A Distributed Mechanism for Power Saving in IEEE 802.11 Wireless LANs *†

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Abstract

The finite battery power of mobile computers represents one of the greatest limitations to the utility of portable computers. Furthermore, portable computers often need to perform power consuming activities, such as transmitting and receiving data by means of a random-access, wireless channel. The amount of power consumed to transfer the data on the wireless channel is negatively affected by the channel congestion level, and significantly depends on the MAC protocol adopted. This paper illustrates the design and the performance evaluation of a new mechanism that, by controlling the accesses to the shared transmission channel of a wireless LAN, leads each station to an optimal Power Consumption level. Specifically, we considered the Standard IEEE 802.11 Distributed Coordination Function (DCF) access scheme for WLANs. For this protocol we analytically derived the optimal average Power Consumption levels required for a frame transmission. By exploiting these analytical results, we define a Power-Save, Distributed Contention Control (PS-DCC) mechanism that can be adopted to enhance the performance of the Standard IEEE 802.11 DCF protocol from a power saving standpoint. The performance of an IEEE 802.11 network enhanced with the PS-DCC mechanism has been investigated by simulation. Results show that the enhanced protocol closely approximates the optimal power consumption level, and provides a channel utilization close to the theoretical upper bound for the IEEE 802.11 protocol capacity. In addition, even in low load situations,

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the enhanced protocol does not introduce additional overheads with respect to the standard protocol.

1 Introduction

The finite battery power of mobile computers represents one of the greatest limitations to the utility of portable computers [10, 17]. Projections on the expected progress in battery technology show that only a 20% improvement in the battery capacity is likely to occur over the next 10 years [14]. Despite this fact, in Ad-Hoc network scenarios, portable computers often need to transmit and receive data by means of a random-access, wireless transmission channel. These activities are among some of the most power consuming operations to perform [11, 15]. If the battery capacity cannot be improved, it is vital that power utilization is managed efficiently by identifying any way to use less power preferably with no impact on the applications, nor on the resources' utilization. Several studies have been carried out in order to define mechanisms useful for Power Saving (PS) in wireless LANs [1, 11]. Strategies for power saving have been proposed and investigated at several layers including the physical-layer, the MAC layer, the transport and the application levels [1, 11, 17]. Transmitter Power Control strategies to minimize power consumption, mitigating interference and increasing the cell capacity have been proposed, and the design aspects of power-sensitive wireless network architectures have been investigated [1, 13, 18]. The impact of network technologies and interfaces on power consumption has been investigated in depth in [15]. The power saving features of the emerging standards for wireless LANs have been analyzed in [12, 17].

In this paper we investigate a power saving strategy at the MAC level. Specifically, we focus on the wireless ad-hoc network paradigm, and on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access mechanism adopted, for example, in the IEEE 802.11 WLANs [9]. The IEEE 802.11 access scheme is based on two access methods: Distributed Coordination Function (DCF) for asynchronous, contention-based, distributed accesses to the channel, and Point Coordination Function (PCF) for centralized, contention-free accesses. We will concentrate our analysis over DCF, which may be significantly affected by the congestion problem, due to distributed random access characteristics.

For these CSMA/CA protocols the amount of power consumed by transmissions is negatively affected by the congestion level of the network. Indeed, by increasing the congestion level, a considerable power is wasted due to the collisions. To reduce the collision probability, the stations perform a variable time-spreading of accesses, which results in additional power consumption, due

to Carrier Sensing [1]. Hence, these protocols suffer a power wastage caused both from transmissions resulting in a collision and from the amount of Carrier Sensing (active reception time) introduced by the time-spreading of the accesses. Furthermore, the transmission phase can be considered at least twice more power-consuming than the reception (or idle) phase. This fact could introduce some kind of transmission policy optimization, by evaluating the risks (i.e. the costs/benefits) of transmission attempts to be performed, given the current congestion conditions, and the system's Power Consumption parameters. As the reduction of the time-spreading periods generally produces an increase in the number of collisions, to minimize the power wastage the access protocol should balance these two costs. Therefore the power saving criterion we adopt throughout this paper is based on balancing the power consumed by the network interface in the transmission and reception (e.g. Physical Carrier Sensing) phases. Since these costs change dynamically, depending on the network load, a power-saving protocol must be adaptive to the congestion variations in the system. In addition, a Power Saving strategy should balance the need for high battery lifetime with the need to maximize the channel utilization and the QoS perceived by the network users [11].

In this paper, we propose a Power-Save, Distributed Contention Control (PS-DCC) mechanism which can be used on top of the IEEE 802.11 DCF access method to maximize the power saving while accessing the wireless channel. The proposed mechanism dynamically adapts the behavior of each station to the congestion level of the system and, beyond providing power saving, it contributes to obtain an optimal channel utilization, see [5].

The work is organized as follows: in Section 2 we present the actual Standard 802.11 DCF access scheme, and critical aspects connected to the contention level of the system; in Section 3 the DCC mechanism proposed in [2] is summarized; in Section 4 the analytical model of the system is presented; in Section 5 the new PS-DCC mechanism is defined an analyzed; in Section 6 simulation results are presented and commented; in Section 7 conclusions and future researches are given.

2 IEEE 802.11 Standard DCF for Wireless LANs

For the detailed explanation of the IEEE 802.11 Standard we address interested readers to [9]. Throughout we denote as *active station* a station with at least a frame to transmit. The *Basic Access* method in the IEEE 802.11 MAC protocol is the Distributed Coordination Function (DCF) which is a CSMA/CA MAC protocol. Every active station is required to perform a Carrier Sensing activity to determine the current state of the channel (idle or busy). If the medium is found busy, the

[1] The latter point has been faced in some cases; for example, IEEE 802.11 networks try to reduce the amount of Physical Carrier Sensing (CS), by exploiting Virtual CS based on Network Allocation Vectors' (NAV) updating [9].

station defers transmission. Whenever the channel becomes idle for at least a Distributed Interframe Space time interval (DIFS), the station (re)starts its Basic Access mechanism. To avoid collisions as soon as an idle DIFS is sensed on the channel, the Collision Avoidance mechanism adopted in the Standard 802.11 DCF is based on a Binary Exponential Backoff scheme [6, 7, 9]. When the channel is idle, time is measured in units of constant length indicated as *slots* in the following. Throughout $Slot_Time$ will be used to denote the length of a slot. The Binary Exponential Backoff scheme is implemented by each station by means of the $Backoff_Counter$ parameter, which maintains the number of empty slots the tagged station must observe on the channel, before performing its own transmission attempt. At the time a tagged station needs to schedule a new transmission, it selects a particular slot among those of its own Contention Window, whose size is maintained in the local parameter CW_Size. Specifically, the Backoff value is defined by the following expression [9]:

$$Backoff_Counter(CW_Size) = int(Rnd() * CW_Size) \tag{1}$$

where Rnd() is a function returning pseudo-random numbers uniformly distributed in [0..1]. The Backoff_Counter is decreased as long as a slot is sensed idle, it is frozen when a transmission is detected, and reactivated after the channel is sensed idle for at least a further DIFS. As soon as the Backoff_Counter reaches the value Zero the station transmits its own frame. Positive acknowledgements are employed to ascertain a successful transmission. This is accomplished by the receiver (immediately following the reception of the data frame) which initiates the transmission of an acknowledgement frame (ACK) after a time interval *Short InterFrame Space* ($SIFS$), which is less than $DIFS$. If the transmission generates a collision[2], the CW_Size parameter is doubled for the scheduling of the retransmission attempt, thus obtaining a further reduction of the contention. The Binary Exponential Backoff is then characterized by the expression which gives the dependency of the CW_Size parameter by the number of unsuccessful transmission attempts ($Num_Att - 1$) already performed for a given frame. In [9] it is defined that CW_Size is set equal to CW_Size_min (assuming low contention), when a new frame is transmitted, and doubled each time a collision occurs up to a maximum value CW_Size_MAX, as follows:

$$CW_Size(Num_Att) = min(CW_Size_MAX, CW_Size_min * 2^{Num_Att-1}) \tag{2}$$

The increase of the CW_Size parameter value after a collision is the reaction that the 802.11 Standard provides to make the access mechanism adaptive to channel conditions. This mechanism could introduce a low utilization of the channel bandwidth, due to high collision rates in congested scenarios [2]. The choice to initially assume a low level of congestion in the system avoids a great

[2] A collision is assumed whenever the ACK from the receiver is missing [9].

access delay when the load is light. Unfortunately this also represents a problem in bursty arrival scenarios, and in congested systems, because it introduces a concentration of accesses in a reduced time window, and hence it causes a high collision probability. Moreover, Collision Detection (CD) results not practicable in wireless channels, and this makes the cost of each collision proportional to the maximum size among colliding frames.

3 The DCC mechanism

The reasons explained in the previous section, motivated the studies to improve the performance of a random access scheme, by exploiting early and meaningful information concerning the actual state of the channel congestion. The idea presented in [2] involves an estimate of the resource's congestion level, which can be given by the utilization rate of the slots (*Slot Utilization*) observed on the channel by each station. The estimate of the Slot Utilization has to be maintained and updated by each active station, during the defer phase that precedes a transmission attempt, also indicated as Backoff interval. Specifically, during its own Backoff interval, every active station counts the number of transmission attempts it observes on the channel (Num_Busy_Slots), and then divides this number by the total number of slots available for transmission observed on the channel. Hence, a simple and intuitive definition of the Slot Utilization estimate is given by:

$$Slot_Utilization = \frac{Num_Busy_Slots}{Num_Available_Slots} \in [0..1] \quad . \tag{3}$$

The Slot Utilization provides a normalized lower bound for the actual contention level of the channel. In fact, as some stations may transmit in the same slot, it provides a lower bound to the effective number of stations trying to access the channel during the last observed Backoff interval. By assuming a time-locality of contention, such an information is significant about the state of the channel in immediately successive slots.

A station which knows there are few possibilities for a successful transmission, should defer its transmission attempt. Such a behavior could be achieved in an IEEE 802.11 network by exploiting the DCC mechanism proposed in [2]. According to DCC, each station controls its transmission attempts via a new parameter named *Probability of Transmission* ($P_T(...)$) which is dependent on the contention level (Slot_Utilization) of the channel [2]:

$$P_T(Slot_Utilization, Num_Att) = (1 - Slot_Utilization^{Num_Att}) \tag{4}$$

where Num_Att is the number of transmission attempts already performed for a given frame (including the current one). Each station, after the Slot Utilization estimate, computes the Probability

of Transmission value, and with the same probability performs a real access to the shared channel. If the station decides to defer the transmission, it reschedules a new attempt, as in the case of a collision occurred. The Slot_Utilization is interpreted here as the inhibition power of the DCC mechanism on the accesses, depending on the contention level it represents. Num_Att is used in the DCC mechanism as an indicator of the dynamic level of privilege achieved by a station. The lowest privilege is given to stations performing, for a given frame, the first transmission attempt, while the privilege level linearly increases with the number of collisions experienced. The aim is to privilege old transmission requests, obtaining a queue-emptying behavior for the system. To better understand what it has been obtained, we can observe the Figure 1. The proposed DCC mechanism

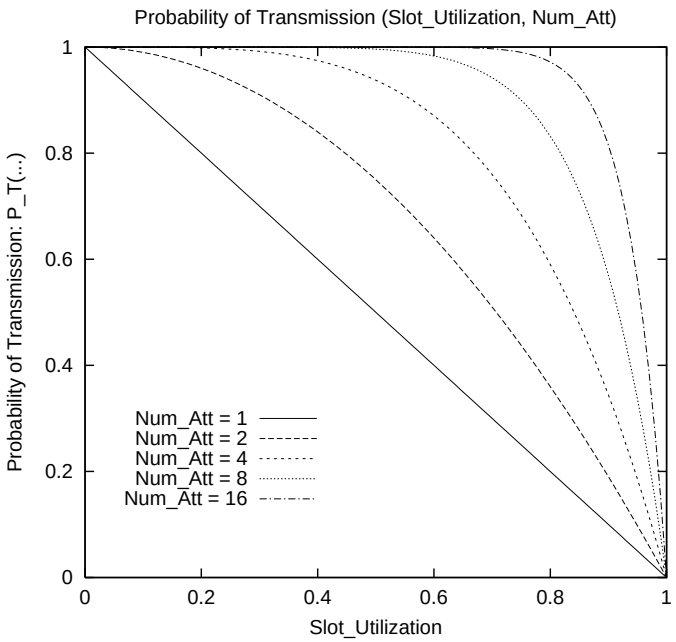

Figure 1: Probability of Transmission

has the effect to asymptotically reduce the Slot Utilization level induced on the system, when the congestion level grows indefinitely (Figure 1). If the Slot Utilization asymptotically approximates the maximum value (One), then the mechanism's effect reduces the Probability of transmission to Zero, for every station in the system. This means no accesses in the next slot. Hence, a Slot Utilization equal to One can only be asymptotically obtained over a CW_size_MAX backoff interval. This fact can be exploited by opportunely modifying the Probability of Transmission expression, in order to induce an arbitrary upper limit (SU_limit) to the Slot Utilization of the system:

$$P_T(Slot_Utilization, Num_Att, SU_limit) = 1 - min(1, \frac{Slot_Utilization}{SU_limit})^{Num_Att} \quad (5)$$

By adopting the expression (5), the DCC mechanism would perform asymptotically by reducing

Table 1: System parameters

Number of stations	from 2 to 200
CW_Size_min - CW_Size_MAX	16 - 1024
Max channel TX rate	2 Mb/s
Average Payload size	2.5 and 100 Slot Units
ACK size	4 Slot Units
Header size	2.72 Slot Units
Slot Time	50 μS
SIFS	0.56 Slot Units (28 μS)
DIFS	2.56 Slot Units (128 μS)
Propagation Time (τ)	$< 1\mu$S

all the probabilities of transmission in correspondence of Slot Utilization values equal to or greater than the SU_limit value. All remaining characteristics of the DCC mechanism are maintained.

4 Power Consumption Analysis

In this section the IEEE 802.11 DCF MAC power consumption is analytically estimated by developing an approximated model with a finite number, M, of active stations operating in asymptotic conditions (i.e. stations always have a packet ready for transmission). Once obtained the power consumption expression, we minimize it to identify the optimal power consumption level for the given network and load configurations. In the following we assume the physical and protocol parameters' values reported in Table 1.

Among the considered system's parameters, we also define PTX, indicating the power consumed (in mW) by the Network Interface (NI) during the transmission phases, and PRX indicating the power consumed (in mW) by the NI during the reception (or carrier sensing) phases.

Our model is based on the assumption that, for each transmission attempt, a station uses a backoff interval sampled from a geometric distribution with parameter p, where $p = 1/(E[B] + 1)$ and $E[B]$ is the average backoff time (in slot units). In the real IEEE 802.11 backoff algorithm, the protocol behavior depends on the past history, however, results presented in [5] have shown that a model of the protocol behavior based on the geometric assumption provides accurate estimates (at least from a capacity analysis standpoint) of the IEEE 802.11 DCF protocol behavior. In our model, we also assume that for all stations the payload length of transmitted frames is sampled from a geometric distribution with parameter q, such that $P\{frame_payload = x\} = q^{x-1} \cdot (1 - q)$.

The general scenario would require to assume a general distribution of the payload length, with the estimation of the mean and the variance (using techniques similar to the RTT estimation in [16]). The assumption of a constant payload distribution implies a constant collision length distribution characterized by the same parameter q. In order to obtain a more realistic approximated model we consider the geometric distribution which allows to consider the additional length of a collision with respect to the average payload. This introduces in the model a characterization of the collision overhead, which could be easily substituted by the corresponding analytical definition related to any other considered traffic distribution. The obtained model results robust for each distribution type of the payload size, and it could be defined for a deterministic distribution, obtaining a close form definition [3].

To perform our analysis we focus on a tagged station and we observe the system at the end of each successful transmission of the tagged station. From the geometric backoff assumption, all the processes which define the occupancy pattern of the channel (i.e. empty slots, collisions, successful transmissions) are regenerative with respect to the sequence of time instants corresponding to the completion of tagged-station successful transmissions. By using the regenerative behavior of the system, we derive a closed formula for the IEEE 802.11 DCF energy consumption. Specifically, by defining as the $j-th$ renewal period the time interval between the $j-th$ and $(j+1)-th$ successful transmission ($j-th$ virtual transmission time) of the tagged station, from renewal theoretical arguments [8] it follows that:

$$E[Energy] = E[Energy_j] \tag{6}$$

where $Energy$ is the energy required to a station to perform a successful transmission, and $Energy_j$ is the tagged station energy consumption during the j-th renewal period (i.e., the j-th successful transmission). By exploiting (6), the power consumption analysis can thus be performed by studying the system behavior in a generic renewal period also referred to as *virtual transmission time*. When more than one station is active, during a virtual transmission time the tagged station is involved in a successful transmission and in some collisions (see Figure 2). Specifically, Figure 2 shows that before the tagged station performs a successful transmission, it may experience a number of collisions and a number of *not_used* slots. A *not_used* slot is both a time interval in which the transmission medium remains idle due to the backoff algorithm, and a time interval in which the tagged station does not transmit but the transmission medium is busy due to the transmission attempts of some of the other $M-1$ stations. During a *not_used* slot the tagged station is in the receiving state, hence to determine the tagged-station power consumption during this period

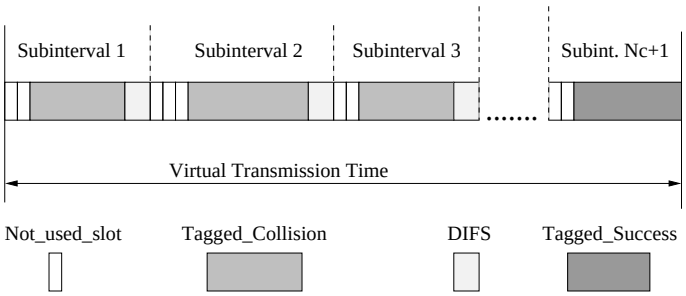

Figure 2: Structure of a virtual transmission time

we need to estimate its length. By denoting with N_C the number of collisions experienced by a tagged station in a virtual transmission time, we can subdivide a virtual transmission time into $N_C + 1$ subintervals, see Figure 2. N_C subintervals terminate with a transmission attempt of the tagged station which results in a collision, while the last subinterval (i.e., $(N_C + 1) - th$ subinterval) terminates with a successful transmission of the tagged station. In each subinterval, there are a number, $N_{not_used_slot}$, of *not_used* slots (from the tagged station standpoint) before the transmission attempt of the tagged station. The number of *not_used* slots in successive subintervals are i.i.d. random variables sampled from a geometric distribution. Specifically, by considering that the tagged station transmits in a slot with probability p, it can be shown that

$$E[N_{not_used_slot}] = (1 - p)/p \tag{7}$$

To simplify the presentation it is useful to introduce the following random variable definitions, which make reference to a general $j - th$ virtual transmission time (we will omit the index j). We denote with

- N_nus_k: number of consecutive *not_used_slots* during the $k - th$ subinterval in which the tagged station is in the receive state
- $Energy_{nus_k}$: power consumption during the N_nus_k slots of the $k - th$ subinterval in which the tagged station is in the receive state
- $Energy_{tagged_collision_k}$: power consumption experienced by the tagged station while it experiences the $k - th$ collision during the $j - th$ virtual transmission time
- $Energy_{tagged_success}$: power consumption experienced by the tagged station when it obtains the $j - th$ successful transmission

By exploiting the above definitions, the tagged-station's power consumption (6) can be expressed

as:

$$E[Energy] = E[\sum_{n=1}^{N_C}(Energy_{nus_n} + Energy_{tagged_collision_n}) + Energy_{nus_n+1} + Energy_{tagged_success}] \quad (8)$$

The above formula (8) can be re-written as:

$$E[Energy] = E[\sum_{n=1}^{N_C+1} Energy_{nus_n}] + E[\sum_{n=1}^{N_C} Energy_{tagged_collision_n}] + E[Energy_{tagged_success}] \quad (9)$$

By exploiting the definition of conditioned averages:

$$\begin{aligned} E[\sum_{n=1}^{N_C+1} Energy_{nus_n}] &= \sum_{x} E[\sum_{n=1}^{N_C+1} Energy_{nus_n} | N_C = x] \cdot P\{N_C = x\} \\ &= \sum_{x} E[Energy_{nus_1} + ... + Energy_{nus_x}] \cdot P\{N_C = x\} \end{aligned} \quad (10)$$

Furthermore, by noting that the random variables $Energy_{nus_i} (i = 1..x)$ have the same distribution, which does not depend on the N_C value, and by denoting with $E[Energy_{nus}]$ their common average value, it follows that:

$$E[\sum_{n=1}^{N_C+1} Energy_{nus_n}] = E[N_C + 1] \cdot E[Energy_{nus}] \quad (11)$$

where $E[Energy_{nus}] = E[N_{not_used_slot}] \cdot E[Energy_{not_used_slot}]$, and $E[Energy_{not_used_slot}]$ is the average power consumption of the tagged station while it senses a sequence of *not_used_slot*.

In a similar way we can show that:

$$E[\sum_{n=1}^{N_C} Energy_{tagged_collision_n}] = E[N_C] \cdot E[Energy_{tagged_collision}] \quad (12)$$

where $E[Energy_{tagged_collision}]$ is the average power consumption of the tagged station while it experiences a collision during a transmission.

Hence, by exploiting (11) and (12) the formula (9) can be written as:

$$\begin{aligned} E[Energy] &= E[N_C + 1] \cdot E[N_{not_used_slot}] \cdot E[Energy_{not_used_slot}] + \\ &\quad E[N_C] \cdot E[Energy_{tagged_collision}] + E[Energy_{tagged_success}] \end{aligned} \quad (13)$$

where $E[N_C], E[Energy_{not_used_slot}], E[Energy_{tagged_collision}], E[Energy_{tagged_success}]$ are derived in the following lemmas[3].

[3] In this work we don't consider the energy consumed in on/off, Rx/Tx and Tx/Rx transitions of the network interface. However, our analytical model can be easily extended including these costs in the Formula (13).

Lemma 4.1 Assuming that for each station the backoff interval is sampled from a geometric distribution with parameter p:

$$E[N_C] = \frac{1-(1-p)^{M-1}}{(1-p)^{M-1}} \tag{14}$$

■

It must be noted that some protocol overheads follow both a collision and a successful transmission: *i)* the maximum propagation delay τ which is required (in the worst case) to sense the channel idle after a transmission, and *ii)* the DIFS idle interval to be sensed after a transmission. Let us denote with $Collision$ and with S the average length of a collision (not involving the tagged station) and of a successful transmission, including their overheads. Hence, by denoting with τ the maximum propagation delay between two WLAN stations[4]:

$$Collision \leq Header + E[Coll_{not_tagged}] + \tau + DIFS \tag{15}$$

where $E[Coll_{not_tagged}]$ (i.e. the average length of a collision not involving the tagged station) has been derived in [5]:

$$\begin{aligned} E[Coll_{not_tagged}] &= \frac{Slot_Time}{1-[(1-p)^{M-1}+(M-1)\cdot p\cdot(1-p)^{M-2}]}\cdot \\ &\cdot\left[\sum_{h=1}^{\infty}\left\{h\cdot[(1-p\cdot q^h)^{M-1}-(1-p\cdot q^{h-1})^{M-1}]\right\}-\frac{(M-1)\cdot p\cdot(1-p)^{M-2}}{1-q}\right] . \end{aligned} \tag{16}$$

A successful transmission in the IEEE 802.11 WLAN includes the time interval between the start of a transmission which does not experience a collision and the end of the first DIFS which follows the successful transmission, hence [5]:

$$S \leq Header + payload + 2\tau + SIFS + ACK + DIFS \tag{17}$$

where, by denoting with q the parameter of the geometric distribution for the payload size, the average length of the transmission ($payload$) in slot units, can be expressed as [5]:

$$payload = \frac{1}{1-q} \quad . \tag{18}$$

[4] As τ is a bound on the propagation delay, it follows the $\leq$ in Collision and S formulas.

Lemma 4.2 By denoting with p the parameter of the geometric distribution which defines the backoff interval, the tagged station average power consumption during a *not_used* slot is:

$$\begin{aligned} E[Energy_{not_used_slot}] &= PRX \cdot [Slot_Time \cdot (1-p)^{M-1} + \\ &\quad S \cdot (M-1) \cdot p \cdot (1-p)^{M-2} + \\ &\quad Collision \cdot (1-(1-p)^{M-1} - (M-1) \cdot p \cdot (1-p)^{M-2})] \end{aligned} \tag{19}$$

■

The analytical study of the average energy required for the frame transmission of a tagged station does not consider the energy consumption required for the transmission of acknowledgements. This is acceptable given the fact that acknowledgements are not subject to contention because they are transmitted immediately after the SIFS following the end of the received frame, see Section 2.

Lemma 4.3 By denoting with p the parameter of the geometric distribution which defines the backoff interval, the tagged station average power consumption, when it performs a successful transmission in a slot, is:

$$E[Energy_{tagged_success}] \leq PTX \cdot (Header + payload) + PRX \cdot (2\tau + SIFS + ACK + DIFS) \tag{20}$$

■

Lemma 4.4 By denoting with p the parameter of the geometric distribution which defines the backoff interval, and with q the parameter of the geometric distribution which defines the payload size, the tagged station average power consumption, when it experiences a collision while transmitting, is:

$$\begin{aligned} E[Energy_{tagged_collision}] &= PTX \cdot (Header + payload) + PRX \cdot \sum_{x=1}^{\infty} q^{x-1} \cdot (1-q) \cdot \\ &\left[\left(\sum_{y=1}^{\infty} y \cdot \sum_{i=1}^{M-1} [(1-q^{y+x})^i - (1-q^{y+x-1})^i] \cdot \frac{\binom{M-1}{i} \cdot p^i \cdot (1-p)^{M-i-1}}{1-(1-p)^{M-1}} \right) + DIFS + \tau \right] \end{aligned} \tag{21}$$

■

By assuming that all the times are expressed in *SlotTime* units, and that the PTX and PRX values are expressed in *mW/SlotTime* units, the average energy requirement for a frame transmission is given (in mJ units) by:

$$E[Energy] = f(p, q, M, PTX, PRX) \qquad . \tag{22}$$

The proofs of previous lemmas can be found in [3]. We define p_{opt} as the value of p (i.e. the average backoff value) which minimizes the Energy consumption, fixed M, q (i.e. the average payload size) and the PTX, PRX system's parameters. The p_{opt} values for various combinations of the proposed parameters have been calculated. In Section 5 we will exploit the results of the analytical model, to define the PS-DCC mechanism.

5 The PS-DCC Mechanism

In Section 3 we presented a mechanism, named DCC, which could be used to control the contention level in an IEEE 802.11-like network. Furthermore, we have shown that the DCC approach can guarantee, given a threshold value SU_limit, that the Slot Utilization in the network is bounded by the threshold value. In Section 4 we defined an approximated analytical model for an IEEE 802.11-like protocol, to study the tuning of the protocol parameters, in order to minimize the power consumption required to successfully transmit a message. In this section, by putting together the above results, we define a mechanism named *Power Save Distributed Contention Control*(PS-DCC), that can be used to enhance an IEEE 802.11 network from the Power Consumption standpoint. Specifically, we first show that the optimal parameter setting for power consumption can be mapped in a boundary value for the network Slot Utilization, named $AsymptoticalContentionLimit(ACL)$. Then, we define the PS-DCC mechanism by adequately inserting the ACL value into the DCC mechanism.

In Section 5.1 we show that a strong relationship exists between the $Slot_Utilization$ and the $(M \cdot p_{opt})$ values. Such a relationship is useful in the definition of the PS-DCC mechanism.

5.1 The relationship between $Slot_Utilization$ and $M \cdot p_{opt}$

In the following we investigate the meaning of the $(M \cdot p_{opt})$ values, and its relationship with the $Slot_Utilization$, in a considered system. As we seen in Section 4, we assume M active stations scheduling their respective transmission attempts in a slot selected following a geometric distribution with parameter p. Under the optimality assumption it has been obtained the expression which defines the optimal value p_{opt} of the p parameter. Let us now assume that each station uses the

optimal backoff value p_{opt}. The $(M \cdot p_{opt})$ value is an upper bound of the Slot Utilization in the system, in fact:

$$Slot_Utilization = 1 - (1 - p_{opt})^M = -\sum_{k=1}^{M} \left(\begin{array}{c} M \\ k \end{array} \right) (-p_{opt})^k \approx M \cdot p_{opt} \tag{23}$$

when p_{opt} is small. Moreover, the negative second order term $-\frac{M \cdot (M-1)}{2} \cdot (-p_{opt})^2$ demonstrates that $M \cdot p_{opt}$ is a tight upper bound of the $Slot_Utilization$ in a system operating with the optimal p value from the power consumption viewpoint.

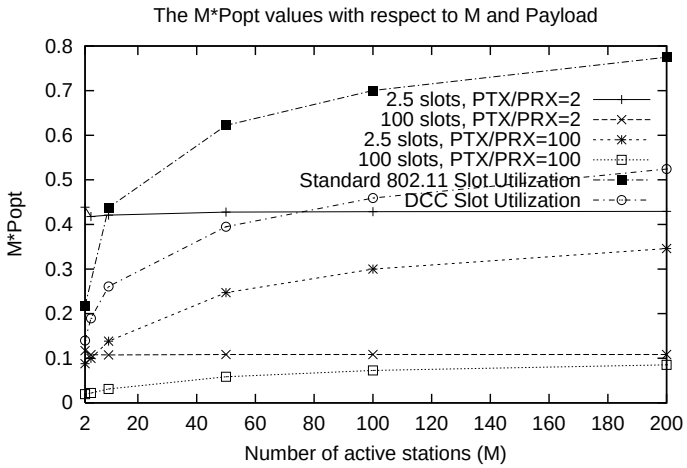

Figure 3: The $M \cdot p_{opt}$ values and the steady-state Slot Utilization

Given the system's parameters of Table 1, in Figure 3 we compare the optimal $Slot_Utilization$ values (represented by the $(M \cdot p_{opt})$ values), with the steady-state $Slot_Utilization$ level estimated (via simulation) in a IEEE 802.11 network with or without the DCC mechanism. The number of active stations M is variable, representing the variable contention level of the channel. The considered systems are characterized by the average *payload* parameter (considered values for the average payload size: 2.5 and 100 SlotTimes) and the PTX/PRX ratio (considered values: 2 and 100). By adopting the IEEE 802.11 protocol the $Slot_Utilization$ level does not depend on the *payload* parameter value, while it is connected only to the number of active stations, M. Results reported in Figure 3 show that in the standard protocol the $Slot_Utilization$ values are generally greater than the optimal values. This result is marked when the mean frame size is large (payload = 100 SlotTimes) because the standard protocol produces a $Slot_Utilization$ level which does not depend on the frame size. On the other hand, in the optimal case, the increase of the frame size (which means an increase in the collision-cost) is balanced by a decrease of the collision probability, achieved by decreasing the $Slot_Utilization$ value. Even if the DCC mechanism [2]

correctly reduces, with respect to Standard 802.11, the *Slot_Utilization* (i.e. the contention level) under high-load conditions, the results presented in Figure 3 indicate that DCC does not produce the optimal contention level. Furthermore, these results indicate that an algorithm which wishes to drive the system to the optimal power consumption must take into consideration the average value of the *payload* parameter.

5.2 Theoretical Power Saving limits: the ACL invariant figures

The $M \cdot p_{opt}$ values allow us to define the optimal contention limits to guarantee the power-saving optimality in the considered systems. Looking at Figure 3 and fixed a given value of *payload*, it can be observed that: *i)* if the PTX/PRX ratio is low (e.g. 2), then the $(M \cdot p_{opt})$ product results quasi-constant for M greater than 2, and *ii)* if the PTX/PRX ratio is high (e.g. 100), then the $(M \cdot p_{opt})$ values are significantly affected by the value of M. Observation *i)* (PTX/PRX=2) means that, fixed the system's parameters of Table 1, it is possible to define a single quasi-optimal value for the product $(M \cdot p_{opt})$, as a function of the *payload* parameter. Hence, fixed the value 2 for the PTX/PRX ratio, it is possible to define an *Asymptotical Contention Limit* function $ACL_{PTX/PRX}(payload), payload \in [2..MPDU]$[5] such that $ACL_2(payload) \approx (M \cdot p_{opt})$, for the considered system. This function can be defined off-line depending on the system's parameters, and represents the indication of the optimal level of Slot Utilization the system should obtain under the given access scheme, to guarantee the power consumption optimality. This definition does not depend on M. In the scenario where PTX/PRX is high (e.g. 100), the optimal definition of a function $ACL_{100}(payload) \approx (M \cdot p_{opt})$ is not possible given the significant influence of M. Anyway, it is possible to define a function $ACL_{100}(payload)$ considering only the high values of M (e.g. 100), and evaluating the overhead introduced by using such a definition in a scenario with few stations. This analysis has been done [3] and the results have shown that the overhead introduced (with respect to the optimal power consumption level) is low. This fact is justified because we potentially introduce a Slot Utilization limit higher than the optimal limit in a scenario with few stations, but in this case the collision probability is low. This encourages us to assume that such an analytical definition of the function $ACL_{PTX/PRX}(payload)$ would give results near to the optimality in terms of power consumption, for each considered system.

[5] Here we assume that the payload size of transmitted frames is $\geq$ 2 Slot Times, and $\leq$ than the maximum protocol data unit (MPDU) expressed in slot units.

5.3 The PS-DCC Mechanism

The previous considerations allow us to set the limit for the Slot Utilization in the considered system, which guarantees a reduced influence of collisions on the power consumption. Specifically, it results possible to incorporate the optimality in the reaction performed by the DCC mechanism, by limiting the Slot Utilization by its optimal upper bound *Asymptotic Contention Limit (ACL)*. Assuming the $ACL_{PTX/PRX}(payload)$ function to be known, in Section 3 we defined the new Probability of Transmission (P_T) definition which realizes the expected effect:

$$P_T(Slot_Utilization, Num_Att, payload) = 1 - min(1, \frac{Slot_Utilization}{ACL_{PTX/PRX}(payload)})^{Num_Att} \quad . (24)$$

The PS-DCC mechanism requires the *payload* and the $Slot_Utilization$ estimations to determine the value of the transmission probability (24). Details regarding the implementation of the estimation algorithms can be found in [3, 4]. The Figure 4 shows an example of the $ACL_{PTX/PRX}(payload)$ functions obtained for the system considered, for M = 100 stations.

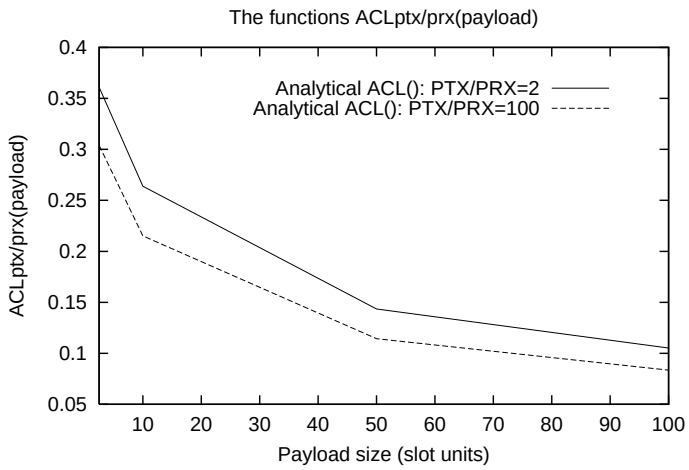

Figure 4: The $ACL_{PTX/PRX}(payload)$ functions

6 Simulation results

The behavior of the proposed PS-DCC mechanism has been studied from the Power Consumption viewpoint, by means of discrete-event simulation. Our interest was to investigate the advantages of the new PS-DCC mechanism, with respect to the actual Standard 802.11 DCF access scheme (STND) and the optimal values (OPT). Specifically, we focused our investigation on the average Power Consumption for a frame transmission, and on the channel Utilization level, when varying

the Contention Level on the transmission channel. The implementation of the Contention Level has been obtained in each simulation by means of a variable number of active stations with continuous transmission requirements. The number of stations has been set variable from 2 to 200, in order to *i)* stress the system, *ii)* show the system's scalability, and *iii)* point out the absence of overheads introduced. The physical characteristics and parameters of the investigated system are reported in Table 1. Simulations consider only two extreme power consumption scenarios with PTX/PRX = 2 and 100. According to the studies of TCP traffic [16] we consider either systems with "long messages" (average payload length of 100 SlotTimes, 1250 Bytes), or systems with "short messages" (average payload length of 2.5 SlotTimes, 32 Bytes). The RTS/CTS option of the IEEE 802.11 protocol [9] has not been explicity considered in our analysis and simulations because the contention phase is restricted to the RTS transmission. After the RTS/CTS transmission all stations not involved in the transmission are frozen. The payload transmission is optimized from the Power Saving point of view because the contention has been solved. Given these consideration, the RTS/CTS option is optimized when short messages transmission is optimized. Simulations will show that the PS-DCC gives advantages with short messages (32 Bytes) that are comparable with RTS messages. Since the RTS threshold is usually greater than 32 Bytes, the PS-DCC mechanism is effective also implementing the RTS/CTS option. The effect of Hidden Terminals [9] or any other spatial inequities have not been considered here. We assume that the only cause of collision between two or more transmissions is given by the selection of the same slot. This allowed us to study the problem of the optimal power consumption in random access schemes, with respect to the contention level influence. If spatial inequities or Hidden Terminals are present in the system, all the enhancements obtained with the proposed PS-DCC mechanism would be in any case lower bounded by the Standard 802.11 DCF results. Simulations performed with a deterministic *payload* distribution have shown a reduction of the Energy parameters of $8 - 10\%$ with long messages and no significant modifications with short messages. All the investigated parameters presented show their confidence intervals, with a confidence level of 95%. To derive these statistics we adopted the independent replication techniques.

6.1 Energy required

Figures 5-8 show the average energy required for a successful frame transmission, in a system characterized by the *payload* parameter values 2.5 and 100 slots, and two (extreme) values for the network interface power consumption ratio PTX/PRX (equal to 2 in Figures 5-6, and equal to 100 in Figures 7-8). The energy required has been investigated as a function of the variable number of active stations M, i.e. the congestion level. The analytically estimated optimal values

for the energy consumption are also reported. These optimal values are compared with the steady-state values obtained by the simulations of the Standard 802.11 DCF access scheme, and by the simulations of the same access scheme enhanced with the PS-DCC mechanism.

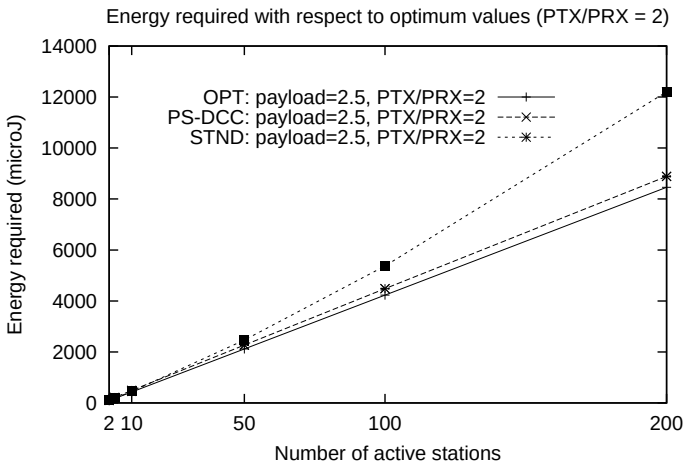

Figure 5: Energy required: Payload=2.5, PTX/PRX=2

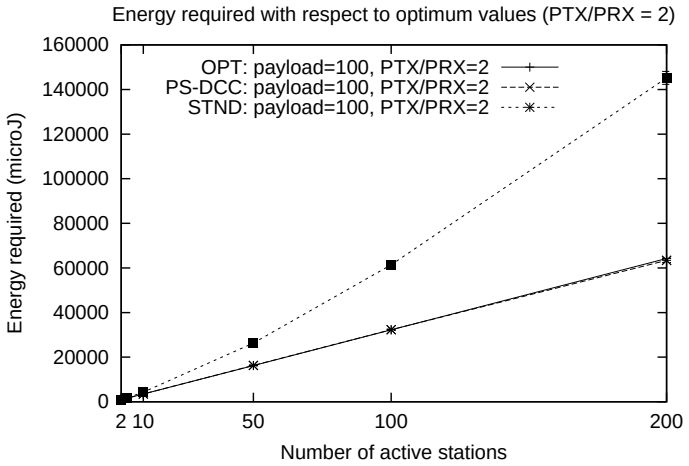

Figure 6: Energy required: Payload=100, PTX/PRX=2

Results show that: *i)* the power consumption in the Standard 802.11 DCF access scheme is negatively affected by the congestion level, and *ii)* the PS-DCC mechanism counterbalances the congestion growth by maintaining the optimality in the power consumption. The energy saving achieved by PS-DCC is significant and increases with the average frame size. No overheads are introduced from the power consumption viewpoint in the considered systems, and the PS-DCC results are very well approximating the optimum values analytically defined (the corresponding

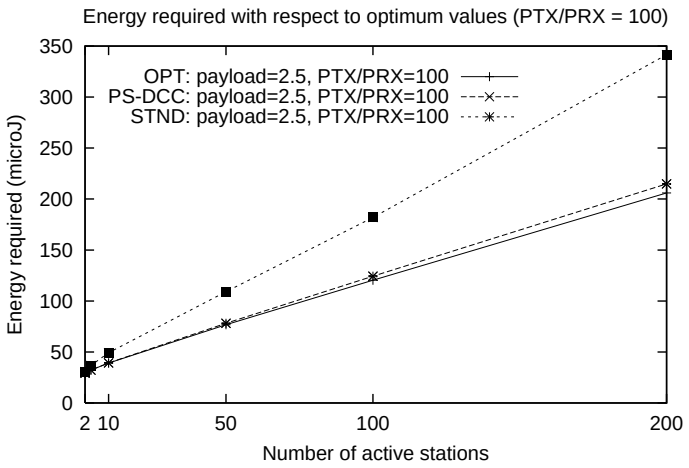

Figure 7: Energy required: Payload=2.5, PTX/PRX=100

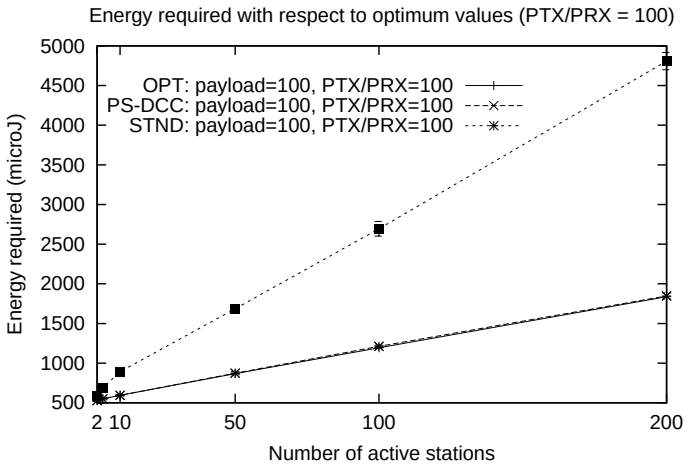

Figure 8: Energy required: Payload=100, PTX/PRX=100

lines reported in the figures can not be easily distinguished).

6.2 99-th percentile of Energy required

Figures 9 and 10 show the 99-th percentile of the Energy considered above. This index is significant about the power-consumption obtained in the "worst case" for a frame transmission in the considered system. The PS-DCC mechanism allows a significant reduction of this performance index, with respect to the Standard. This fact also indicates the enhanced queue-emptying behavior obtained in the considered system, which is related to the priority obtained by old transmission requirements, and connected to the Num_Att parameter.

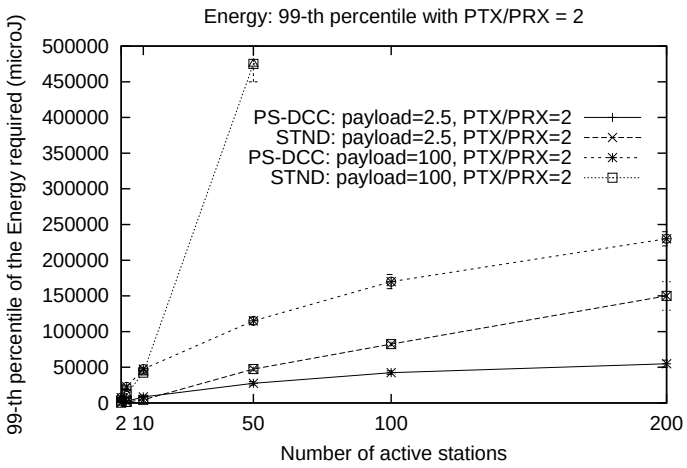

Figure 9: 99-th percentile of Energy required: PTX/PRX=2

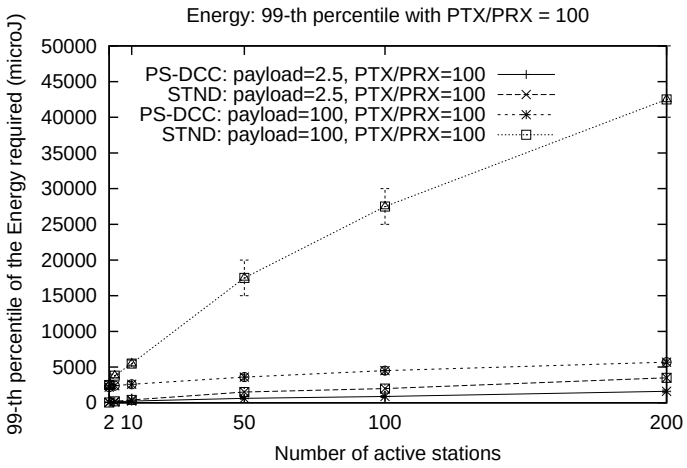

Figure 10: 99-th percentile of Energy required: PTX/PRX=100

6.3 Channel Utilization level

We are interested in investigating the effect of the PS-DCC mechanism on the channel utilization of the considered system. Specifically, we want to compare the channel utilization level when PS-DCC is adopted in the system, with respect to the optimal channel utilization level defined in [5]. Figure 11 shows the utilization level of the Standard 802.11 DCF with respect to the optimal values analytically calculated in [5]. It is immediate to verify that the 802.11 Standard DCF access scheme suffers the high contention situations that could arise in the system, leading to a low channel Utilization with respect to the channel Capacity. The use of the PS-DCC mechanism shows its effectiveness. The utilization curves obtained with PS-DCC, for the different values of PTX/PRX,

are almost not distinguished, so only one is reported. It results clear that the proposed mechanism leads to a quasi-optimal behavior of the system also from the Utilization viewpoint. This makes the power consumption mechanism adopted a conservative method, leading to the quasi-optimality both for the power saving and for the channel utilization. Only a 2% utilization reduction (overhead) is introduced in the system with few stations and short frames, with respect to the actual Standard, as we can see in the direct comparison.

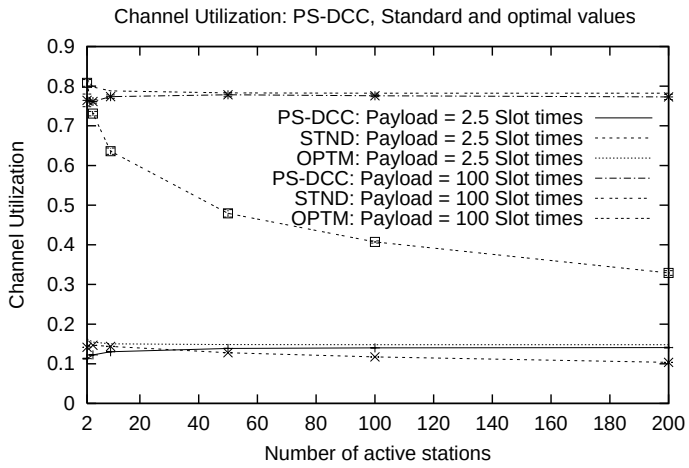

Figure 11: Channel utilization: optimal, Standard 802.11 and PS-DCC values

6.4 The Average Access Delay

About the user's performance indexes investigation, the average MAC access delay has been reported. The average MAC access delay represents the time required between the first transmission scheduling of a given frame, and the completion of its successful transmission. In the Figure 12 it has been reported the simulation data of the Mean Access Delay, with respect to the variable contention level (M) and the average *payload* size of transmitted frames. It results that the new PS-DCC mechanism leads to a reduction of the Mean Access Delay with respect to the actual Standard access scheme. No overheads are introduced, confirming the adaptive behavior of the proposed mechanism. The PS-DCC mechanism, with the implemented priority effect connected to the Num_Att value, makes stations with high Num_Att values transmitting with high probability of success, enhancing the fairness and the queue-emptying behavior of the system. Moreover, the PS-DCC leads to a linear growth of the access delay, with respect to the number of active stations in the system, which outperforms the Standard access scheme.

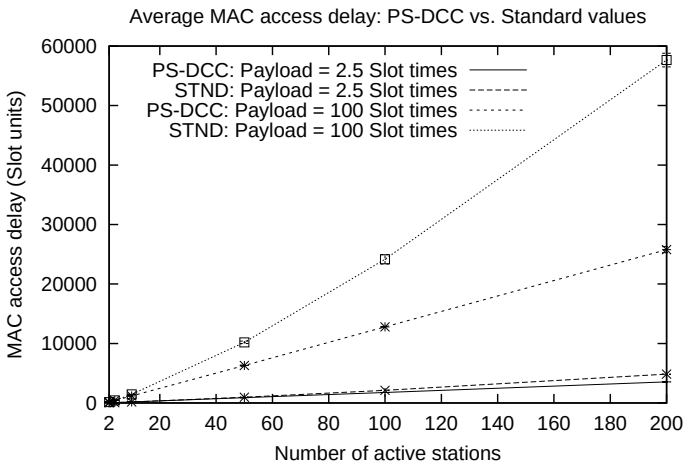

Figure 12: Average MAC access delay

6.5 The dynamic Power Consumption

It is interesting to observe how the system behaves in transient scenarios. Figure 13 reports the simulation traces of the average energy required for a frame transmission with and without the PS-DCC mechanism. Simulation data are obtained by considering a system in steady-state, with 100 stations initially active. After some time, a burst of additional 100 stations activates, causing the contention level to grow up, then it disappear. The additional burst occurs twice during the simulation.

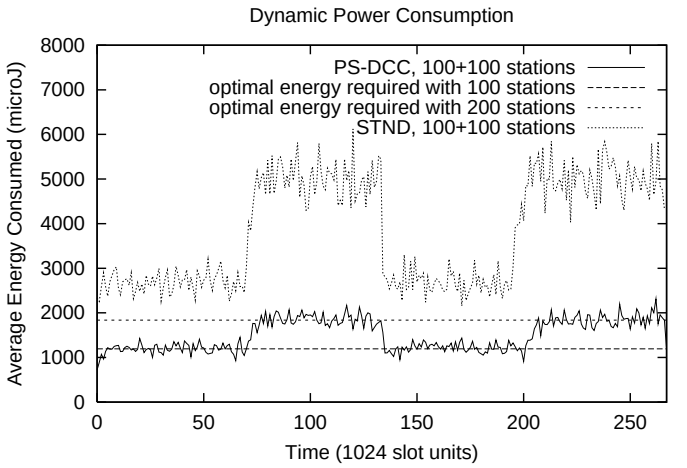

Figure 13: Dynamic Energy requirements vs. contention level

The figure shows how the systems react to the contention variations under the power consumption viewpoint. The Standard system enhanced with the PS-DCC mechanism obtains a lower Energy

requirement for the frame transmissions, with respect to the Standard system. The PS-DCC mechanism is fast to adapt to new contention scenarios. Moreover, as expected from previous results, the PS-DCC mechanism maintains an average Energy requirement which is close to the optimal value in all contention conditions analyzed.

7 Conclusions and future research

We propose and evaluate a Power Save, Distributed Contention Control (PS-DCC) mechanism which is effective in implementing a distributed and adaptive contention control, to guarantee the optimal power consumption of a random-access MAC protocol for a wireless network. Specifically, we considered the IEEE 802.11 DCF access scheme [9] as a testbed for our analysis. The PS-DCC mechanism requires no additional hardware with respect to the Standard, but given the scarce flexibility of the Standard implementations, it will be implementable only as a new protocol, in a new release of the Standard devices or in devices with software radio technologies. The proposed mechanism is completely distributed, and it can be tuned, for the power consumption optimality, on the basis of an analytical model definition. The proposed mechanism dynamically adapts the system to the optimal contention level by means of the Slot Utilization and the average Payload size estimates. Each estimate is obtainable with low cost and with no overheads. The system maintains a stable behavior, both during the steady-state congested phases and during bursty arrivals of transmission requirements. The priority effect implemented by the PS-DCC mechanism, connected to the Num_Att parameter, allows a fair reduction of contention, and enhances the queue-emptying behavior of the system. Simulations show that the proposed mechanism introduces a quasi-optimum channel utilization and power consumption in the considered systems, without significant affection of the contention level. Other system parameters like the Mean Access Delay, the 99-th percentile of the power consumed, the risk of starvation and the transient behavior have been analyzed and resulted enhanced by our mechanism, without overheads introduced. Future research involves the study of further optimization connected to different classes of frame sizes. It also results possible to obtain an external priority mechanism [2], which would allow each station to self-determine a greater priority in the access right to the channel, without any kind of negotiation. The external priority mechanism could be useful if adopted with RTS/CTS messages.

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