

An Energy Efficient Distributed Coordination Function Using Bidirectional Transmissions and Sleep Periods for IEEE 802.11 WLANs

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Abstract—The IEEE 802.11 Distributed Coordination Function (DCF) is the fundamental access method providing asynchronous best-effort services in Wireless Local Area Networks (WLAN). In this standard, the currently employed Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and the Binary Exponential Backoff (BEB) mechanism represent major sources of energy consumption at both the access point and mobile stations of a WLAN. To improve energy efficiency in WLANs, this paper introduces an enhanced DCF protocol incorporating bidirectional transmissions in combination with sleep periods, called Bidirectional Sleep DCF (BDSL-DCF). By following this new scheme, every successfully established connection between a sender and its intended destination can be used to exchange data, hence reducing control overhead and channel contention. Furthermore, this functionality allows those mobile stations not participating in data transmission to activate the sleep mode to conserve energy. Simulation results show that BDSL-DCF can outperform DCF in terms of energy efficiency and throughput, with negligible impact on packet transmission delay.

I. INTRODUCTION

Wireless Local Area Networks (WLAN) have become an essential means of communications for global information exchange in our daily social and business activities, since they support both high data rates and user mobility. A WLAN is commonly deployed in the infrastructure mode, as shown in Fig. 1. Wireless communications occur between mobile stations and central nodes, called Access Points (AP), providing multiple users with a wide range of telecommunications services through the core network or the Internet. The wide deployment of WLANs worldwide and the increasing diversity of portable devices equipped with WLAN interfaces have mainly driven the rapidly growing interest among mobile users to make use of this kind of networks. As a result, WLANs are suffering an increasing data traffic volume leading to significant energy consumption in wireless communication.

WLAN APs widely deployed in hotspots need to be always switched on to offer a seamless wireless connection to multiple mobile stations. Hence, significant energy is required for

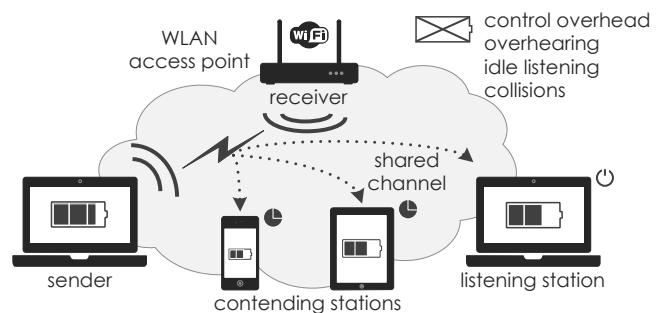


Fig. 1. An infrastructure wireless local area network.

continuous operation [1]. In addition, downloading data using the WLAN interface represents one of the most energy consuming actions in some smart phones [2]. Thus, data-intensive applications, e.g. Skype and YouTube, quickly deplete the batteries of emerging mobile terminals.

The IEEE 802.11 standard [3] defines the specifications for the Medium Access Control (MAC) and physical (PHY) layers of WLANs. It has been widely accepted as the most commonly used interface for short-range wireless communications. The Distributed Coordination Function (DCF) is defined in this standard as the fundamental access method for any compliant device. It is a contention-based mechanism that can be executed in both ad hoc and infrastructure networks and is widely implemented in commercial wireless cards. An optional Point Coordination Function (PCF) is also specified to provide Quality of Service (QoS) in infrastructure-based networks. It relies on the polling strategy and is not usually adopted.

These MAC protocols require both APs and mobile stations to continuously monitor channel activity prior to transmitting or receiving data. Overhearing packets destined to other stations requires a significant amount of energy. Therefore, many solutions addressing energy efficiency in WLANs have been proposed in the literature [4]. Most of the existing works have focused on improving energy efficiency by allowing those stations having no data to transmit to switch off their radio transceivers, based on the IEEE 802.11 Power Save Mode [3]. This energy saving strategy has also shown that in some

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scenarios: (i) the energy consumption of mobile stations may actually increase, and (ii) the user's QoS may experience significant degradation.

Less attention has been given to improving energy efficiency when stations contend for an access to the wireless channel to transmit data. During the contention process, stations need to perform backoff when a packet transmission is detected in the wireless channel. Hence, backoff periods can be used to allow contending stations to conserve energy by turning off their radio transceivers [5]. One of the main challenges in this approach is to achieve energy saving without increasing delays, which may result in throughput degradation. Stations require additional time and energy to turn on and off their radio transceivers [6]–[8]. This is an important aspect that has been usually ignored in the literature.

In this paper, we propose a simple and backwards compatible mechanism called Bi-Directional Sleep DCF (BDSL-DCF) to improve the energy efficiency of DCF, hence prolonging the lifetime of the stations of a WLAN. The key idea is to exploit bidirectional communications to increase throughput and to extend the transmission time, thus allowing other stations to switch off their radio transceivers when not involved in a data exchange. The proposed approach is an extension of our preliminary findings presented in [9].

The main contributions of this work are: (i) the specification of the BDSL-DCF protocol; and (ii) the performance evaluation of BDSL-DCF and comparison with legacy DCF. The simulation results are shown in terms of throughput, energy efficiency, and delay, under different traffic conditions.

The remainder of the paper is organised as follows. Section II provides an overview of the DCF protocol. In Section III, the related work is presented and briefly discussed. The BDSL-DCF protocol is then introduced in Section IV. Section V includes the performance evaluation of BDSL-DCF with respect to the standard. Conclusions are drawn in Section VI.

II. IEEE 802.11 DCF OVERVIEW

This section summarises the IEEE 802.11 DCF protocol [3] and briefly discusses its energy consumption at the MAC layer.

A. Protocol Description

The DCF defines a basic access method and an optional Collision Avoidance (CA) mechanism implemented through the Request-to-Send and Clear-To-Send (RTS/CTS) signalling.

The basic access is based on the Carrier Sense Multiple Access (CSMA) and a Binary Exponential Backoff (BEB) as the collision resolution algorithm. In addition, the RTS/CTS handshake can be used between source and destination before initiating the actual transmission of data to reduce the impact of collisions and to combat the presence of hidden stations.

A station with a data packet to send first listens to the wireless channel. If no activity is detected for a DCF Inter Frame Space (DIFS), the data packet, or an RTS packet in the CA access, is transmitted. Otherwise, when the station receives a data packet or a control packet, either RTS or CTS, not destined to its address, it avoids attempting access

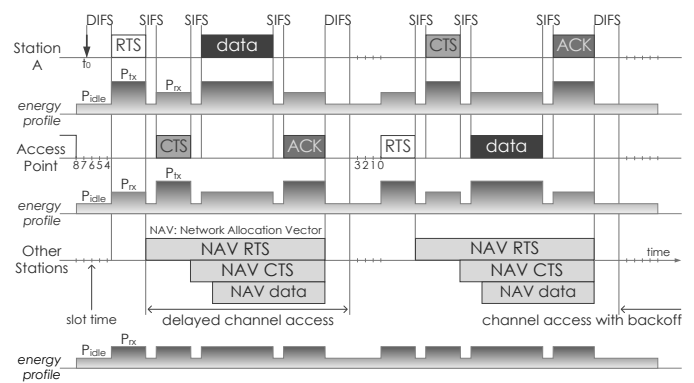


Fig. 2. Operation and energy consumption of IEEE 802.11 DCF.

to the wireless channel for the time indicated in the duration field of the MAC header of such packet. This information is used by the station to update the Network Allocation Vector (NAV), which accounts for the time that the wireless channel is expected to be occupied.

After NAV expires, the station waits until the wireless channel is sensed idle for a DIFS. In order to avoid collisions with packets being transmitted by other stations, it then executes the BEB algorithm and waits a random backoff time before sending the packet. This random period of time is represented by a backoff counter that is uniformly chosen between 0 and $w - 1$, where w is the Contention Window (CW). The w value is set to the minimum CW size (CW_{min}) and doubles up to the maximum CW size (CW_{max}) after each failed retransmission attempt. Table I shows the values of CW_{min} and CW_{max} .

The time following a DIFS is slotted and a station can only transmit at the beginning of each slot. The slot time is set equal to the time required for any station to detect the transmission of any other station (see Table I). The backoff counter is decremented by one whenever the wireless channel is sensed idle for a slot time. The station stops decrementing it whenever the wireless channel is sensed busy. It initiates the transmission only when the backoff counter reaches zero.

To avoid stations capturing the wireless channel for a significant time, a station has to wait for a random backoff time between two consecutive transmissions, even though the wireless channel is sensed idle for a DIFS.

Fig. 2 illustrates an example of the DCF operation. Station A and the AP exchange data by using the CA access, while other stations are listening to, and competing for, the same shared wireless channel. The energy profiles of all the stations during transmit, receive and idle periods are also shown.

After the end of a transmission, the AP waits for a DIFS and chooses a random backoff counter equal to 8 before sending the next data packet to Station A. While it is decrementing its backoff counter for every idle slot time, a new data packet of Station A arrives at t_0 . Station A waits for a DIFS and initiates the RTS/CTS exchange. The RTS transmission occurs in the middle of the slot time corresponding to a backoff counter of 4 for the AP. Since the wireless channel is sensed busy, the AP freezes its backoff counter to 4 and replies to Station A with a CTS packet after a Short IFS (SIFS). Station A sends the

data packet and the AP acknowledges it with an ACK frame. When NAV expires, the AP resumes decrementing its backoff counter up to 0 after a DIFS. Then it sends the data packet to Station A by following a new RTS/CTS handshake. During the CA access, other stations do not attempt to transmit but listen to the wireless channel to update their NAVs according to the duration field of RTS, CTS, and data packets. A significant amount of energy is thus consumed during channel contention.

B. Energy Consumption: Discussion

The main sources of energy consumption in DCF are [4]:

i. Control overhead and IFS. The control packets like RTS, CTS and ACK as well as silent periods such as DIFS and SIFS ensure the proper operation of MAC functions. However, in multi-user environments the overhead of both control packets and IFS represents an important source of bandwidth wastage and energy consumption for continuous MAC operations.

ii. Collisions. Since the wireless channel is shared among multiple stations competing for an access to the wireless channel, collisions may happen. They occur due to the inability of the receiver to receive multiple packets simultaneously. Thus, retransmissions increase latency and energy consumption.

iii. Idle listening and overhearing. To avoid collisions a station with data to transmit enters the backoff stage before transmitting when the wireless channel is sensed busy. The backoff time is unpredictable for each station, since it depends on the channel activity. A station performs continuous channel listening to decrement the backoff counter. Regardless of whether the channel is sensed idle or busy, the station's wireless interface is constantly on. Therefore, monitoring channel activity is another important stage in which idle listening and overhearing lead to significant energy consumption.

III. RELATED WORK

Existing energy efficient solutions for WLANs can be classified into the following three main categories:

1) *Reducing overhead of control packets and IFS.* The Distributed PCF (D-PCF) protocol was first proposed in [10], and deeply analysed later in [11], as a novel MAC protocol combining the advantages of DCF and PCF. D-PCF aims to reduce collisions by using the polling access method in a distributed manner when the traffic load is high. In D-PCF a reduction in the number of control packets is achieved by detecting periods of inactivity of polled stations. On the other hand, the last amendments of the IEEE 802.11 standard [3] define block acknowledgement and packet aggregation to reduce the overhead required for data transmission.

2) *Reducing the number of (re)transmissions.* Link adaptation can minimise packet losses and the transmission time to save energy during packet transmissions. To identify the most energy efficient configuration, [12] introduces a cross-layer methodology which optimises the transmission time and the transmission energy for any given signal-to-noise ratio. In [13] a game-theoretic approach is proposed to set the optimal transmission rate that maximises reliability with minimum energy consumption.

3) *Minimising the time for monitoring channel activity.* To save energy during channel contention, [5] suggests that contending stations should sleep during the entire backoff period, and not listen to the wireless channel. This approach requires a low-power mode with negligible transition time into the active mode, and may degrade throughput and increase delays. To reduce the backoff periods, an analytical framework is introduced in [14]. It derives the CW sizes that maximise throughput under both saturated and non-saturated conditions.

These works provide energy saving by improving different aspects of the MAC layer. However, the proposed designs do not address all the issues of energy consumption at the MAC layer in a holistic approach. In [9], we elaborate on this idea and propose an improved DCF operation incorporating bidirectional transmissions, called Bidirectional DCF (BD-DCF). This MAC protocol aims to reduce: (i) the protocol overhead, (ii) the number of collisions, and (iii) the time for channel contention. In BD-DCF, the RTS/CTS handshake can be used to exchange data between source and destination.

In this paper, the approach discussed in [9] is extended to provide energy saving by allowing listening stations to enter the sleep mode during data exchanges. Unlike other approaches described in this section, our proposal has minimum protocol overhead, increased throughput, higher energy efficiency and standard compatibility.

IV. THE BDSL-DCF PROTOCOL

In this section, the novel BDSL-DCF protocol is presented.

A. Network Model

The basic building block of the IEEE 802.11 network is the cell, also known as the Basic Service Set (BSS). A BSS consists of an AP and a number of mobile stations. All stations located within the same BSS are allowed to communicate through the AP.

From the perspective of energy consumption, a station can operate in one of the following four modes: transmit, receive, idle and sleep. In the first two modes the radio transceiver is actively used to send and receive information. In the idle mode, the wireless interface is inactive, but still powered on. In the sleep mode, most of the components of the wireless interface are turned off to save power.

When an awoken station identifies an opportunity to sleep, a transition from idle to sleep takes place. Similarly, a transition from sleep to idle occurs when the station decides to wake up. These transitions require additional time and energy consumption. The transition time between sleep and idle modes takes about 250 μ s [6]. The idle-to-sleep power consumption ($P_{i \rightarrow s}$) is substantially lower than the power consumed while sleeping (P_{sleep}) whereas the sleep-to-idle power consumption ($P_{s \rightarrow i}$) is significantly higher than the power consumed in idle (P_{idle}) [7]. Thus, a compensation in power consumption can be achieved between these transitions. If $P_{i \rightarrow s} \ll P_{sleep}$ and $P_{s \rightarrow i} \gg P_{idle}$, then $P_{i \rightarrow s} = P_{sleep}$ and $P_{s \rightarrow i} = P_{idle}$, where $P_{i \rightarrow s} \ll P_{s \rightarrow i}$. To be conservative, we assume that $P_{s \rightarrow i} = \alpha \times P_{idle}$, where α is the switchover cost and $\alpha \geq 1$.

B. Protocol Description

The proposed BDSL-DCF function extends the standard DCF with an improved version of bidirectional transmissions [9] and an energy saving strategy for contending stations.

With bidirectional transmissions, a station can transmit a data packet whenever it has received a data packet, and seizes the wireless channel to transmit an ACK packet. Therefore, it does not have to contend for an access to the wireless channel, hence reducing overall contention in the network, improving throughput and saving energy.

To indicate a bidirectional type of transmission, the CA access is required. A station having received an RTS packet from the AP sends back a CTS packet with the duration field covering the whole data exchange, including the data packets and the terminating ACK packet from the AP. This information is used by all other stations to adjust their NAVs.

Similarly, the AP can also take advantage of bidirectional transmissions to deliver data packets destined to the mobile stations. When a mobile station sends an RTS packet to the AP, the AP checks whether it has packets addressed to that station in the queue. If so, it sends a CTS packet with the value for the NAV that corresponds to the duration of the bidirectional transmission. In case of having no such packets, the AP is allowed to send a data packet destined to another station, which will immediately acknowledge it with an ACK packet after successful reception.

Since the AP usually carries a significantly larger amount of traffic than the stations, this strategy allows the AP to have a fairer channel access. Notice that this scheme requires a certain degree of bidirectional traffic to work efficiently. Therefore, the bidirectional mode will be executed only when a station which receives a data packet has a data packet ready to transmit.

By using bidirectional transmissions, the duration of data exchanges (data and control overhead) is extended in comparison with the transmission of a single packet. This longer duration of the transmission time may allow other stations to enter the sleep mode at the beginning of the bidirectional transmission and wake up before the end of the data exchange.

Fig. 3 shows an example of this energy saving strategy. Station A has a data packet to transmit at t_0 . After a DIFS, it sends an RTS to the AP, which sends back a CTS signalling bidirectional transmissions. Other stations overhearing the CTS read the duration field, set their NAVs and wakeup timers, and turn to the sleep mode. The wakeup timers are calculated accordingly to allow the stations to switch from sleep to idle modes before NAV expires. Then, Station A sends the data packet and the AP acknowledges it with another data packet. Station A replies with an ACK, which signals the end of the bidirectional transmission. At this time, all the stations are awoken and a new channel contention starts after a DIFS.

The approach also considers the case where the AP has no packets in exchange with Station A but has a data packet for another station. Let us denote this new station as Station B. In this example, the AP sends the CTS to Station B, instead of Station A. This ensures that Station B would not go to sleep after receiving the CTS addressed to Station A. Station A

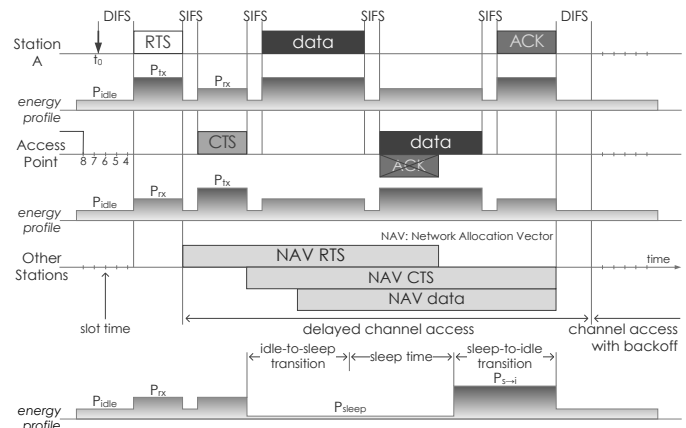


Fig. 3. Operation and energy consumption of the BDSL-DCF protocol.

overhears the CTS destined to Station B and interprets this as a transmission grant from the AP. Then, it sends the data packet and the AP acknowledges it with a data packet to Station B, which replies with an ACK to end the data exchange.

In the presence of fading channels, data packets are more vulnerable to channel errors than control packets. In a data exchange, the bidirectional data packet is used to acknowledge the new received data packet. If the bidirectional transmission fails, both data packets will be retransmitted, hence increasing delay and energy consumption. Therefore, the proposed protocol should be carefully analysed in fading channels. This aspect will be part of the future work on this topic.

V. PERFORMANCE EVALUATION

This section provides the performance evaluation of the proposed BDSL-DCF network and comparison with the BD-DCF and legacy DCF networks.

A. Simulation Model

A custom-designed simulator in Python, where the protocol rules are implemented, has been developed.

The simulation scenario consists of a single BBS with an AP and 20 associated stations. All stations are within the transmission range of each other. The AP and the stations generate data packets of constant length by following a Poisson arrival distribution. The data packets of the stations are addressed to the AP. The destination of each data packet arriving at the AP is randomly selected among all the stations of the network, with equal probability. All packets are assumed to be received without errors, hence making the obtained results to correspond to an upper-bound performance of the protocols studied. To balance the uplink and the downlink, the AP is assumed to carry the amount of traffic proportional to the number of associated stations. For example, for the traffic generation rate of a single station (λ_{STA}) of 200 Kbps and the number of associated stations (n) of 20 the AP will carry $n \times \lambda_{STA} = 4$ Mbps. This makes the total offered traffic load of the network to be 8 Mbps, 4 Mbps from the AP and 4 Mbps equally distributed among the stations.

Table I summarises the simulation parameters. The system parameters follow the IEEE 802.11g MAC/PHY specifications

TABLE I
SIMULATION PARAMETERS.

Parameter	Value	Parameter	Value
SIFS	10 μ s	Preamble	16 μ s
DIFS	28 μ s	Signal	4 μ s
EIFS	86.33 μ s	Signal Extension	6 μ s
Slot Time	9 μ s	Switchover Time	250 μ s
Tail	16 bits	Service	6 bits
RTS	20 bytes	CTS, ACK	14 bytes
MAC Header	34 bytes	MPDU	1500 bytes
Data Rate	48 Mbps	Control Rate	6 Mbps
Time of RTS	56.33 μ s	Time of CTS, ACK	48.33 μ s
Time of Data	319.33 μ s	CW_{min}, CW_{max}	16, 1024
Transmit Mode	1.65 Watts	Receive Mode	1.4 Watts
Idle Mode	1.15 Watts	Sleep Mode	0.045 Watts
Switchover Mode	1.73 Watts	Sleep Time	217 μ s
No. of Sta.	20	Simulation Time	15 s

[3]. The Extended Inter Frame Space (EIFS) is the time interval following a collision of RTS packets, which includes a DIFS, a SIFS and the transmission time of an ACK. The switchover time (T_s) is defined as the time required to transit between sleep and idle modes [6]. The IEEE 802.11g frame format includes the MAC Protocol Data Unit (MPDU). The transmission times of control packets (e.g. T_{ACK}) are obtained for the lowest basic rate (control rate). Both the control and data rates are used to calculate the transmission time of a data packet (T_{data}). The values of power consumption in transmit, receive, idle and sleep modes are taken from [8]. The switchover mode refers to the power consumed during the sleep-to-idle transition ($P_{s \rightarrow i}$). A station will consume $P_{s \rightarrow i} = \alpha \times P_{idle} = 1.73$ Watts, where $\alpha = 1.5$ and $P_{idle} = 1.15$ Watts. The sleep time refers to the actual duration of the sleep period. It is obtained from Fig. 3 as $(3 \times SIFS + 2 \times T_{data} + T_{ACK}) - 2 \times T_s$. To conclude, all simulation runs were carried out for the duration of 15 s.

B. Simulation Results

To evaluate the performance of the three different networks, we focus on the throughput, energy efficiency, average packet transmission delay and energy consumption, as a function of the total offered traffic load.

1) Throughput

The throughput is defined as the net delivered bits (obtained from the payload of data packets) over the simulation time.

Fig. 4a captures the throughput of the three networks. All the three curves grow linearly as the traffic load increases until the saturation point is reached, where the performance is stabilised. The saturation throughput of BDSL-DCF and BD-DCF is higher than that of DCF, achieving a maximum improvement of 28.04% for 48 Mbps as shown in Fig. 5a. This figure also includes the throughput gain under 36 Mbps and 54 Mbps, where the maximum gain varies from 24.10% to 30.08% depending on the selected data rate.

In the legacy DCF network, the overall throughput as measured at the stations (see Fig. 4b) decreases dramatically, when the offered traffic load exceeds the saturation limit. On the contrary, the average per-station throughput measured at the AP (see Fig. 4c) still continue to increase. DCF distributes

transmission opportunities and fairness equally among the contending stations and the AP. This leads to unfairness for the AP, as it carries traffic for all the stations.

A different behaviour is observed in the BDSL-DCF and BD-DCF networks. By taking advantage of bidirectional transmissions, the AP is granted transmission opportunities without performing channel contention. Hence, the throughput available to the stations is significantly improved, in the order of 1000%. This implies fewer chances to access the wireless channel for the stations, since the AP is significantly capturing the wireless channel to deliver data packets to the stations. Thus, the average per-station throughput is reduced by 32.03% in comparison with the DCF network.

2) Energy Efficiency

The energy efficiency is defined as the net delivered bits over the total energy consumption. The results of energy efficiency in the BDSL-DCF network are shown for $\alpha = [1, 1.5, 2]$, or $P_{s \rightarrow i} = \alpha \times P_{idle} = [1.15, 1.73, 2.30]$ Watts. While $\alpha = 1$ is considered as a balanced choice [7], $\alpha = [1.5, 2]$ are for a more conservative behaviour.

The energy efficiency of the system is provided in Fig. 4d. BDSL-DCF attains the highest performance under all evaluated levels of power consumption. For 48 Mbps and $\alpha = 1.5$ the maximum improvements of 59.82% and 102.68% over BD-DCF and DCF, respectively, are shown in Fig. 5b.

Fig. 5c records the energy efficiency gains of BDSL-DCF for different data rates and values of α , having as reference the energy efficiency of DCF. For 48 Mbps, the improvement varies from 75.24% to 142.34%, depending on the selected α .

In Fig. 4e the energy efficiency of the AP for the BDSL-DCF network is independent of α and the gain is obtained from the throughput improvement of 1000% (see Fig. 4b). On the other hand, the average energy efficiency per station in the BDSL-DCF network (see Fig. 4f) experiences variations with α , since the stations consume more or less energy during the transition from sleep to idle. The gains of 35.56% and 11.46% can only be achieved for $\alpha = [1, 1.5]$, respectively.

3) Average Packet Transmission Delay

The average packet transmission delay is defined as the average time elapsed since a data packet arrives at the MAC layer of the sender node until it is successfully acknowledged by the destination node. In the case of bidirectional transmissions, the delay of the first packet is calculated when the sender node reads the MAC header of the second packet. For the second packet, the delay is calculated as in the general case.

Fig. 4g captures the system-level average packet transmission delay. As the offered load grows, the average packet transmission delay in the DCF network experiences a high increase above 19 Mbps. In contrast, BDSL-DCF, and BD-DCF, achieves average delays below 200 ms up to 24 Mbps.

Figs. 4h and 4i depicts the average packet transmission delay measured at the AP and the stations, respectively. The conclusions drawn from Fig. 4g can also be applied to Fig. 4h. The average packet transmission delay of stations in Fig. 4i is maintained below 200 ms up to 37 Mbps for DCF. It rises above 200 ms after 24 Mbps for BDSL-DCF and BD-DCF.

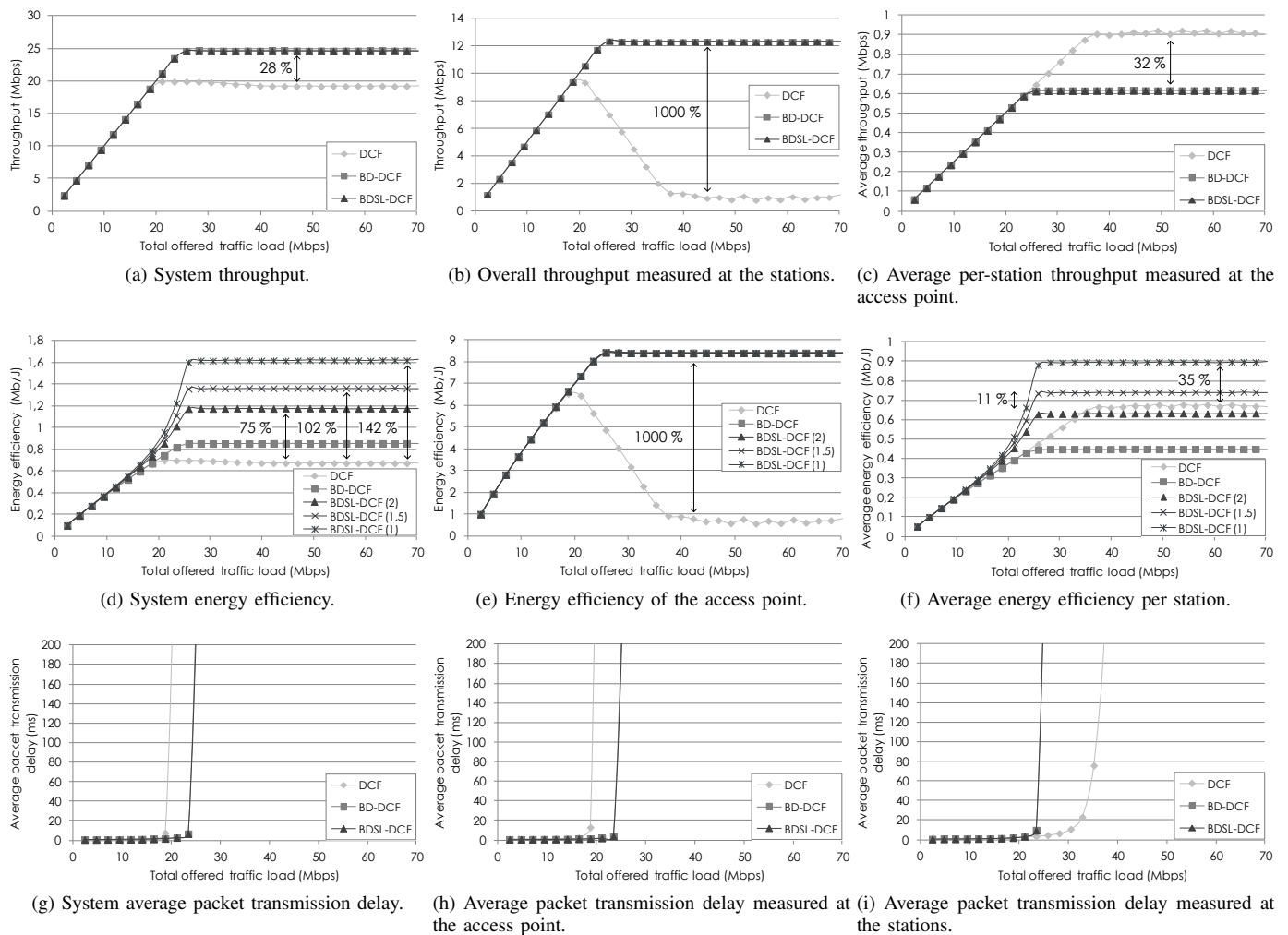


Fig. 4. Throughput, energy efficiency and average packet transmission delay of BDSL-DCF, BD-DCF and DCF protocols for 20 stations, 48 Mbps and switchover costs (α) of 2, 1.5 and 1.

4) Energy Consumption

The energy consumption is defined as the product of the power consumption during each of the operating modes, namely transmit (tx), receive (rx), idle (id), and sleep (sl), and the time spent in each of them. Fig. 6 details the time and energy contributions of these operating modes.

In the DCF network (Fig. 6a), the impact of the idle energy consumption is high for low traffic loads, since the channel activity is low and stations are idle most of time. As the traffic load increases, the weight of the energy consumed for packet reception grows rapidly due to overhearing, and becomes clearly predominant after 19 Mbps. The share of the transmission energy has a small overall contribution.

In the BDSL-DCF network, a lower fraction of the reception energy is reported as the traffic load increases (see Fig. 6b). As more opportunities for bidirectional transmissions emerge, the stations start switching to the sleep mode more often and stop listening to the wireless channel. After the sleep mode, the stations wake up and consume energy to transit from sleep to idle. As a result, the energy consumption during this transition,

whose impact is represented in the figure as part of the idle energy, is significantly increased. The weight of the sleep energy also increases, with a small overall contribution due to the low power consumption of the sleep mode.

Fig. 6c shows the amount of time that the network stays in the different operating modes. The fraction of time that the network remains in the sleep mode increases with the traffic load of the network. The maximum is 39% of the total time, although the contribution of sleeping to the overall energy consumption is small.

VI. CONCLUSIONS

BDSL-DCF has been proposed in this paper as a new MAC protocol based on the DCF of the IEEE 802.11 standard to improve the energy efficiency of WLANs. Unlike existing proposals that focus on duty-cycling when mobile stations have no data to transmit, our proposal exploits bidirectional transmissions to allow mobile stations to perform duty-cycle in the middle of data exchanges, in a packet-per-packet basis. By using bidirectional transmissions, any station receiving a data packet can transmit a data packet, without consuming time

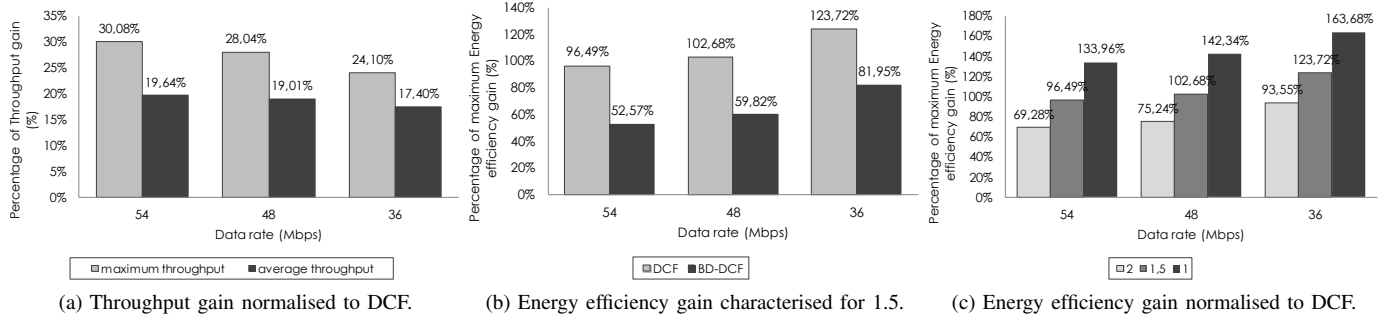


Fig. 5. Maximum throughput and energy efficiency gains of the BDSL-DCF protocol for 54, 48 and 36 Mbps and switchover costs (α) of 2, 1.5 and 1 in comparison with DCF and BD-DCF protocols.

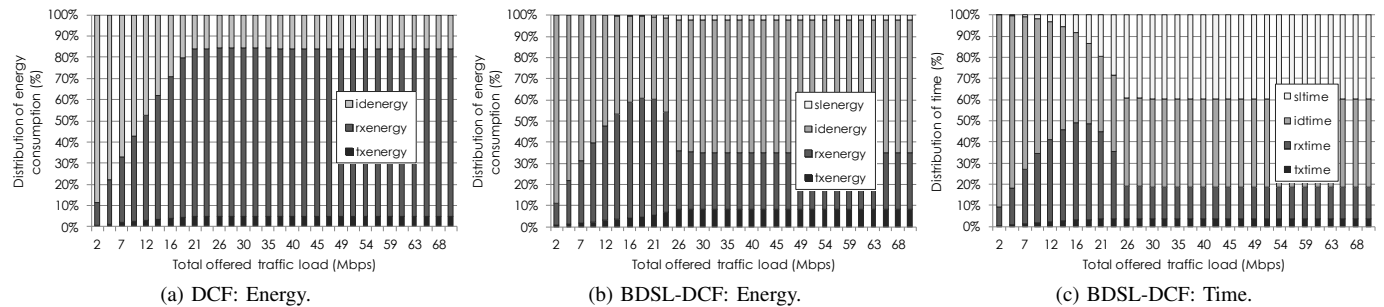


Fig. 6. Distribution of time and energy consumed during transmission (tx), reception (rx), idle (id) and sleep (sl) periods in the BDSL-DCF protocol for 20 stations, 48 Mbps and a switchover cost (α) of 1.5.

and energy for channel contention. Other stations overhearing the beginning of the bidirectional transmission can activate the sleep mode until the end of the data exchange to save energy.

By following a detailed simulation analysis, the results of this work show that BDSL-DCF can outperform DCF in terms of throughput and energy efficiency at both the access point and mobile stations of a WLAN. Depending on the different data rates and power consumption scenarios evaluated in this paper, the maximum throughput improvement that can be achieved is between 24.10% and 30.08% whereas the maximum energy efficiency gain can vary from 69.28% to 163.68%. These results show that the proposed approach could achieve higher energy efficiency in comparison with DCF as the transmission rate decreases, since the transmission time, and also the sleep time, would be increased.

The proposed scheme can be dynamically adopted in distributed and centralised environments according to the conditions of the traffic load in the network. A future work on this topic will analyse and evaluate the BDSL-DCF protocol under fading channels and different classes of traffic.

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