{CE}\right)P_t\\ E_r&{=}\left(T_B{+}N\left(2T_{DATA}{+}T_{ACK}\right){+}T_{CE}\right)NP_r\\ E_i&{=}\left(T_{PIFS}{+}\left(2N{+}1\right)T_{SIFS}\right)(N{+}1)\,P_i \end{aligned} \tag{5}$$

4) GreenPoll: The energy consumption ratio of GreenPoll ($E_{GreenPoll}$) is based on $E_{BidPoll}$ but it introduces two new energy consumption components, namely, switching between idle and sleeping (E_{sw}), and sleeping (E_s). The time and power consumption associated with the transition from idle to sleep is referred to as $T_{i\to s}$ and $P_{i\to s}$, respectively, and as $T_{s\to i}$ and $P_{s\to i}$ regarding the transition from sleep to idle. The power consumed by a STA while sleeping is denoted as P_s and the total sleep period as T_s. Based on [3]–[5], $T_{i\to s}$ and $T_{s\to i}$ are similar and therefore we assume that $T_{i\to s}$ is equal to $T_{s\to i}$. In addition, the works in [3]–[5] showed that $P_{i\to s}$ is substantially lower than P_s and that $P_{s\to i}$ is significantly higher than P_i. Thus, we assume that $P_{i\to s}$ is equal to P_s and we model $P_{s\to i}$ as αP_i, where α is defined as the transition coefficient between sleep and idle states and $\alpha > 1$.

In GreenPoll, each STA of the polling list progressively returns to the sleep state once it successfully performs a data exchange with the AP. Due to the time required to switch between idle and sleep states, the last STA of the polling list may be unable to go to sleep and wake up before a CFP ends.

Therefore, in order to compute the closed expression of the energy consumption for GreenPoll we assume that the last polled STA does not enter the sleep state. Then, we introduce a correction factor that takes into account those STAs of the polling list that cannot go to sleep apart from the last STA. To express this, we define M as the number of active STAs during the whole polling period. M can be calculated in the following steps: *(i)* determine the total duration of a CFP to allow a data exchange (in both directions) between the AP and each STA of the polling list, *(ii)* subtract the total transition time between awake and sleep states from the total CFP time, *(iii)* divide by the time required to complete a single bidirectional data exchange between the AP and a STA (T_D), *(iv)* subtract the resulting value from the N STAs of the polling list, and *(v)* apply a ceiling function to the final value. As a result, the formula of M is expressed as

$$M = \left\lceil N - \frac{NT_D + T_{CE} - \left(T_{i\to s} + T_{s\to i}\right)}{T_D} \right\rceil \tag{6}$$

where $T_D = 2T_{DATA} + T_{ACK} + 2T_{SIFS}$.

The expression of $E_{GreenPoll}$ is thus written as

$$\begin{aligned} E_{GreenPoll} &= \frac{1}{2N}\left(E_t + E_r + E_i + E_{sw} + E_s\right) \\ E_t &= \left(T_B + N\left(2T_{DATA} + T_{ACK}\right) + T_{CE}\right)P_t \\ E_r &= \left(\frac{N+1}{2}N + \frac{M-1}{2}M\right)\left(2T_{DATA} + T_{ACK}\right)P_r \\ &\quad + \left(NT_B + MT_{CE}\right)P_r \\ E_i &= \left(N\left(N+2\right) + M\left(M-1\right) + 2N + 1\right)T_{SIFS}P_i \\ &\quad + \left(N+1\right)T_{PIFS}P_i \\ E_{sw} &= \left(T_{i\to s}P_{i\to s} + T_{s\to i}P_{s\to i}\right)\left(N-M\right) \\ E_s &= T_sP_s \end{aligned} \tag{7}$$

where T_s is expressed as

$$\begin{aligned} T_s &= \left(\frac{N}{2}\left(N-1\right) - \frac{M-1}{2}M\right)T_D \\ &\quad + \left(T_{CE} - \left(T_{i\to s} + T_{s\to i}\right)\right)\left(N-M\right) \end{aligned} \tag{8}$$

The different energy consumption components of $E_{GreenPoll}$ in (7) are described as follows.

- Transmission period: the AP and the N STAs of the polling list consume the same amounts of energy as those in BidPoll.
- Reception period: the AP consumes energy for receiving a data packet from each STA of the polling list. In contrast with the AP, each polled STA consumes energy for receiving the beacon and a data packet and an ACK packet from the AP. Depending on its polling order, a STA also consumes energy for overhearing a number of data and ACK transmissions between the AP and the other STAs before being polled. Note that the last M STAs of the polling list consume energy for overhearing all the transmissions and for receiving the CE packet from the AP.
- Idle period: the AP and all the STAs consume energy to listen to the wireless channel for a PIFS interval. Then, each STA of the polling list listens to a number of SIFS intervals until it goes to sleep whereas the AP and the last M STAs of the polling list are idle during all the SIFS intervals.
- Switch period: the $N-M$ sleeping STAs consume energy during the transition from idle to sleep and during the transition from sleep to idle.
- Sleep period: each STA of the polling list, but the last M STAs, sleeps during the data exchanges between the AP and the rest of STAs until the CFP end, except for when it needs to switch between idle and sleep states.

V. EVALUATION RESULTS

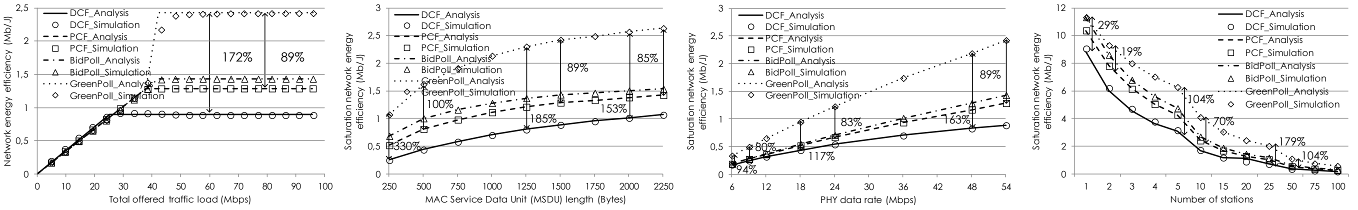
The energy efficiencies of DCF, PCF, BidPoll, and GreenPoll are evaluated in this section by means of the analysis presented in the previous section and computer-based simulations through a custom-made simulator coded in Python.

We simulate a BSS composed of an AP and 20 non-hidden static STAs, all of them operating in the ERP-OFDM-only mode. The AP and the STAs generate data packets of constant length through a Poisson arrival process and all data packets are received with no errors. The DCF is implemented with the RTS/CTS enabled and no PCF operating whereas the polling-based MAC protocols are implemented with the DCF not used. The system parameters used to plot both the analytical and simulation results and their values are provided in Table II. The power consumption values and the transition times are taken from [3]–[5]. The value of power consumed from sleeping to idle corresponds to a transition coefficient (α) of 1.5. All simulation runs were repeated 10 times for the duration of 15 seconds each and the simulation results in the plots are obtained with a 95% confidence interval lower than 0.01.

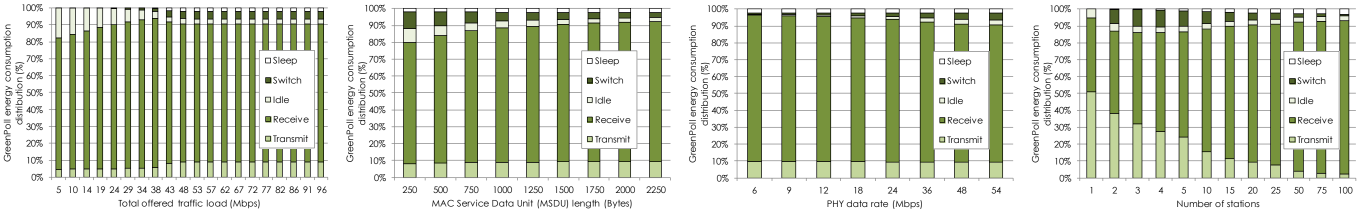
Fig. 2 shows the analytical and simulation results in terms of network energy efficiency for the evaluated protocols considering different values of the traffic load, MSDU length (1500 bytes), PHY data rate (54 Mbps), and number of STAs (20). In the figure, the contributions of the different operational states (i.e., transmit, receive, idle, switch, and sleep) to the total energy consumption of GreenPoll are also presented for the aforementioned parameters.

Fig. 2a shows that PCF, BidPoll, and GreenPoll, outperform DCF for high traffic loads because there is no contention and thus collisions of packets can be completely avoided. Also, BidPoll and GreenPoll outperform PCF due to the lower overhead of control packets. Moreover, in contrast to BidPoll, GreenPoll achieves the highest energy efficiency as the STAs can go to sleep during the polling activity. In Fig. 2e, it is seen that most of energy (up to 90%) in GreenPoll is consumed for receiving and overhearing packets and less than 10% of the total energy consumption is due to sleeping and switching between idle and sleep states.

The results in Fig. 2b show that GreenPoll achieves the highest energy efficiency for all packet lengths, although the gains decrease as the packet length increases when compared



(a) Energy efficiency vs. Load. (b) Energy efficiency vs. MSDU. (c) Energy efficiency vs. Rate. (d) Energy efficiency vs. No. STAs.



(e) GreenPoll: Energy vs. Load. (f) GreenPoll: Energy vs. MSDU. (g) GreenPoll: Energy vs. Rate. (h) GreenPoll: Energy vs. No. STAs.

Fig. 2. Network energy efficiency of the DCF, PCF BidPoll, and GreenPoll protocols and GreenPoll energy consumption distribution in the different operational states as a function of the traffic load, the MSDU length (1500 bytes), the PHY data rate (54 Mbps) and the number of STAs (20).

to both the DCF (330-146%) and PCF (108-85%). The reason for this is that the data transmission time has a higher impact on the total transmission time for longer packet lengths, thus increasing the total energy consumption for transmitting, receiving and overhearing, and sleeping. In particular, Fig. 2f captures this effect and shows that the contribution of energy consumed for receiving and overhearing to the total energy consumption becomes more significant as the packet length increases.

Fig. 2c shows that GreenPoll also performs the best for all data rates. The energy efficiency gains of GreenPoll versus DCF (94-172%) and PCF (79-89%) increase as the data rate increases. In contrast with longer packet lengths, faster data rates imply shorter data transmission times, hence reducing the energy consumed for receiving and overhearing as shown in Fig. 2g.

In Fig. 2d we observe that the gains of BidPoll and GreenPoll versus DCF (29-205%) and PCF (9-109%) increase with the number of STAs and that GreenPoll is the most energy efficient when there are two STAs or more. In Fig. 2h, we can see that the energy consumed for receiving and overhearing increases as the number of STAs increases. It is also worth mentioning that the contribution of energy consumed for switching is higher when the number of STAs is small as the STAs has to listen to fewer data transmissions before sleeping.

VI. CONCLUSIONS

The maximum achievable energy efficiency of GreenPoll has been theoretically derived in this paper. GreenPoll is a new energy-efficient MAC protocol for WLANs based on IEEE 802.11, which combines the polling strategy of the legacy PCF and the IEEE 802.11ac TXOP PSM (i.e., sleep when other STAs transmit) to achieve energy savings for the STAs. The derived equations have been used to evaluate the performance of the system tuning relevant system parameters such as the traffic load, packet length, data rate, and number of STAs in the network. Results, compared to those of the DCF, PCF, and BidPoll, show that GreenPoll is the most energy-efficient solution especially for high traffic loads, short packet lengths, fast data rates, and large numbers of STAs. For instance, the maximum energy efficiency gains of GreenPoll versus the DCF and PCF vary from 330% and 108% to 146% and 85%, respectively, as the packet length increases, and from 94% and 79% to 172% and 89%, respectively, as the data rate increases.

In order to validate the high energy efficiency of GreenPoll in a more realistic environment, ongoing work is aimed at implementing GreenPoll in programmable wireless platforms.

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