A Distributed Contention Control Mechanism for Power Saving in random-access Ad-Hoc Wireless Local Area Networks [*†]

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Abstract - The power consumption of mobile computers connected to wireless networks is negatively affected by the congestion level of the channel, and significantly depends on the Medium Access Control (MAC) protocol policy adopted [14]. This paper illustrates the design and the performance evaluation of a new mechanism for the distributed contention control of the random accesses to the shared transmission channel of a Wireless LAN (WLAN). Our aim is the design of a distributed access scheme where each frame transmission leads to an optimal power consumption level, from the Network Interface (NI) viewpoint. To achieve this goal, we present a new analytical model to define the optimal average power consumption required by the NI for a frame transmission, and for a given random-access scheme. Specifically, we considered the Standard IEEE 802.11 Distributed Coordination Function (DCF) access scheme for WLANs. By exploiting the optimal values analytically derived, we define a parametric and adaptive Power-Save, Distributed Contention Control (PS-DCC) mechanism. The proposed mechanism has been investigated via simulation. The power consumption of the proposed mechanism approximates the analytically defined optimal level, outperforming the Standard 802.11 DCF access scheme. To confirm the absence of overheads introduced, the channel utilization still results closely approximating the optimal values [4].

I. Introduction

The finite battery power of mobile computers represents one of the greatest limitations to the utility of portable computers [8, 14]. Projections on the expected progress in battery technology show that only a 20% improvement in the battery capacity would occur over the next 10 years [11]. 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 could result some of the most power consuming operations to perform [9, 12]. 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 to define mechanisms useful for Power Saving (PS) in Wireless LANs [1, 9]. 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]. The impact of network technologies and interfaces on power consumption has been investigated in depth in [12]. The power saving features of the emerging standards for wireless LANs have been analyzed in [10, 14].

The work presented in this paper is located in the area of the MAC level optimization of the Network Interface's (NI) power consumption, with respect to the congestion level of the channel. The amount of power consumed by transmissions results negatively affected by the congestion level of the network. Specifically, in a distributed, contention-based access scheme to wireless channels, a considerable power waste is caused by collisions. On the other side, to adaptively reduce the contention for the accesses to the shared channel, the active stations perform a variable time-spreading of accesses, which also constitutes a power consuming activity. Hence, this system is subject to a power waste caused both from transmissions resulting in a collision and from the amount of active reception time (Carrier Sensing) introduced by the time-spreading of the accesses. The latter point has been faced in some cases, e.g. IEEE 802.11 networks try to reduce the amount

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of Physical Carrier Sensing (CS) favoring the NI's sleep mode, by exploiting Virtual CS based on Network Allocation Vectors' (NAV) updating [7]. However, it is worth noting that a considerable amount of energy is consumed in the state transitions (off-on) of the NI [12]. As the reduction of the time-spreading intervals generally produces an increase in the number of collisions, to minimize the power wasted the access protocol should balance these two conflicting costs. Since these costs change dynamically, depending on the network load, it is evident the need for the adaptive behavior of such protocols, with respect to the congestion variations in the system. In [12] it has been demonstrated how the dominant cost in terms of transmission power consumption comes proportionally from the whole amount of time the NI is in the active (transmitting or receiving) state. Despite this fact, for a set of NI devices currently available, the transmission phase can be considered at least twice more power-consuming than the reception (or idle) phase, and many times more power consuming than the sleeping mode. This fact could introduce some kind of MAC policy optimization, by evaluating the risk (i.e. the costs/benefits) of transmission attempts to be performed, given the current congestion conditions, and the system's power consumption parameters.

In this paper, we propose a *Power-Save, Distributed Contention Control (PS-DCC)* mechanism which is based upon an analytical model definition. The analytical model allows to investigate the effect of a variable congestion level of the wireless channel, from the Network Interface's power consumption standpoint. Our model definition depends on the MAC protocol adopted in the system. The analytical results obtainable can be used to adaptively tune the system's parameters to the current congestion level, obtaining the optimal NI's power consumption in every scenario. The adaptive reaction of the system to the congestion would result optimized from the NI's power consumption viewpoint. The obtained mechanism is based on some properties of the *Distributed Contention Control (DCC)* mechanism proposed in [2]. In our analysis we consider the ad-hoc wireless network paradigm, characterized by the lack of a fixed wired infrastructure. Specifically, we consider the IEEE 802.11 access scheme for Wireless LANs [7]. We will concentrate our analysis over the IEEE 802.11 Distributed Coordination Function (DCF), which may be significantly affected by the congestion problem, due to distributed random access characteristics. The considered system has been modeled, the PS-DCC mechanism has been tuned by exploiting the analytical results, and the effect of the proposed mechanism has been evaluated via simulation. A power saving strategy should balance the need for a high battery lifetime with the need to provide a reasonable cell capacity and Quality of Service (QoS) [9]. The proposed PS-DCC mechanism contributes to obtain an optimal channel utilization, i.e. the channel capacity, as resulted in [4].

The work is organized as follows: in II we present a brief explanation of the actual Standard 802.11 DCF access scheme, and critical aspects connected to the contention level of the system; in III we summarize some ideas and properties of the DCC mechanism proposed in [2]; in IV the proposed analytical model of the system is sketched; in V the analytical results obtained are discussed and the new PS-DCC mechanism is defined; in VI simulation results are presented and commented; in VII conclusions and future researches are drawn.

II. IEEE 802.11 Standard DCF

For the detailed explanation of the IEEE 802.11 Standard (specifically the *IEEE 802.11 Standard Distributed Coordination Function - DCF*), the interested readers can address to [7]. The 802.11 DCF is based on a *Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)* MAC protocol which requires every active station (i.e. a station with frames to transmit) to perform a carrier sensing activity to determine the current state of the channel (idle or busy). If the medium is found to be busy, the active station defers the 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 [5, 7]. 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 (CW), whose size is maintained in the local parameter CW_Size. Specifically, the $Backoff\_Counter$ value is defined by the following expression [7]:

$$Backoff\_Counter(CW\_Size) = int(Rnd() * CW\_Size)$$

where $Rnd()$ is a function returning pseudo-random numbers uniformly distributed in [0..1]. The $Backoff\_Counter$ is decreased as long as a $SlotTime$ is sensed as idle, it is frozen when a transmission is detected, and reactivated after the channel is sensed as idle for at least a further DIFS. As soon as the $Backoff\_Counter$ reaches the value zero the station transmits its own frame. Positive acknowledgments 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 acknowledgment frame (ACK) after a time interval $ShortInterFrameSpace$ (SIFS), which is less than a DIFS.

If the transmission generates a collision[1], 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 transmission attempts (Num_Att) already performed for a given frame (including the current one). In [7] it is defined that the first transmission attempt for a given frame is to be performed with CW_Size equal to the minimum value CW_Size_min (assuming low contention). After each unsuccessful (re)transmission of the same frame, the station doubles CW_Size until it reaches the maximum value fixed by the standard, i.e. CW_Size_MAX, as follows:

$$CW\_Size(Num\_Att) = \min(CW\_Size\_MAX, CW\_Size\_min * 2^{Num\_Att-1})$$

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. It is worth noting that this mechanism could introduce a low utilization of the channel bandwidth, due to high collision rates in congested scenarios. The choice to initially assume a low level of congestion in the system avoids a great 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 significant under the channel utilization and the power consumption viewpoints.

III. 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 current state of congestion of the channel. 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. It is worth noting that the *Slot Utilization* could assume the role of an early and significant contention level indication [2].

A. The Slot Utilization estimate

The estimate of the *Slot Utilization* has to be maintained and updated by each station, during the defer phase that precedes a transmission attempt, also indicated as Backoff interval. The 802.11 Standard mechanism assumes that every station is able to perform a Carrier Sensing activity such that the evolution of the state of the channel is known by each station. Specifically, during its own Backoff interval, every station could count 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 ($Num\_Available\_Slots$). Hence, a simple and intuitive definition of the *Slot Utilization* estimate is given by:

$$Slot\_Utilization = \frac{Num\_Busy\_Slots}{Num\_Available\_Slots} \quad . \tag{1}$$

High values of the *Slot Utilization* (i.e. near to One), imply that during the last backoff interval the system was in presence of a high level of contention for the channel. By assuming a time locality of contention, this information will be significant about the state of the channel in immediately successive slots.

To summarize, the *Slot Utilization* estimate constitutes a contention indication before the access (without the need to experience collisions), it is completely distributed, it provides a significant indication of the actual contention level, and it is obtained with no costs and overheads introduced. Furthermore, it is obtainable with a full integration with the standard, because all the information required are already available to each 802.11 station.

B. Management of contention in DCC

Given the *Slot Utilization* estimate definition, in [2] is given a proposal to adopt it in a distributed mechanism for the adaptive control of the contention. This is obtained by introducing a filtering of access indications between the standard access scheme adopted in the system (i.e. the MAC protocol adopted), and the physical layer, as shown in Fig. 1.

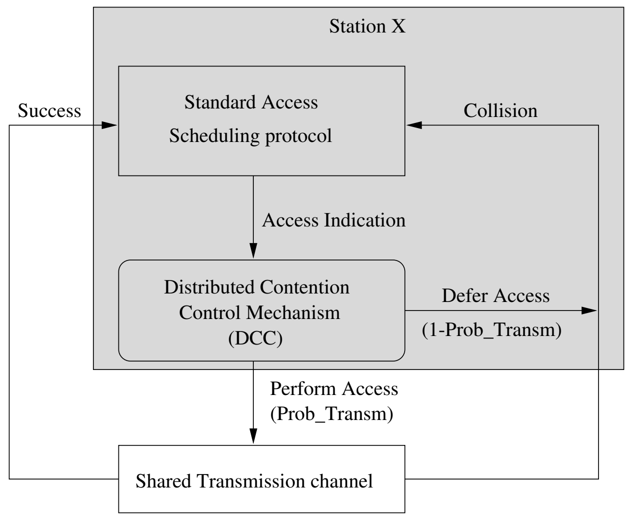

Fig. 1: Architectural collocation of DCC

Each station evaluates its opportunity to perform or to defer the scheduled transmission attempt. This deci-

[1] A collision is assumed whenever the Ack from the receiver is missing [7].

sion is based on the information obtained before to try a blind transmission attempt. A station which knows there are few possibilities for a successful transmission should defer its transmission attempt[2]. For this reason, according to the DCC mechanism definition [2], each station should base its transmission attempt on the value of a new local parameter named *Probability of Transmission* (P_T). The value of this parameter is dependent on the contention level of the channel (i.e. the *Slot Utilization* estimate). After the backoff phase, each active station computes the *Slot Utilization* estimate and the *Probability of Transmission* value. The obtained P_T value represents the probability threshold (of a uniform probability distribution) to perform 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, see Fig. 1. Hence, this mechanism realizes the expected effective reduction of contention, on a statistical basis, and generates a lower probability of collision with respect to the Standard. Moreover, the effect of this mechanism is transparent to the MAC protocol and the upper layers.

The DCC mechanism also introduces the way to implement a distributed privilege mechanism for the accesses. The set of active stations is logically and dynamically partitioned according to the number of transmission attempts already performed (Num_Att) for the current frame. Each subset is associated with a different level of privilege in the accesses, i.e. the Num_Att parameter value. The heuristic expression to evaluate the *Probability of Transmission (P_T)* adopted in the DCC mechanism is the following [2]:

$$P\_T(Slot\_Utilization, Num\_Att) = \\ (1 - Slot\_Utilization^{Num\_Att}) \quad . \tag{2}$$

The $Slot\_Utilization$ assumes values in the interval [0..1], by definition. The $Slot\_Utilization$ is interpreted as the inhibition power of the DCC mechanism on the accesses. The lowest privilege is given to stations performing the first transmission attempt, for a given frame ($Num\_Att = 1$). The privilege level linearly increases with the number of collisions experienced (Num_Att). 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 Fig. 2. The Fig. 2 shows the *Probability of Transmission* curves with respect to the $Slot\_Utilization$ values estimated, for users with Num_Att attempts performed. Assuming a $Slot\_Utilization$ close to Zero, each station obtains a *Probability of Transmission* close to One. This means that the proposed mechanism has no effect on the system, and each user performs its accesses just like in the standard access scheme, without any additional contention control. This point is significant considering the absence of overhead introduced in low load cases. The generalized reduction of contention, and the effect of the different level of privilege (Num_Att parameter) appears when the $Slot\_Utilization$ grows. Assuming a $Slot\_Utilization$ value close to one, e.g. 0.8, a station with the highest Num_Att value obtains a *Probability of Transmission* greater than other stations. It is worth noting that this mechanism is completely distributed. It is also possible to obtain the indication about the channel congestion, and then about the opportunity to tune the CW_Size parameter, without necessarily performing a blind access with a high collision-risk.

[2]This would also contribute to power saving, as in this way it can be saved the power required by a transmission attempt which has a low probability to be successful.

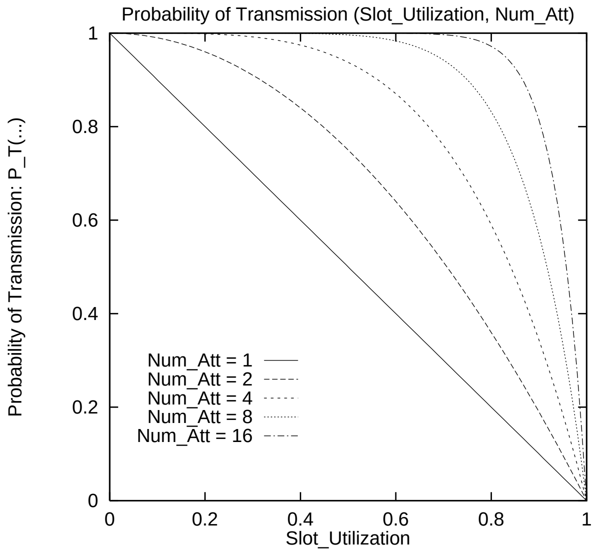

Fig. 2: Probability of Transmission

To sum up, the DCC realizes the abstraction of a distributed, statistical access-authorization mechanism, based upon a priority principle, and devoted to obtain a reduction of contention, only when it is needed. The mechanism leads to a probabilistic capture of the resource by those users with the highest privilege in the accesses. The mechanism is also adaptive and stable due to the feedback effect of the $Slot\_Utilization$ estimate [2]. No overheads are introduced, and good characteristics are obtainable, from the performance viewpoint, as shown in [2]. It is worth noting that the DCC mechanism has the effect to asymptotically reduce the *Slot Utilization* level induced on the system, when the congestion level grows indefinitely, see Fig. 2. This means that a *Slot Utilization* level equal to One can only be asymptotically obtained over a CW_size_MAX backoff interval. This fact can be exploited, by manipulating the *Probability of Transmission* expression, in order to induce an arbitrary upper limit for the *Slot Utilization* of the system. The DCC mechanism's effect guarantees such a limit to be an upper bound for the *Slot Utilization* level induced on the system.

IV. Power Consumption in 802.11

In this paper the IEEE 802.11 DCF MAC power consumption is analytically estimated by developing a model with a finite number, M, of active stations operating in asymptotic conditions. This means that all the M network 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.

Table 1: System parameters

NUMBER OF STATIONS (variable)	from 2 to 200
CW_Size_min - CW_Size_MAX	16 - 1024
MAX CHANNEL TX RATE	2 Mb/s
PAYLOAD SIZE (variable)	from 2.5 to 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 (128μS)
PROPAGATION TIME	< 1 μS

Among the considered system's parameters, we also define PTX, indicating the average power consumed (in mW) by the Network Interface (NI) during the transmission phases, and PRX indicating the average 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 $Slot\_Time$ units). In the real IEEE 802.11 backoff algorithm, a station's transmission-probability depends on the past history, however, results presented in [4] 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 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 $P\{frame\_payload = x\} = q^{x-1} \cdot (1-q)$.

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's 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 [6] it follows that:

$$E[Energy] = E[Energy_j] \qquad (3)$$

where $Energy$ is the energy required to a station to perform a successful transmission, and $Energy_j$ is the tagged-station's energy consumption during the j-th renewal period (i.e., the j-th successful transmission). By exploiting (3), 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 Fig. 3.

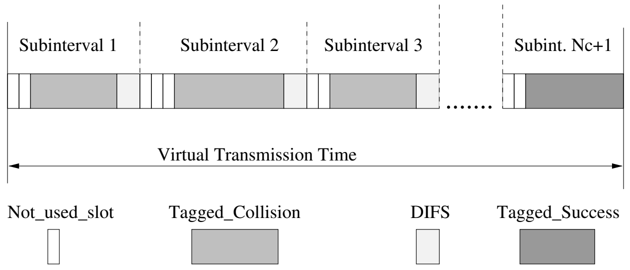

Fig. 3: Structure of a virtual transmission time

Specifically, the Fig. 3 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 a slot in which the tagged station does not transmit. It could be both a time interval in which the transmission medium remains idle due to the backoff algorithm, and a time interval in which 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[3], hence to determine the tagged-station's power consumption during this period we need to estimate its length.

Analytical expressions for the unknown quantities were derived in [3]. By exploiting these expressions it is easy to show that:

$$E[Energy] = f(p, q, M, PTX, PRX) \quad . \qquad (4)$$

[3] In this work we perform the worst case analysis by assuming that the NI remains in the active state during other stations' transmissions (i.e. active carrier sensing). The model could be extended by introducing virtual carrier sensing. It is worth noting that the effect of virtual carrier sensing can be easily considered in our model by reducing the PRX value.

We define p_{opt} as the value of p which minimizes the Energy consumption (4), fixed M, q and the PTX, PRX system's parameters. The p_{opt} values for various combinations of the proposed parameters have been calculated. Minimizing the Energy expression (4) with respect to p, implies a minimization of the NI's power consumed for transmissions, with respect to the mean Backoff window size (i.e. the adaptive parameter of the system with respect to the congestion level). In the next section we will exploit the results of the analytical model, to define the PS-DCC mechanism.

V. The PS-DCC Mechanism

In this section, by exploiting results presented in Sections III and IV, we define the *Power Save, Distributed Contention Control* (PS-DCC) mechanism, which leads to a quasi-optimal power consumption, independently from the contention level and the mean message length in the system. In Section III, we introduced the $Slot\_Utilization$ parameter to estimate the channel contention level. In Section IV we defined the analytical power-consumption expression which allows to define the optimal backoff parameter (p_{opt}) in the system characterized by the remaining M, q, PTX and PRX parameters' values. Now we show that a strong relationship exists between the $Slot\_Utilization$ and the $(M \cdot p_{opt})$ values. Such a relationship results useful in the definition of the PS-DCC mechanism.

A. $Slot\_Utilization$ and $M \cdot p_{opt}$ relationship

In the following we investigate the meaning of the $(M \cdot p_{opt})$ value, and its relationship with the $Slot\_Utilization$ in a considered system. As we seen in Section IV, we assume M active stations scheduling their respective transmission attempts in a slot selected following a geometric distribution with parameter p. It has been obtained the expression (4) which defines the optimal value p_{opt} of the p parameter, from the power consumption standpoint. Let us assume that each station uses the optimal backoff value p_{opt}.

We denote with N_{tr} the number of stations that make a transmission attempt in a slot. Hence, $P\{N_{tr} = i\}$ is the probability that exactly i stations transmit in a slot, and $P\{N_{tr} = 0\}$ is the probability that a slot remains empty. Let us observe that $(M \cdot p_{opt})$ is the average number of stations which transmit in a slot:

$$\begin{aligned} M \cdot p_{opt} &= \sum_{i=1}^{M} i \cdot P\{N_{tr} = i\} \geq \\ &\geq 1 - P\{N_{tr} = 0\} = Slot\_Utilization \ . \end{aligned} \tag{5}$$

Hence, given the optimum conditions, $(M \cdot p_{opt})$ is an upper bound on the probability to observe a busy slot, i.e. $(M \cdot p_{opt}) \geq Slot\_Utilization$. Furthermore results presented in [4] indicate that if the stations utilize the optimal p value, the collision probability is low (e.g. in average one collision occurs out of several virtual times). This means that

$$P\{N_{tr} > 1 | N_{tr} > 0\} << P\{N_{tr} = 1 | N_{tr} > 0\}, \tag{6}$$

and hence from (5) it results 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.

Given the previous considerations, the $(M \cdot p_{opt})$ values represent the optimal level of the *Slot Utilization* the system should obtain under the given access scheme, to guarantee the optimality under the power consumption viewpoint.

B. The optimal Slot Utilization

In the previous section we show that in the "ideal scenario" (i.e. the stations tune the window size according to the optimal p value) the *Slot Utilization* level is bounded by $(M \cdot p_{opt})$.

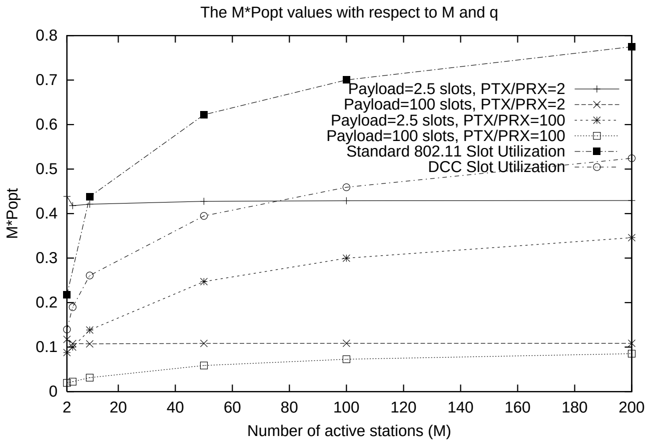

Fig. 4: The $M \cdot p_{opt}$ values for the given system, compared to the steady-state $Slot\_Utilization$.

Given the system's parameters of Table 1, in Fig. 4 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. The Fig. 4 also shows the effect of the generalized DCC mechanism [2] on the *Slot Utilization* of the network. The considered systems are characterized by the average payload parameter q (average payload size: 2.5 and 100 $Slot\_Times$) and the PTX/PRX ratio (considered values: 2 and 100). The number of active stations M is variable, representing the variable contention level of the channel. It is worth noting that by adopting the IEEE 802.11 protocol the $Slot\_Utilization$ level does not depend by the q parameter value, while it is connected only to the number of active stations, M. Results reported in Fig. 4 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 size equal to 100 SlotTimes). 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. Obviously to decrease the collision probability (in the optimal case) we decrease the *Slot_Utilization* value. Even if the DCC mechanism [2] correctly reduces the *Slot_Utilization* under high load conditions, with respect to the Standard 802.11, the results presented in Fig. 4 indicate that the general DCC mechanism [2] does not produce the optimal contention level (from the power saving standpoint). Furthermore, these results indicate that an algorithm which wishes to drive the system to the optimal power consumption must take into consideration the value of the q parameter.

C. The ACL invariant figures

The previous considerations allow us to define the optimal contention limits to guarantee the power saving optimality in the considered systems. Now, we analyze the optimal contention limits obtained, in order to identify the best way to use them in the PS-DCC mechanism. Looking at Fig. 4 and fixed a given value of q (payload), it can be observed that: i) if the PTX/PRX[4] ratio is low (e.g. 2), then the $(M \cdot p_{opt})$ product results quasi-constant for M greater than 2, and more precisely, it shows only a little decrease when M grows, ii) if the PTX/PRX ratio is high (e.g. 100), then the $(M \cdot p_{opt})$ values are much more significantly affected by the value of M. In the former case (PTX/PRX=2), this 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 parameter q. Hence, fixed the value 2 for the PTX/PRX ratio, it is possible to define a common *Asymptotic Contention Limit* function $ACL_{PTX/PRX}(q), q \in [\frac{1}{2}..1]$[5] such that $ACL_2(q) \approx (M \cdot p_{opt})$, for the considered system. This function can be defined off-line depending on the system's parameters, using (4), and would represent the indication of the optimal level of *Slot Utilization* the system should obtain under the given access scheme, to guarantee the optimality under the power consumption viewpoint. It is worth noting that this definition does not depend on M. In the scenario where PTX/PRX is high (e.g. 100), the optimal definition of a function $ACL_{100}(q) \approx (M \cdot p_{opt})$ would not be possible given the significant influence of M. Anyway, it would be possible to define a function $ACL_{100}(q)$ considering the great values of M (e.g. 100), and evaluating the overhead introduced by using such a definition in scenarios with few stations. This analysis has been done [3] and the results shown that the overhead introduced would be really low, with respect to the optimal power consumption level. This fact is justified because such a definition represents a conservative assumption, under the contention control viewpoint. This means that we potentially introduce a power-waste overhead due to some additional amount of idle waiting time, instead of transmission time subject to collisions. As in this case the waiting time requires about 1/100 the power required by the equivalent transmission time, the overhead introduced is low. This encourages us to assume that such an analytical definition of the function $ACL_{PTX/PRX}(q)$ would give results near to the optimality in terms of power consumption, for each considered system.

D. The PS-DCC Mechanism

The previous considerations allow to set out the limit for the *Slot Utilization* in the considered system, which guarantees a reduced influence of collisions for the power consumption. Specifically, it results possible to incorporate the optimality in the reaction performed by the MAC protocol, by limiting the *Slot Utilization* by its optimum upper bound *Asymptotic Contention Limit (ACL).* The optimal *Slot Utilization* limit $ACL_{PTX/PRX}(q)$ could be introduced in the system as the asymptotic contention limit, by exploiting the DCC characteristics [2]. On the other side, the adaptive behavior of the DCC mechanism in low load conditions should avoid to introduce a significant power consumption due to idle slots. Let's define how the $ACL_{PTX/PRX}(q)$ limit for the *Slot Utilization* could be imposed to the given system. To this end, in Section III, it has been introduced a characteristic of the DCC mechanism, i.e. the fact that the defined *Slot_Utilization* of the channel never reaches the value One. Assuming the *Slot_Utilization* value close to One, the DCC mechanism would perform asymptotically by reducing all the local *Probabilities of Transmission*, see Fig. 2. This means that the contention level (*Slot_Utilization*) in the near future would be decreasing below the value One. This asymptotic effect is due to the *P_T* definition (2). Intuitively, if the value One would be replaced by the $ACL_{PTX/PRX}(q)$ value in (2), then the DCC mechanism would perform asymptotically by reducing all the *Probabilities of Transmission* in correspondence of *Slot Utilization* values equal to or greater than the $ACL_{PTX/PRX}(q)$ value. This means that the system would naturally perform below the given upper limit of *Slot Utilization.* All remaining characteristics of the DCC mechanism [2] are maintained. Assuming the $ACL_{PTX/PRX}(q)$ function to be known, the new *Probability of Transmission* (*P_T*) definition we propose is:

$$P\_T(Slot\_Utilization, Num\_Att, q) = 1 - \min\left(1, \frac{Slot\_Utilization}{ACL_{PTX/PRX}(q)}\right)^{Num\_Att} \quad . \qquad (7)$$

Note that the *P_T* expression has been manipulated in order to maintain the original DCC's shape in (2). The

[4] The PTX/PRX ratio has been considered in order to obtain qualitative results independent by the adopted device. The effect of virtual carrier sensing (NI's sleep mode) can be represented by growing the value of the ratio.

[5] Here we assume that the payload size of transmitted frames is $\geq$ 2 SlotTimes, i.e. $q \in [\frac{1}{2}..1]$.

$P\_T(...)$ values obtained with (7) fluctuates between 0 and 1.

E. The ACL(q) definition

Now we give a definition for the Asymptotic Contention Limit (ACL) functions, depending on the frame size parameter q, and the system's physical parameters reported in Table 1. We consider only two extreme power consumption scenarios regarding the PTX/PRX values 2 and 100. Fixed the system's physical parameters, we obtained the optimal values ($M \cdot p_{opt}$), for large values of M. By interpolating as a function of q the optimal values, we define the analytical $ACL_{PTX/PRX}(q)$ expression.

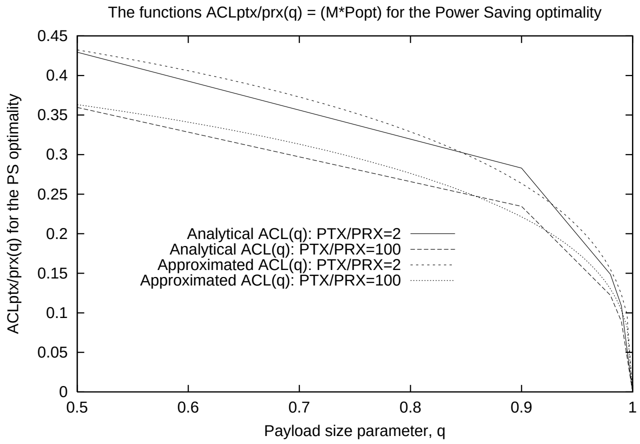

Fig. 5: The $ACL_{PTX/PRX}(q)$ functions: the optimal and approximated definitions.

The Fig. 5 shows the optimal values obtained for the system considered, (for $M = 100$ stations). In the same figure are reported the values of the approximated, interpolated functions $ACL_{PTX/PRX}(q)$ used in the simulations:

$$\begin{array}{lcll} ACL_2(q) & = & 0.5 \cdot (1 - q^{3/2})^{1/3} & and \\ ACL_{100}(q) & = & 0.42 \cdot (1 - q^{3/2})^{1/3} & . \end{array} \quad (8)$$

It has to be considered that these expressions realize a rough approximation of the optimal values, because we are interested in a simple and low-computational-cost definition. To capture the power consumption optimality, the q parameter estimate and the *Slot Utilization* estimate should be introduced in the system. The details regarding how these estimates could be obtained in the considered system can be found in [3]. The $ACL_{PTX/PRX}(q)$ upper limit functions (8) are supposed to be calculated off-line, and known by each station.

The simulation data reported in the next section show the obtained results.

VI. Simulation results

The behavior of the proposed PS-DCC mechanism has been studied from the power consumption viewpoint, via 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 analytically obtained optimum values (OPT). Specifically, we investigated the effect of the Contention Level (i.e. the channel congestion) both on the average power consumption for a frame transmission, and on the Utilization level of the channel. The implementation of the Contention Level has been obtained in each simulation by varying the number of active stations with continuous transmission requirements. The number of active stations has been set variable from 2 to 200, in order to stress the system, to show the obtained system's scalability and the absence of overheads introduced. The physical characteristics and parameters of the investigated system are reported in Table 1. According to the studies of TCP traffic [13] we consider either systems with "long messages" (average payload length of 100 $Slot\_Times$, 1250 Bytes), or systems with "short messages" (average payload length of 2.5 $Slot\_Times$, 32 Bytes). In the simulations we focused our attention on some performance indexes, investigating the contention level influence on them. The effect of Hidden Terminals [7] or any other spatial inequities and channel errors have not been considered here. We assume that the only cause of collision between two or more transmissions is given by their common slot selection. This allowed us to study the problem of the optimal power consumption in random access schemes, strictly connected to the contention level influence. It is worth noting that, if spatial inequities, channel errors or Hidden Terminals are present in the system, all the results obtained with the proposed PS-DCC mechanism would be in any case lower bounded by the Standard 802.11 DCF results. All the investigated parameters presented show their confidence intervals, with a confidence level of 95%.

A. Average Energy required

The Fig. 6 and 7 show the average energy required for a frame transmission, on behalf of a station in the system characterized by the average payload size parameter q, the variable number of active stations M, and two extreme network interface's power consumption ratio PTX/PRX (equal to 2 in Fig. 6, and equal to 100 in Fig. 7). The analytically-estimated optimal values (4) for the energy consumption in the same system are reported. These values are compared with the steady-state values obtained by the simulation of the Standard 802.11 DCF system, and by the same access scheme with the PS-DCC mechanism implemented on top. It results that: i) the Standard 802.11 DCF access scheme is significantly affected by the congestion growth from the power consumption viewpoint, ii) the PS-DCC mechanism allows to counterbalance the congestion growth by maintaining the optimality in the power consumption required for transmissions, iii) the analytical model is well predicting the system behavior, validating the simulation results and vice versa. It is worth noting that the obtainable advantages in terms of power consumption are significant, especially when the average frame size is great. No overheads are introduced from the power consumption viewpoint in the considered systems, and the PS-DCC's results are very well approximating the optimum values analytically defined for the given system (the corresponding lines reported in the Fig. 6 and 7 match almost exactly).

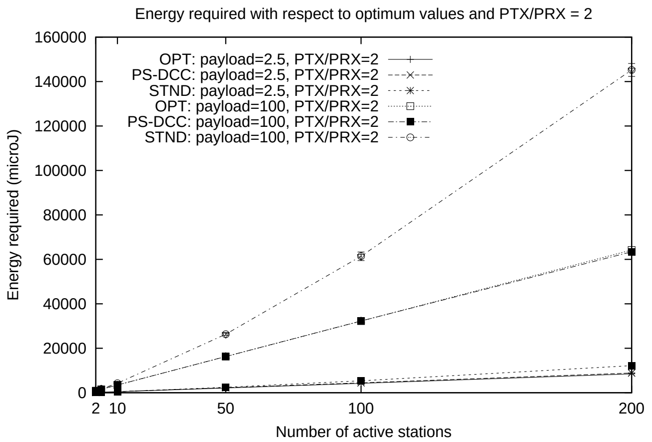

Fig. 6: Average Energy required for a frame transmission: PTX/PRX=2.

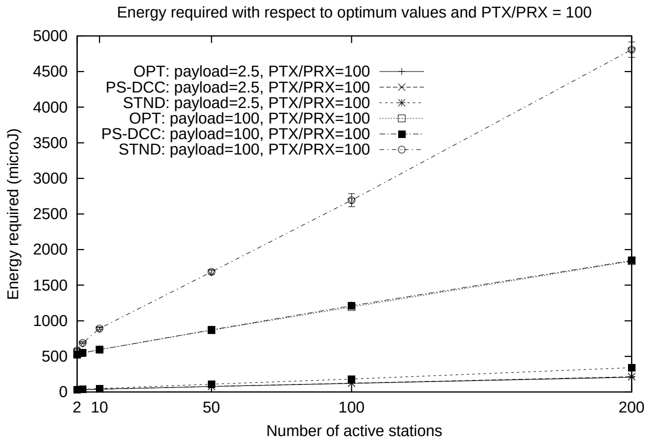

Fig. 7: Average Energy required for a frame transmission: PTX/PRX=100.

B. Channel Utilization level

We are interested also in the investigation of the effect of the PS-DCC mechanism on the channel utilization of the considered system. The power consumption optimality should be obtained even with no costs in the user's performance nor in the resource's utilization [9]. Here we show that the channel utilization maintains an optimal level, as it has been obtained in [4], even with the proposed mechanism. The Fig. 8 shows the Utilization level of the Standard 802.11 DCF, compared with the optimum values calculated with the specific analytical model defined in [4]. The given values have been calculated for each value of q and M, and have been reported in the Fig. 8. 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 application of the proposed PS-DCC mechanism shows its effect in the Fig. 8. The figure shows the channel Utilization obtained in the system compared with the analytically defined optimal Utilization level. The utilization curves obtained with PS-DCC for the different values of PTX/PRX are almost not distinguishable, so only one is reported. It results that the proposed mechanism leads to a quasi-optimal behavior of the system even from the channel Utilization viewpoint. The ACL contention limit obtained for the power consumption optimality is lower than the one obtainable under the channel utilization viewpoint [4]. This makes the adopted PS-DCC mechanism a conservative method, leading to the quasi-optimality from both the power saving and the channel utilization viewpoints. Only a little 2% utilization 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. Moreover, the system Utilization maintains its analytical optimality even in high contention situations.

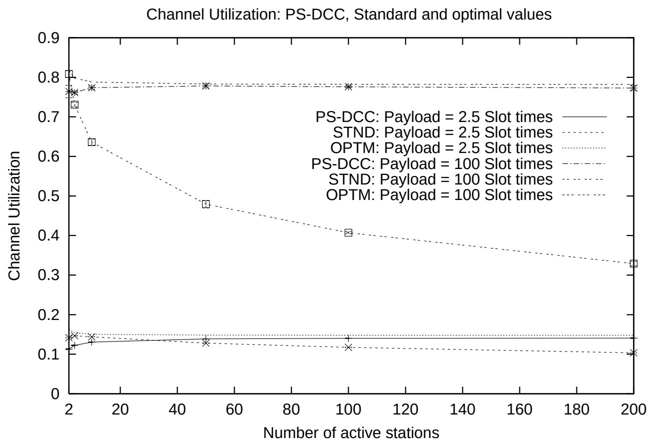

Fig. 8: Utilization comparison: optimal values, Standard 802.11 DCF and PS-DCC mechanism.

C. 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 DCF time required between the first transmission scheduling of a frame, and its successful transmission completion. In the Fig. 9 it has been reported the simulation data regarding the Mean Access Delay, considering only the DCF time, with respect to the variable channel contention level and the mean *Frame Size* of transmitted frames. It results that the new PS-DCC mechanism leads to a reduction

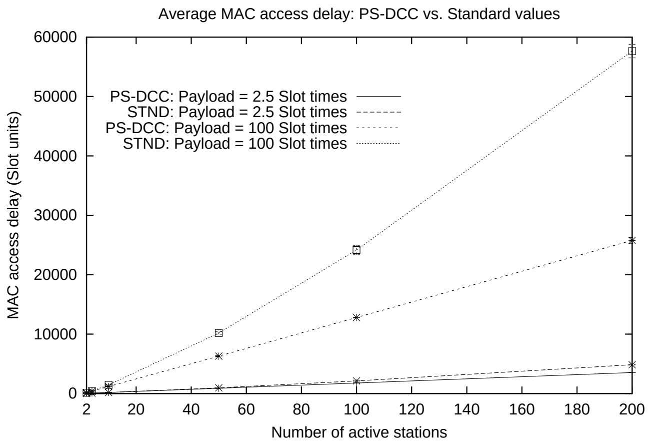

Fig. 9: Average MAC access delay

of the mean access delay with respect to the actual Standard access scheme. It is worth noting that no overheads are introduced, confirming the optimal adaptive behavior of the proposed mechanism. When the Contention Level is significant, the proposed mechanism introduces a Num_Att-based priority effect in the reduction of contention, enhancing the fairness and the queue-emptying behavior of the system. It is worth noting that the PS-DCC leads to a linear growth of the access delay, with respect to the number of active stations in the system. This outperforms the behavior of the Standard access scheme.

VII. Conclusions

We propose and analyze a Power Save, Distributed Contention Control (PS-DCC) mechanism for the distributed, adaptive contention control in a random access scheme for a Wireless network. We present a new analytical model to define the expected NI's power consumption required for transmissions, which is based on the MAC protocol policy adopted. Specifically, we considered the IEEE 802.11 DCF access scheme [7]. The analytical results obtained are used to define the optimum contention level in the system, and to tune the PS-DCC's parameters. The mechanism is adaptive by adopting the *Slot Utilization* and the average *Frame Size* estimates. Each estimate is obtained with low cost and with no overheads or further hardware introduced, with respect to the actual Standard definition [3]. The power consumption and the channel utilization obtained with the PS-DCC result quasi-optimal and are almost not affected by the contention level in the system. The good characteristics of DCC [2] are maintained by the proposed mechanism. Future research involves the study of further optimization connected to different classes of frame sizes. Another future research could be given by the External Priority mechanism [2] investigation, connected to the QoS requirements and RTS/CTS messages exploitation.

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