Performance Analysis of Energy-Efficient MAC Protocols using Bidirectional Transmissions and Sleep Periods in IEEE 802.11-based WLANs*

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Abstract—The Distributed Coordination Function (DCF) is the mandatory access method for any compliant device in Wireless Local Area Networks (WLANs) based on the IEEE 802.11 Standard. WLAN Access Points (APs) and stations (STAs) contend for the access to the wireless channel in order to transmit data by using a variation of Carrier Sense Multiple Access (CSMA). In doing so, they consume a significant amount of energy for continuously monitoring the channel state. In this paper we investigate backwards-compatible mechanisms to increase throughput and energy efficiency in WLANs during contention periods based on DCF. The first mechanism is called Bi-Directional DCF (BD-DCF) because it allows for bidirectional transmissions between APs and STAs with a single channel access invocation. The second mechanism is called Bi-Directional Sleep DCF (BDSL-DCF) as it allows overhearing STAs to enter access invocation. The results of this work show that the BD-DCF and BDSL-DCF protocols can improve throughput up to 60% and energy efficiency up to 360% when compared to legacy DCF.

I. INTRODUCTION

Currently, energy consumption in Wireless Local Area Networks (WLANs) based on the IEEE 802.11 Standard [1] represents a serious problem. The typical deployment of a WLAN is shown in Fig. 1. WLAN Access Points (APs) consume significant amounts of energy to provide continuous wireless Internet access for multiple users [2]. In addition, with the proliferation of portable devices equipped with WLAN interfaces, long device autonomy has become an essential requirement. However, devices with limited size, like the smart phones, may consume a significant part of their energy resources when they communicate through their WLAN interfaces [3]. The research community and the wireless industry have identified these problems and have actively worked to propose enhancements to the WLAN technology [4].

The IEEE 802.11 Standard defines the specifications for the Medium Access Control (MAC) and Physical (PHY) layers of WLANs. In this standard, a compliant device, a.k.a. station (STA), shall execute the Distributed Coordination Function (DCF) to access the wireless channel. This access method is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism and a Binary Exponential Backoff (BEB) algorithm. Thus, a STA continuously listens to the wireless channel and gets random access to it through competition. Keeping the radio transceiver always on and receiving packets destined to other STAs require considerable amounts of energy. Therefore, a STA experiences high energy consumption even if it does not transmit or receive data.

To reduce energy consumption, a STA shall enable the Power Save Mode (PSM). A PSM STA can enter a low-power state, called the sleep state, where the radio transceiver is turned off, when it does not expect to transmit and receive data. Periodically, a PSM STA returns to the awake state, i.e., turns on the radio transceiver, to retrieve all their buffered packets from the AP. A PSM STA may also wake up to transmit data at any time. When the wireless channel is congested, the performance of a PSM STA may be severely degraded, since access delays increase and buffered packets may be deleted by the AP. As a result, a PSM STA may spend a significant amount of time in channel contention and its energy consumption may actually increase.

Previous works [4] mainly focus on optimizing the performance of PSM in order to increase the energy efficiency of DCF. The subsequent amendments of the Standard also

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go into this direction by specifying enhanced mechanisms based on PSM. However, none of the proposed solutions properly address the issues of energy consumption during active periods, when a STA is involved in channel contention.

When the wireless channel is sensed busy, a STA backs off for a random period of time and consumes a significant amount of energy to monitor the channel state. The inspiring work in [5] propose that a STA shall enter the sleep state to conserve energy when another STA is transmitting data and during the backoff periods. However, the proposed mechanism requires a low-power state with a negligible transition time into the awake state with respect to the packet transmission time, and may degrade throughput and increase access delays. In addition, the authors do not specify how much power is consumed during the transitions between awake and sleep states. As shown in [6]–[8], this aspect should not be neglected.

In our previous works [9], [10], we presented and evaluated the performance of a new mechanism based on DCF, coined Bi-Directional DCF (BD-DCF). BD-DCF allows the AP and the STAs to exchange data in both directions once one of them has obtained a transmission opportunity. Results showed significant throughput gains when compared with DCF due to a reduction of communication overhead. In [11], we extended the operation of BD-DCF to exploit the longer duration of bidirectional transmissions to allow those STAs not involved in the communication to go to sleep in a way similar to [5]. We called the proposed mechanism Bi-Directional Sleep DCF (BDSL-DCF). In contrast with [5], BDSL-DCF can achieve energy saving with longer transition times by doubling the time of data transmissions, and not only improve energy efficiency but also overall network throughput. The main contributions of this paper are:

1) We theoretically derive the maximum throughput and energy efficiency of the two previously proposed protocols.
2) We analyze and discuss the performance limits of the two proposed protocols considering different data packet lengths and data rates. We also study the impact of switching between awake and sleep states on the overall energy consumption.

The structure of the paper is as follows. For completeness, the DCF, BD-DCF, and BDSL-DCF protocols are briefly summarized in Section II. Section III describes the analysis of throughput and energy efficiency for the protocols under evaluation. The performance analysis and discussion of the protocols is then provided in Section IV. Finally, Section V concludes the paper.

II. PROTOCOL DESCRIPTION

In this section, we provide a brief description of the DCF, BD-DCF, and BDSL-DCF protocols and show an example of operation of each protocol.

A. DCF

DCF [1] specifies a basic access mechanism by which the transmitting STA transmits its data packets with no previous communication with the receiving STA. An optional Request-To-Send/Clear-To-Send (RTS/CTS) mechanism is also provided by which a handshake of RTS and CTS packets is performed before the transmission of data. The aim of this mechanism is to reduce the impact of collisions of data packets and to combat the problem of hidden STAs. Fig. 2a shows an example of operation of DCF with the RTS/CTS mechanism enabled, where STA 1 and AP exchange a pair of data packets.

STA 1 and AP receive at their MAC layers a data packet destined to each other at $T_0$ and $T_1$, respectively. They sense the wireless channel for a DCF Inter Frame Space (DIFS) and then invoke the backoff procedure before attempting to transmit their data packets. Thus, they wait for a random backoff time by randomly choosing a backoff counter uniformly distributed within a Contention Window (CW). Their backoff counters are decremented by one, down to zero, each slot time that the wireless channel is sensed idle. STA 1 seize the wireless channel earlier and sends a RTS packet to AP. AP freezes its backoff counter and replies with a CTS packet after a Short Inter Frame Space (SIFS). STA 1 sends its data packet and AP responds with a positive acknowledgment (ACK) packet. After DIFS, AP resumes decrementing its backoff counter and then initiates a RTS/CTS exchange to transmit a data packet to STA 1. Other STAs perform the virtual carrier sense mechanism by which their Network Allocation Vectors (NAVs) are updated with the time that the wireless channel will remain busy. This information is carried in the duration field contained in the MAC header of RTS, CTS, data, and ACK packets.

B. BD-DCF

BD-DCF [9], [10] is aimed at improving the performance of DCF by enabling data exchanges between AP and the STAs with minimum channel contentions. The operation rules of DCF only allow the transmission of data from the transmitting STA to the receiving STA. The receiving STA is restricted to send back an ACK packet when the data packet is received without errors. Thus, BD-DCF introduces a simple modification into the operation rules of DCF to allow the receiving STA to transmit a data packet together with the ACK packet.

An example of operation of BD-DCF when the RTS/CTS mechanism is enabled is shown in Fig. 2b. When the AP receives the RTS packet from STA 1, it identifies an opportunity for bidirectional transmissions and checks in its queue if there is a data packet ready to transmit to STA 1. As such data packet exists, it replies with a CTS packet whose duration field includes the additional time required to transmit that data packet. Upon successful reception of the CTS packet, STA 1 transmits its data packet to AP after SIFS. When AP receives the data packet, it sets its backoff counter to zero and responds with a data packet after SIFS. STA 1 concludes the data exchange by sending an ACK packet to AP after SIFS.

C. BDSL-DCF

BDSL-DCF [11] represents an extension of BD-DCF to reduce the energy consumed by a STA when it listens to a data transmission where it is not involved. Specifically,
the overheard CTS packet, set their NAVs and wakeup timers, and enter the sleep state. The wakeup timers are calculated to allow the transition from the sleep state to the awake state before their NAVs expire. When the data exchange between AP and STA 1 concludes, sleeping STAs enter the awake state and may contend for the channel after DIFS. Therefore, the STAs can save energy during channel contention without increasing access delays.

III. ANALYSIS

In this section we derive the expressions of maximum theoretical throughput and energy efficiency for the protocols under consideration, i.e., DCF, BD-DCF, and BDSL-DCF. We first describe the network model and enumerate the assumptions made to carry out the analysis.

A. Network Model and Assumptions

We consider a Basic Service Set (BSS) composed of an AP and $N$ associated STAs all equipped with IEEE 802.11g wireless interfaces. Thus, full capabilities of IEEE 802.11g can be exploited. We assume that all the STAs of the BSS are able to overhear the transmissions between each STA and the AP. The AP can also deliver data packets to the STAs, and all data packets have a constant length.

Since the aim is to compute the upper bound of the throughput and energy efficiency in idealistic conditions, we assume that: 1) the probability of collision is negligible, 2) there are no packet losses due to channel errors. In addition, no packet losses exist due to buffer overflow. We do not consider the transmission of any type of management packets, such as beacon and association packets. Fragmentation is not used and the propagation delay is neglected.

While in on state, the IEEE 802.11g wireless interface of a STA can be in one of the following operational states: transmitting, receiving or overhearing (i.e., receiving packets not destined to itself), idle, and sleeping. In the first two states, the radio transceiver is actively used to send and receive information. In the idle state, the wireless interface is ready to receive but not signal is received by the radio transceiver. In the sleep state, the radio transceiver is turned off to save energy. Each of these operational states has an associated power consumption. In addition, each transition between states incurs a certain switching time that cannot be neglected. These values will vary depending on the product hardware.

Let $P_t$, $P_r$, $P_i$, and $P_s$ denote the power consumed while transmitting, receiving, idle, and sleeping, respectively. When an idle STA identifies an opportunity to sleep, a transition from idle to sleep takes place. Similarly, a transition from sleep to idle occurs when the STA decides to wake up. Based on [6]–[8], the transition time from idle to sleep ($T_{s\rightarrow i}$) is shown to be similar to the transition time from sleep to idle ($T_{i\rightarrow s}$). Hence, we assume that $T_{i\rightarrow s}$ is equal to $T_{s\rightarrow i}$. Regarding the power consumed during these transitions, the works in [6]–[8] show that the power consumed from idle to sleep ($P_{i\rightarrow s}$) is substantially lower than $P_s$. In contrast, the power consumed from sleep to idle is shown to be significantly higher than

Fig. 2c shows an example of operation of BDSL-DCF. The use of the RTS/CTS mechanism is mandatory for the proper operation of the protocol. Following the same description as in Fig. 2b as for BD-DCF, other STAs read the duration field of

the NAV period is used to allow a STA not involved in a data transmission to enter the sleep state to conserve energy while the wireless channel will be occupied. An essential requirement to accomplish this is that the transmission time is sufficiently long so that a STA can enter the sleep state and return to the awake state before its NAV expires. The transmission time of a single packet may not compensate for the overall time required to switch between sleep and awake states, even though the RTS/CTS exchange precedes the transmission of data. Therefore, bidirectional transmissions are used specifically for this purpose, since the exchange of a pair of packets will imply a longer transmission time.

The use of the RTS/CTS mechanism is mandatory for the proper operation of the protocol. Following the same description as in Fig. 2b as for BD-DCF, other STAs read the duration field of
Thus, we assume that \( P_{s \rightarrow i} \) is equal to \( P_s \) and we model \( P_{s \rightarrow i} = \alpha P_s \), where \( \alpha \) is defined as the transition coefficient between sleep and idle states and \( \alpha > 1 \).

### B. IEEE 802.11g ERP-OFDM Physical Layer

The IEEE 80211g amendment introduces an Extended Rate PHY (ERP) specification that uses the OFDM modulation and provides 8 transmission modes with different modulation schemes and coding rates. Table I summarizes the characteristics of each mode, where the supported data rates and the Number of Data Bits per OFDM Symbol \( (N_{DBPS}) \) are shown.

The structure of an ERP-OFDM packet is shown in Fig. 3. Each MAC data packet or MAC Protocol Data Unit (MDPU) consists of a MAC header, frame body or MAC Service Data Unit (MSDU), and Frame Check Sequence (FCS). The MAC header and FCS together are up to 34 octets, the RTS packet is 20 octets, and theCTS and ACK packets are 14 octets.

When a MDPU is to be transmitted, it is passed to the PHY Layer Convergence Procedure (PLCP) sublayer where it is called PLCP Service Data Unit (PSDU). In order to form a PLCP Protocol Data Unit (PPDU), a PLCP preamble and a PLCP header are added to a PSDU. The duration of the PLCP preamble field \( (T_{pre}) \) is 16 \( \mu \)s. The PLCP header expect the SERVICE field constitutes the SIGNAL field whose duration \( (T_{sym}) \) equals the duration of a single OFDM symbol \( (T_{sym}) \) with 4 \( \mu \)s.

The 16-bit SERVICE field \( (L_{serv}) \) and the MPDU along with 6 tail bits \( (L_{tail}) \) and pad bits, represented by DATA, are transmitted at the data rate specified in the RATE field. Finally, a period of no transmission with a length of 6 \( \mu \)s called the signal extension \( (T_{sigEx}) \) follows after the end of ERP-OFDM transmission. All the above parameters and their values are provided in Table II.

The BSS basic rate set determines the set of data rates that should be supported by all the STAs of a BSS. The mandatory rates are the rates that use 1/2 rate coding, i.e., 6, 12, and 24 Mbps, as shown in Table I. To allow the transmitting STA to calculate the value of the duration field, control response packets like CTS and ACK should be transmitted at the highest basic rate that is less than or equal to the rate of the received packet. This means that CTS and ACK packets are transmitted at 6, 12, or 24 Mbps if the RTS and data packets were received at 6 or 9, 12 or 18, and 24, 36, 48 or 54 Mbps, respectively.

We can thus obtain the time to transmit each packet at theIEEE 802.11g PHY layer. The transmission times of a data packet with \( L_{MSDU} \) octets of data payload, a RTS packet, and CTS and ACK packets are given in (1), (2), and (3), respectively. The ceiling function \( \lceil x \rceil \) returns the smallest integer value greater than or equal to \( x \). Table I shows the transmission time of each packet for each transmission rate. The transmission time of the data packet is given for 1500 octets of data payload.

\[
T_{DATA} = T_{pre} + T_{sig} + T_{sigEx} + T_{sym} \left[ L_{serv} + (L_{MAChdr} + L_{MSDU} + L_{FCS}) + L_{tail} \right] \quad \text{[Mbps]} \quad (1)
\]

\[
T_{RTS} = T_{pre} + T_{sig} + T_{sym} \left[ L_{serv} + L_{RTS} + L_{FCS} \right] \quad \text{[Mbps]} \quad (2)
\]

\[
T_{CTS} = T_{pre} + T_{sig} + T_{sym} \left[ L_{serv} + L_{ACK} \right] \quad \text{[Mbps]} \quad (3)
\]

#### C. Throughput Analysis

Throughput is defined as the amount of bits contained in a MSDU divided by the time in microseconds required to transmit the data packet that includes the MSDU. This is expressed by (4).

\[
\text{Throughput [Mbps]} = \frac{\text{MSDU length}}{\text{Delay per MSDU}} \quad (4)
\]

1) DCF: As shown in Fig. 2a, a transmission cycle of DCF consists of a DIFS interval, a backoff period, a RTS transmission, a SIFS interval, a CTS transmission, a SIFS interval, a data transmission, a SIFS interval and an ACK transmission. The duration of a DIFS interval \( (T_{DIFS}) \) is calculated with (5), where \( T_{SIFS} \) is the duration of a SIFS interval and \( T_{slot} \) is the duration of a slot time. Since there are no collisions of data packets, the average backoff time \( (T_{BO}) \) is given by (6). The values associated with these periods are shown in Table II. As a result, we can express the maximum throughput of DCF by (7) contained in Table III.

\[
T_{DIFS} = T_{SIFS} + 2T_{slot} \quad (5)
\]
TABLE I
ERP-OFDM PHY MODES AND TRANSMISSION TIMES IN µS FOR CONTROL AND DATA PACKETS IN IEEE 802.11g.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modulation</th>
<th>Code rate</th>
<th>Data rate</th>
<th>( N_{DBPS} )</th>
<th>( T_{RTS} )</th>
<th>( T_{CTS} )</th>
<th>( T_{ACK} )</th>
<th>( T_{DATA} ) (( L_{MSDU} ) in bytes, e.g., 1500 bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BPSK</td>
<td>1/2</td>
<td>6 Mbps</td>
<td>24</td>
<td>35</td>
<td>50</td>
<td>50</td>
<td>16+4+4 ( (16+(30+L_{MSDU}+8)+6)/24 ) + 6 = 20/75</td>
</tr>
<tr>
<td>2</td>
<td>BPSK</td>
<td>3/4</td>
<td>9 Mbps</td>
<td>45</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>16+4+4 ( (16+(30+L_{MSDU}+8)+6)/36 ) + 6 = 13/94</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>1/2</td>
<td>12 Mbps</td>
<td>60</td>
<td>38</td>
<td>48</td>
<td>48</td>
<td>16+4+4 ( (16+(30+L_{MSDU}+8)+6)/48 ) + 6 = 10/54</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>3/4</td>
<td>18 Mbps</td>
<td>72</td>
<td>38</td>
<td>72</td>
<td>72</td>
<td>16+4+4 ( (16+(30+L_{MSDU}+8)+6)/72 ) + 6 = 7/10</td>
</tr>
<tr>
<td>5</td>
<td>16-QAM</td>
<td>1/2</td>
<td>24 Mbps</td>
<td>96</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>16+4+4 ( (16+(30+L_{MSDU}+8)+6)/96 ) + 6 = 5/42</td>
</tr>
<tr>
<td>6</td>
<td>16-QAM</td>
<td>3/4</td>
<td>36 Mbps</td>
<td>144</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>16+4+4 ( (16+(30+L_{MSDU}+8)+6)/144 ) + 6 = 3/70</td>
</tr>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>2/3</td>
<td>48 Mbps</td>
<td>192</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>16+4+4 ( (16+(30+L_{MSDU}+8)+6)/192 ) + 6 = 2/86</td>
</tr>
<tr>
<td>8</td>
<td>64-QAM</td>
<td>3/4</td>
<td>54 Mbps</td>
<td>216</td>
<td>30</td>
<td>34</td>
<td>34</td>
<td>16+4+4 ( (16+(30+L_{MSDU}+8)+6)/216 ) + 6 = 2/54</td>
</tr>
</tbody>
</table>

\[ T_{BO} = \left( \frac{CW_{\text{min}}}{2} \right) T_{\text{slot}} \] (6)

2) BD-DCF: Based on Fig. 2b, a transmission cycle of BD-DCF contains the same as that of DCF but it includes an additional data transmission and a SIFS interval. To compute the maximum throughput of BD-DCF, we assume that the receiver of a data packet, either the AP or a STA, has a data packet ready to send to the transmitter. Therefore, a pair of data packets can be exchanged within a BD-DCF transmission. The maximum throughput of BD-DCF is then given by (8).

3) BDSL-DCF: The maximum throughput of BDSL-DCF is exactly the same as that of BD-DCF because BDSL-DCF has been designed to improve energy efficiency.

D. Energy Efficiency Analysis

Energy efficiency is defined as the amount of bits contained in a MSDU divided by the energy consumed in microjoules to transmit the data packet that includes the MSDU. This is represented by (12).

Energy Efficiency \( [\text{Mb}/\mu\text{j}] = \frac{\text{MSDU length}}{\text{Consumed energy per MSDU}} \) (12)

1) DCF: During the transmission cycle of DCF shown in Fig. 2a, the transmitter, either the AP or a STA, consumes energy to transmit the RTS packet and the data packet and to receive the CTS packet and the ACK packet from the receiver. On the other hand, the receiver consumes energy to receive the RTS packet and the data packet from the transmitter and to respond with the CTS packet and the ACK packet. Meanwhile, the \( N-1 \) STAs not involved in transmission consume energy to overhear the exchange of packets. The \( N \) STAs and the AP also consume energy to listen to the channel for a DIFS interval, a backoff period, and all SIFS intervals. As a result, we obtain the maximum energy efficiency of DCF by (9).

2) BD-DCF: Within the data exchange through BD-DCF depicted in Fig. 2b, the energy consumed by the AP and the STAs is similar to that of DCF. However, the receiver consumes energy to transmit a data packet and not an ACK packet and to receive an ACK packet from the transmitter. On the contrary, the transmitter consumes energy to receive the data packet and to send back the ACK packet. In addition, the \( N-1 \) STAs consume energy to overhear the data packet from the receiver. The \( N \) STAs and the AP also consume energy for being idle during an additional SIFS interval. The maximum energy efficiency of BD-DCF can thus be expressed by (10).

3) BDSL-DCF: As shown in Fig. 2c, BDSL-DCF builds on top of BD-DCF and allows overhearing STAs to switch to the sleep state during data exchanges. For easy comprehension, we split the energy consumed by the AP and the STAs into the different operational states, namely, transmitting \( (E_t) \), receiving \( (E_r) \), idle \( (E_i) \), switching between idle and sleeping \( (E_{sw}) \), and sleeping \( (E_s) \).

In the transmission period, the transmitter sends a RTS packet, a data packet and an ACK packet to the receiver whereas the receiver replies with a CTS packet and a data packet. In the reception period, the transmitter and the receiver consume energy to receive the CTS packet and the data packet and the RTS packet, the data packet, and the ACK packet, respectively. The \( N-S \) STAs only consume energy to overhear the RTS packet and the CTS packet as they can then switch to the sleep state to save energy. \( S \) denotes the number of active STAs, which is just 1. In the idle period, all the STAs and the AP consume energy to listen to the channel during a DIFS interval, a backoff period, and a SIFS interval. After that, only the transmitter and the receiver are awake for the remaining SIFS intervals. In the switching period, the \( N-S \) sleeping STAs consume energy during the transition from idle to sleep and during the transition from sleep to idle. In the sleep period \( (T_s) \), the \( N-S \) STAs can sleep during the data exchange except for when they have to switch between idle and sleep states. This happens provided that \( T_s \) is greater than zero. Otherwise, none of the overhearing STAs can sleep and the energy consumed by BDSL-DCF is the same as for BD-DCF. The maximum energy efficiency of BDSL-DCF is given by (11).

IV. NUMERICAL RESULTS

In this section, we use the expressions derived in the previous section to discuss the upper bounds of the different protocols. The results have been obtained considering different values for the MSDU length and the PHY data rate because these variables have a strong influence on the performance of the protocols. In addition, the distribution of energy consumption in each operational state is shown.

A. System Layout

We consider a BSS consisting of an AP and 20 associated STAs all operating in the ERP-OFDM-only mode. Thus, we can take advantage of the additional features provided by pure IEEE 802.11g. The system parameters and their values are provided in Table II. The optional slot time of 9 µs is used.
The SIFS interval is 10 µs, which makes the DIFS interval be 28 µs by (5). The minimum CW size is 15 and so the average backoff time is 67.5 µs according to (6), since there are no collisions. The values of the power consumed for transmitting, receiving, idle, and sleeping are taken from [6]–[8], which are 1.65, 1.4, 1.15, and 0.045 W, respectively. The transitions between idle and sleeping take 250 µs each [6]–[8]. The power consumed from idle to sleeping is 0.045 W. The value of power consumed from sleeping to idle is 1.725 W, which corresponds to a transition coefficient (α) of 1.5.

### B. Discussion

The maximum throughput versus the MSDU length is plotted in Fig. 4a. We consider a data rate of 54 Mbps. In general, the throughput of the protocols under evaluation increases as the data payload increases since more information is transmitted. We observe that the proposed BD-DCF and BDSL-DCF protocols outperform DCF for all MSDU lengths. However, the throughput gain decreases as the packet length increases. This can be explained as follows. The BD-based protocols reduce the time for channel contention, the overhead of control packets, and the silent periods for the transmission of a pair of data packets. When the packet length is short, the impact of data transmission on the overall transmission time is small when compared with that of control transmission and backoff periods. As the packet length increases, the time to transmit a data packet increases and its contribution to the overall transmission time becomes more significant.

Fig. 4d shows the maximum throughput versus the PHY data rate for a constant MSDU length of 1500 bytes. The throughput of each protocol increases as the data rate increases since the time to transmit a data packet decreases. The proposed protocols outperform DCF for all data rates and can achieve higher gains as the data rate increases. This can be understood by the explanations given above for the MSDU length.

We plot the maximum energy efficiency versus the MSDU length for the protocols under consideration in Fig. 4c. Similar conclusions can be drawn for the protocols except for BDSL-DCF. The energy efficiency of BDSL-DCF increases as that of BD-DCF until the packet length is sufficiently long to let the STAs enter the sleep state within a data exchange. This corresponds to a packet length that makes the sleep period (Ts) be greater than zero. For a data rate of 54 Mbps, the critical MSDU length is 1250 bytes for which the sleep period is zero. For MSDU lengths above this value, the energy efficiency of BDSL-DCF increases significantly showing outstanding gains in comparison with DCF and BD-DCF.

Fig. 4d presents the maximum energy efficiency versus the PHY data rate considering a 1500-byte MSDU. The energy efficiency of the DCF and BD-DCF protocols shows great similarities to what is plotted in Fig. 4b for the throughput. In contrast, BDSL-DCF significantly improves the energy efficiency of DCF and BD-DCF for all data rates. Furthermore, the highest gain is achieved for the lowest data rate. Then, it decreases as the data rate increases. The main reason for this is that the transmission time of each single packet increases as the data rate decreases. Therefore, the STAs can remain longer in the sleep state during data exchanges.

To conclude, we study the contribution of each operational state to the overall energy consumption considering different

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**TABLE III**

**Formulas of Throughput and Energy Efficiency.**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCF maximum throughput</td>
<td>( L_{MSDU}^8 \frac{1}{2}(T_{DIFS}+T_{BO}+T_{RTS}+T_{DATA}+T_{ACK}+3T_{SIFS}) )</td>
</tr>
<tr>
<td>BD-DCF maximum throughput</td>
<td>( L_{MSDU}^8 \frac{1}{2}(T_{DIFS}+T_{BO}+T_{RTS}+T_{DATA}+2T_{DATA}+T_{ACK}+4T_{SIFS}) )</td>
</tr>
<tr>
<td>DCF maximum energy efficiency</td>
<td>( L_{MSDU}^8 \frac{1}{2}(T_{RTS}+T_{DATA}+T_{ACK})(P_1+N_1) + (T_{DIFS}+T_{BO}+3T_{SIFS})(N+1)P_i )</td>
</tr>
<tr>
<td>BD-DCF maximum energy efficiency</td>
<td>( L_{MSDU}^8 \frac{1}{2}(T_{RTS}+T_{DATA}+2T_{DATA}+T_{ACK})(P_1+N_1P_r) + (T_{DIFS}+T_{BO}+4T_{SIFS})(N+1)P_i )</td>
</tr>
<tr>
<td>BDSL-DCF maximum energy efficiency</td>
<td>( L_{MSDU}^8 \frac{1}{2}(E_i + E_r + E_s + E_s + E_s) )</td>
</tr>
</tbody>
</table>

\( E_i = (T_{RTS} + T_{DATA} + T_{ACK}) P_i \)
\( E_r = [((T_{RTS} + T_{DATA}) N + (2T_{DATA} + T_{ACK}) S] P_r \)
\( E_i = ((T_{DIFS} + T_{BO} + T_{SIFS}) (N+1) + 3T_{SIFS} (S + 1) P_i \)
\( E_s = (T_{s} + T_{s} + T_{s} + T_{s}) (N_S) \) where \( T_s = 2T_{DATA} + T_{ACK} + 3T_{SIFS} - (T_{s} + T_{s} + T_{s}) \) and \( T_s > 0 \)
MSDU lengths and data rates. Figs. 4e, 4h show the distribution of energy consumption versus the MSDU length in DCF and BDSL-DCF, respectively. Likewise, Figs. 4f, 4g illustrate the distribution of energy consumption versus the data rate in DCF and BDSL-DCF, respectively. We can see that for DCF most of the energy resources (up to 90%) are dedicated to receiving and overhearing activities. The share of energy consumed during reception periods increases with longer packet lengths while it decreases with higher data rates. On the contrary, BDSL-DCF reduces significantly the energy consumed for receiving packets. However, it introduces the components of energy consumed for sleeping and switching between idle and sleeping. While the energy consumed during sleep periods has a small contribution (up to 10%), the energy consumed during switch periods has a strong influence on the overall energy consumption (up to 70%). These results show the importance of considering the transitions between awake and sleep states in the energy efficiency analysis of MAC protocols based on low-power states.

V. CONCLUSIONS

In this paper, we have analyzed the upper bounds of the throughput and energy efficiency of two energy-efficient MAC protocols, namely, BD-DCF and BDSL-DCF. Unlike DCF, BD-DCF allows the receiving STA of a data packet to respond with a data packet together with the ACK packet. Unlike BD-DCF, BDSL-DCF allows the overhearing STAs to switch to the sleep state to conserve energy during data exchanges. We have derived closed expressions for the maximum achievable throughput and energy efficiency for the proposed protocols and have shown numerical results as a function of the data payload length and data rate. A comparison with the performance of DCF has also been provided. The throughput gains vary from 60% to 20% as the packet length increases and from 6% to 30% as the data rate increases. The energy efficiency gains range from 60% to 120% with increasing packet lengths and from 360% to 80% with increasing data rates. Furthermore, the results have shown the importance of taking into account the wakeup transitions in the energy efficiency analysis of power-save MAC protocols, since those transitions represent the 70% of the total energy consumption.

Ongoing work is aimed at modeling the throughput and energy efficiency of the proposed protocols considering the backoff periods and contention, as well as non-saturated traffic conditions.

REFERENCES