Run-Time Optimization of IEEE 802.11 Wireless LANs performance

L. Bononi(*), M. Conti, E. Gregori
National Research Council (CNR)
IIT Institute
Via G. Moruzzi, 1 - 56124 Pisa - Italy
e-mail: {marco.conti, enrico.gregori}@iit.cnr.it

(*) Department of Computer Science
University of Bologna
Mura Anteo Zamboni, 7, 40127 Bologna - Italy
e-mail: bononi@cs.unibo.it

Abstract

IEEE 802.11 is the standard for Wireless Local Area Networks (WLANs) promoted by the Institute of Electrical and Electronics Engineers. Wireless technologies in the LAN environment are becoming increasingly important, and the IEEE 802.11 is the most mature technology to date [Sta01]. Previous works have pointed out that the standard protocol can be very inefficient, and that an appropriate tuning of its congestion control mechanism (i.e., the backoff algorithm) can drive the IEEE 802.11 protocol close to its optimal behavior. To perform this tuning a station must have exact knowledge of the network contention level; unfortunately, in a real case, a station cannot have exact knowledge of the network contention level (i.e. number of active stations and length of the message transmitted on the channel) but it, at most, can estimate it. This paper presents and evaluates a distributed mechanism for the contention control in IEEE 802.11 Wireless LANs. Our mechanism, named Asymptotically Optimal Backoff (AOB), dynamically adapts the backoff window size to the current network contention level, and guarantees that an IEEE 802.11 WLAN asymptotically achieves its optimal channel utilization. The AOB mechanism measures the network contention level by using two simple estimates: the slot utilization, and the average size of transmitted frames. These estimates are simple and can be obtained by exploiting information that is already available in the standard protocol. AOB can be used to extend the standard 802.11 access mechanism without requiring any additional hardware. The performance of the IEEE 802.11 protocol, with and without the AOB mechanism, is investigated in the paper via simulation. Simulation results indicate that our mechanism is very effective, robust and has traffic differentiation potentialities.

Keywords: Wireless LAN (WLAN), IEEE 802.11, multiple access protocol (MAC), protocol capacity, performance analysis

1. Introduction

For decades Ethernet has been the predominant network technology for supporting distributed computing. In recent years, the proliferation of portable and laptop computers has led to LAN technology being required to support wireless connectivity ([For 94], [Imi 94], [Sta01]). The success of WLANs is connected to the development of networking products that can provide wireless network access at a competitive price. A major factor in achieving this goal is the availability of appropriate networking standards. IEEE Std 802.11 defines a Medium Access Control (MAC) and Physical Layer (PHY) specification for a Wireless Local Area (WLAN) network to provide wireless connectivity for fixed, portable, and moving stations within a local area [IEE97].

Two different approaches can be followed in the implementation of a WLAN: an infrastructure-based approach, or an ad hoc networking one ([Cha00], [Sta96]). An infrastructure-based architecture imposes the existence of a centralized controller for each cell, often referred to as Access Point. The Access Point is normally connected to the wired network thus providing the Internet access to mobile devices. In contrast, an ad hoc network is a peer-to-peer network formed by a set of stations within range of each other that dynamically configure themselves to set up a temporary network. The IEEE 802.11 technology can be used to implement both infrastructure[1] and ad hoc WLANs. Specifically, the IEEE 802.11 WLAN can be configured as a single-hop ad hoc network. In addition, it is emerging as one of the most promising technologies for constructing multihop mobile ad hoc networks [Cor99].

Currently, the most promising use of IEEE 802.11 technology is for constructing hot-spot services by adopting infrastructure-based configurations. The use of IEEE 802.11 based ad hoc networks is a medium-/long-term objective.

Hot spots are typically located in places where people meet such as: conference/meeting rooms, airport, shopping centers, etc. People come to the hot spot service area, power the terminal on, and then perform applications such as e-mail and www browsing.

Wireless communications, and (in the case of ad hoc networks) the lack of fixed infrastructures, generate new research problems compared with wired networks: dynamic topologies, limited bandwidth, energy-constrained operation, wireless vulnerabilities. Because nodes can move arbitrarily, the network topology can change randomly and rapidly. In addition, the number of mobile hosts belonging to the same WLAN can be highly variable. Consider, for example, a burst of users with mobile devices moving in the same meeting room at a given time instant, thus generating a sharp increase in the traffic of the corresponding WLAN. In a hot spot, the number of hosts connected to a WLAN may be large, and highly variable. Since the wireless links will continue to have significantly lower capacity than wired links, the WLAN congestion is more problematic than in wired networks.

In WLANs, medium access control (MAC) protocol is the main element that manages the congestion situations that may occur inside the network. For this reason in this paper we focus on the efficiency of the IEEE 802.11 MAC protocol, and we propose a solution for increasing both protocol efficiency and the protocol's ability to react to congestion conditions.

The IEEE 802.11 access scheme incorporates two access methods: Distributed Coordination Function (DCF) for asynchronous, contention-based, distributed access to the channel, and Point Coordination Function (PCF) for centralized, contention-free access ([IEE97], [Sta96]). PCF is intended to support real-time services (by using a centralized polling mechanism), but is not generally supported by current cards. Hereafter, we will concentrate our study on DCF only.

The DCF is based on a Carrier Sensing Multiple Access protocol with Collision Avoidance,

---

[1] In this case, it is the natural wireless counterpart of Local Area Networks, i.e., *Ethernet on the air*.

CSMA/CA, see for example ([Che94], [Ham88], [Tas86]). The CSMA/CA protocol is typically adopted in a wireless environment due to its reliability, flexibility and robustness. However, the performance of a WLAN based on the CSMA/CA protocol may be degraded by the presence of hidden terminals [Tob 75]. A pair of stations is referred to as being *hidden* from each other if a station cannot hear the transmission from the other station. This event makes the carrier sensing unreliable, as a station wrongly senses that the wireless medium has been idle while the other (hidden) station is transmitting. To avoid the hidden terminal problem, the CSMA/CA protocols are extended with a virtual carrier sensing mechanism, named *Request To Send* (*RTS*) / *Clear To Send* (*CTS*). This mechanism has been studied extensively; several variations and analyses of the RTS/CTS scheme can be found in the literature, see for example ([Bar94], [Gar96], [Ful97], [Gar99]). IEEE 802.11 includes an optional RTS/CTS mechanism. As explained in Section 2, in this paper we do not explicitly consider the RTS/CTS mechanism but we focus our study on the basic DCF access method.

The relevance of the IEEE 802.11 standard has generated extensive literature on its MAC protocol. A complete survey of the IEEE802.11 literature it is out of the scope of this paper. Below we will show the main research areas together with some related references. Simulation studies of the IEEE 802.11 protocol performance are presented in ([Wei97] [Ana00]). IEEE 802.11 analytical models are proposed and evaluated in ([Bia96], [Bia00], [Cal00a], [Cal00b], [Chh97], [Vis02a], [Vis02b]]). The use of the PCF access method for supporting real-time applications is investigated in ([Cou00], [Vee01]). The optimization of the DCF mechanism from the power-saving standpoint is investigated in ([Bon99], [Jun02]). Recently, considerable research activity has concentrated on supporting service differentiation on the IEEE 802.11 DCF access method (e.g., [Sob99], [Ver00], [Aad01], [Qia02]), and on the use of IEEE802.11 for constructing multi-hop ad hoc networks ([Xu01], [Xu02]) .

In this paper we propose and evaluate a mechanism, *Asymptotically Optimal Backoff* (*AOB*), for improving the efficiency of the IEEE 802.11 standard protocol. In the literature, it is extensively recognized that the backoff algorithm plays a crucial role in achieving a high aggregated throughput and a fair allocation of the channel to the stations, see [Bar94]. To meet this target the backoff value should reflect the actual level of contention for the media. The IEEE 802.11 adopts a binary exponential backoff protocol ([IEE97], [Goo85], [Ham88]) which does not always adequately guarantee the best time-spreading of the users' access for the current congestion level. Each station, to transmit a frame, accesses the channel within a random self-defined amount of time, whose average length depends on the number of collisions previously experienced by the station for that frame. When the network is congested, for each transmitted frame, a station must experience several collisions to increase the backoff window size thus achieving a time spread of transmission attempts adequate to the current congestion level. No experience from the previous transmitted frame is exploited. On the other hand, our AOB mechanism extends the binary exponential backoff algorithm of IEEE 802.11 to guarantee that the backoff interval always reflects the current congestion level of the system (in the standard backoff any new transmission assumes a low congestion level in the system). Our mechanism forces the network stations to adopt a backoff window size that maximizes the channel utilization[2] for the current network condition. There are two main factors that reduce the channel utilization: collisions and idle periods (introduced by the spreading of accesses). As these two factors are conflicting (i.e., reducing one causes an increase of the other), the optimal tuning of the backoff algorithm is approximately achieved by equating these two costs ([Cal98], [Cal00a], [Gal85]). Since these costs change dynamically (depending on the network load), the backoff should adapt to congestion variations in the system. Unfortunately, in a real case, a station does not have an exact knowledge of the network and load configurations but, at most, can estimate them. The most promising direction for improving backoff protocols is to obtain information of the network status through channel observation ([Ger77], [Haj82], [Kel85]). A great amount of work has been done on studying the information that can be obtained by observing the system's parameters ([Geo85], [Riv87], [Tsi87]). Our work follows the same direction of feedback-based protocols but provides original contributions as it is based on an analytical characterization of the optimal channel utilization, and uses a very simple feedback signal: slot utilization.

Several authors have investigated the enhancement of the IEEE 802.11 backoff protocol to increase its performance. In [Wei96], given the Binary Exponential Backoff scheme adopted by the Standard, heuristic solutions have been proposed for a better time spread of the transmission attempts.

In ([Bia96], [Bia00], [Cal98], [Cal00a], [Cal00b]) feedback-based mechanisms have been proposed for adapting the station backoff to the network congestion and maximizing channel utilization. Recently, these mechanisms have been generalized to achieve both optimal channel utilization and weighted fairness in a IEEE802.11 network with traffic streams belonging to different classes [Qia02]. All the feedback-based mechanisms cited above, are based on analytic models of an IEEE 802.11 network. These models provide the optimal setting of the backoff parameters for achieving the maximum channel utilization. Unfortunately, these methods require an estimation of the number of users in the system that could prove expensive, difficult to obtain and subject to significant error, especially in high contention situations [Cal00b]. The AOB mechanism proposed in this paper goes a step further:

i. by exploiting the analytical characterization of optimal IEEE 802.11 channel utilization presented in ([Cal00a]), we show that the optimal value is almost independent of the network configuration (number of active stations), and hence the maximum channel utilization can be obtained without any knowledge of the number of active stations;
ii. the AOB mechanism tunes the backoff parameters to the network contention level by using two simple and low-cost load estimates (obtained by the information provided by the carrier sensing mechanism): slot utilization and average size of transmitted frames;
iii. AOB extends the standard 802.11 access mechanism without requiring any additional hardware.

Specifically, AOB schedules the frames' transmission according to the IEEE 802.11 backoff algorithm but adds an additional level of control before a transmission is enabled. A transmission already enabled by the standard backoff algorithm is postponed by AOB in a probabilistic way. The

---

[2] In the literature, the maximum channel utilization is called *protocol capacity*, see [Con97]. For this reason, hereafter maximum channel utilization and protocol capacity are used interchangeably.

probability of postponing a transmission depends on the network congestion level, and is equal to one if the channel utilization tends to exceed the optimal value. The postponed transmission is rescheduled as in the case of a collision, i.e., the transmission is delayed by a further backoff interval.

In this paper, via simulation, we have extensively evaluated the performance of the IEEE 802.11 access scheme, with and without the AOB mechanism. The IEEE 802.11 performance has been investigated both in steady-state, and under transient conditions. Furthermore, we also investigate the mechanism robustness to errors and its potential for traffic differentiation.

The work is organized as follows: in Section 2 we present a brief explanation of the IEEE 802.11 standard, and we sketch the critical aspects connected to the contention level of the system. In Section 3 we present a simple mechanism to extend the 802.11 standard and in Section 4 we discuss its tuning. In Sections 5, 6 and 7 the AOB performance is deeply investigated via simulation. Section 8 discusses an AOB potential for traffic differentiation. Conclusions and future research are outlined in Section 9.

2. IEEE 802.11

In 1997, the IEEE adopted the first wireless local area network standard, named IEEE 802.11, with data rates up to 2Mbps [IEE97]. Since then, several task groups (designated by the letters *a*, *b*, *c*, etc.) have been created to extend the IEEE 802.11 standard [IEE802]. The task groups 802.11b and 802.11a have completed their work by providing two relevant extensions to the original standard. The 802.11b task group produced a standard for WLAN operations in 2.4 GHz band, with data rates up to 11 Mbps. This standard, published in 1999, has been very successful. Currently, there are several IEEE 802.11b products available on the market. The 802.11a task group created a standard for WLAN operations in the 5 GHz band, with data rates up to 54 Mbps. Of the other task groups, it is worth mentioning task group 802.11e (which attempts to enhance the MAC with QoS features to support voice and video over 802.11 networks), and the task group 802.11g (that is working to develop a higher speed extension to the 802.11b).

Hereafter, we only sketch the portions of the IEEE 802.11 standard that are relevant for this paper. A detailed description can be found in ([IEE97], [Bru02a], [Cro97]).

The IEEE 802.11 standard defines a MAC layer and a Physical Layer for WLANs. The basic access method in the IEEE 802.11 MAC protocol is the *Distributed Coordination Function* (DCF) which is a *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) MAC protocol. In addition to the DCF, the IEEE 802.11 also incorporates an alternative access method known as the *Point Coordination Function* (PCF) - an access method that is similar to a polling system and uses a point coordinator to determine which station has the right to transmit.

The DCF requires that every station, before transmitting, performs a Carrier Sensing activity to determine the state of the channel (idle or busy). If the medium is found to be idle for an interval exceeding the *Distributed InterFrame Space* (DIFS), the station continues with its transmission. If the medium is busy, the transmission is deferred until the ongoing transmission terminates. When the channel becomes idle, a Collision Avoidance mechanism is adopted. The IEEE 802.11 Collision

Avoidance mechanism is a *Binary Exponential Backoff* scheme ([IEE97], [Goo85], [Ham88], [Has96]). According to this mechanism, a station selects a random interval, called *backoff interval*, that is used to initialize a *backoff counter*.

When the channel is idle, the length of the time is measured in constant units (*Slot_Time*) indicated as slots in the following. The backoff interval is an integer number of slots and its value is uniformly chosen in the interval (0, *CW_Size*-1), where *CW_Size*, in each station, is a local parameter defining the current station *Contention Window* size. Specifically, the backoff value is defined by the following expression [IEE97]:

$$Backoff\_Counter = INT\left(Rnd(\;)\cdot CW\_Size\right) \quad ,$$

where *Rnd()* is a function which returns pseudo-random numbers uniformly distributed in [0..1).

The backoff counter is decreased as long as the channel is sensed to be idle, stopped when a transmission is detected on the channel, and reactivated when the channel is sensed to be idle again for more than a DIFS. A station transmits when its backoff counter reaches zero.

The Binary Exponential Backoff is characterized by the expression giving the dependency of the *CW_Size* parameter by the number of *unsuccessful transmission attempts* (*N_A*) already performed for a given frame. In [IEE97] it is defined that the first transmission attempt for a given frame is performed adopting *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:

$$CW\_Size(N\_A) = \min\left(CW\_Size\_MAX, CW\_Size\_\min\cdot 2^{(N\_A-1)}\right) \quad .$$

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 Inter Frame Space* (SIFS), which is less than DIFS.

If the transmission generates a collision[3], the *CW_Size* parameter is doubled for the new scheduling of the retransmission attempt thus further reducing contention.

The increase of the CW_Size parameter value after a collision is the reaction that the 802.11 standard DCF provides to make the access mechanism adaptive to channel conditions.

2.1 IEEE 802.11 congestion reaction

Figure 1 shows simulation data regarding the channel utilization of a standard 802.11 system running in DCF mode, with respect to the contention level, i.e. the number of active stations with continuous transmission requirements. The parameters adopted in the simulation, presented in Table 1, refer to the Frequency Hopping Spread Spectrum implementation [IEE97].

Figure 1 plots the channel utilization versus the number of active stations obtained in asymptotic conditions, i.e., we assume that the stations always have a frame to transmit. By analyzing the behavior

---

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

of the 802.11 DCF mechanism some problems could be identified. Specifically, the results presented in the figure show that the channel utilization is negatively affected by the increased contention level.

Table 1: System's physical parameters

parameter	value
Number of Stations (*M*)	variable from 2 to 200
CW_Size_min	16
CW_Size_MAX	1024
Channel transmission rate	2 Mb/s
Payload size	Geometric distribution (parameter *q*)
Acknowledgement size	200 μsec (50 Bytes)
Header size	136 μsec (34 Bytes)
SlotTime (t_{slot})	50 μsec
SIFS	28 μsec
DIFS	128 μsec
Propagation time	< 1 μsec

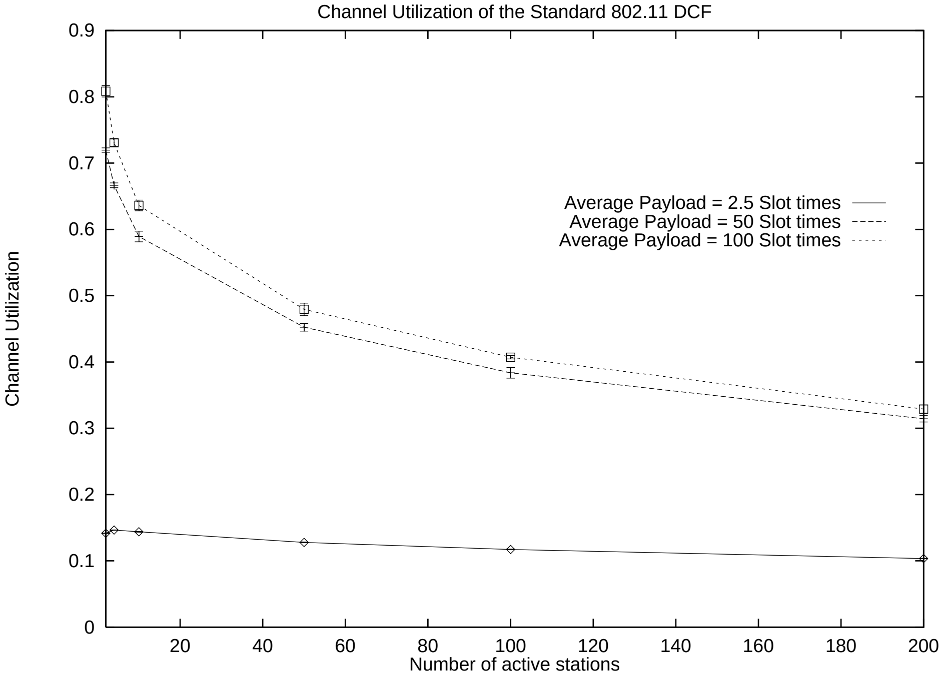

Figure 1: Channel utilization of the IEEE 802.11 DCF access scheme

These results can be explained since, in the IEEE 802.11 backoff algorithm, a station selects the initial size of the Contention Window by assuming a low level of congestion in the system. This choice avoids long access delays when the load is light. Unfortunately, this choice causes efficiency problems in bursty arrival scenarios, and in congested systems, because it concentrates the accesses in a reduced time window, and hence may cause a high collision probability. In high-congestion conditions each station reacts to the contention taking into consideration only the number of collisions already experienced while transmitting the current frame. Every station performs its attempts blindly, with a late collision reaction performed (increasing *CW_Size)*. Each increase of the *CW_Size* is obtained at the cost of a collision. It is worth noting that, as a collision detection mechanism is not implemented in the IEEE 802.11, a collision implies that the channel is not available for the time required to transmit the longest colliding packet. Furthermore, after a successful transmission the *CW_Size* is set again to the minimum value without maintaining any knowledge of the current contention level. To summarize, the IEEE 802.11 backoff mechanism has two main drawbacks: *i*) the increase in the *CW_Size* is obtained at the cost of a collision, and *ii*) after a successful transmission no memory of the actual contention level is maintained.

2.2 IEEE 802.11 RTS/CTS

To avoid the hidden terminal problem, and to improve its efficiency when long messages are transmitted, the IEEE 802.11 basic access mechanism is extended with an optional mechanism, called Request To Send (RTS) / Clear To Send (CTS), that provides a virtual carrier sensing. By adopting the RTS/CTS mechanism, after gaining access to the medium, and before starting the transmission of a frame, a short control packet, called RTS, is sent to the receiving station announcing the upcoming transmission. The receiver replies to this with a CTS packet to indicate its readiness to receive the data. RTS and CTS packets contain the projected length of the transmission. This information is stored by each active station that observes at least one of these two control packets. Therefore, all stations within the range of at least one of the two stations (receiver and transmitter) know how long the channel will be used for this data transmission, i.e., virtual carrier sensing. The tuning of the RTS/CTS mechanism is discussed in [Chh97].

In this work we do not explicitly consider the RTS/CTS mechanism. The results presented in our paper always refer to the data transmission using the basic access only. A methodology for analyzing the optimal tuning of the backoff algorithm when a portion of the traffic is transmitted using the RTS/CTS mechanism can be found for example in ([Bia00], [Bru02]). In addition, recent simulation and experimental results indicate that phenomena occurring at the physical layer make the effectiveness of the RTS/CTS mechanism arguable, since the hidden station phenomenon rarely occurs ([Van02], [Con02a]). These results indicate that the carrier sensing mechanism is still effective even if the transmitting stations are “apparently hidden” from each other. Indeed, a distinction must be made at least between transmission range, and carrier sensing range.

- The Transmission Range (TX_Range) represents the range (with respect to the transmitting station) within which a transmitted packet can be successfully received.
- The Physical Carrier Sensing Range (PCS_Range) is the range (with respect to the transmitting station) within which the other stations detect a transmission, i.e. channel busy.

Typically, the PCS_Range is greater than twice the TX_Range[4], and this is why the hidden-station phenomenon rarely occurs. The hidden station phenomenon is further reduced in infrastructure-based networks where all stations must be within the TX_Range of the access point, and hence all stations synchronized with the same access point should have a distance shorter than PCS_Range.

Finally, also in IEEE802.11 ad hoc networks, the usefulness of the current RTS/CTS mechanism is under discussion ([Xu01], [Xu02]).

---

[4] For example in the IEEE 802.11 model implemented in Ns2 (QualNet) the default values are TX_Range=250m (376m), and PCS_Range=550m (670m).

3. Low-cost dynamic tuning of the backoff window size

The drawbacks of the IEEE 802.11 backoff algorithm, explained in the previous section, indicate a direction for improving the performance of a random access scheme, by exploiting the information on the current network congestion level that is already available at the MAC level. Specifically, the utilization rate of the slots (*Slot Utilization*) observed on the channel by each station is used as a simple and effective estimate of the channel congestion level. The estimated Slot Utilization must be frequently updated. For this reason in [Bon00] it was proposed that an estimate be updated by each station in every *Backoff interval*, i.e., the defer phase that precedes a transmission attempt.

A simple and intuitive definition of the slot utilization (*S_U*) is then given by:

$$S\_U = \frac{Num\_Busy\_Slots}{Num\_Available\_Slots} \quad ,$$

where *Num_Busy_Slots* is the number of slots, in the backoff interval, in which a transmission attempt starts, hereafter referred to as *busy slots*. A transmission attempt can be either a successful transmission or a collision; and *Num_Available_Slots* is the total number of slots available for transmission in the backoff interval, i.e. the sum of idle and busy slots.

In the 802.11 standard mechanism every station performs a Carrier Sensing activity and thus the proposed *S_U* estimate is simple to obtain. The information required to estimate *S_U* is already available to an IEEE 802.11 station and no additional hardware is required.

The current *S_U* estimate can be used by each station (before trying a “blind” transmission) to evaluate the opportunity to either perform or defer its scheduled transmission attempt. In other words, if a station knows that the probability of a successful transmission is low, it should defer its transmission attempt. This can be achieved in an IEEE 802.11 network by exploiting the DCC mechanism proposed in [Bon00]. According to DCC, each IEEE 802.11 station performs an additional control (beyond carrier sensing and backoff algorithm) before any transmission attempt. This control is based on a new parameter named *Probability of Transmission P_T(...)* whose value depends on the current contention level of the channel, i.e., *S_U*. The heuristic formula proposed in [Bon00] for *P_T*(...) is:

$$P\_T(S\_U,\ N\_A) = 1 - S\_U^{N\_A}$$

where, by definition, S_U assumes values in the interval [0,1], and *N_A* is the number of attempts already performed by the station for the transmission of the current frame.

The *N_A* parameter is used to partition the set of active stations in such a way that each stations’ subset is associated with a different level of privilege to access the channel. Stations that have performed several unsuccessful attempts have the highest transmission privilege [Bon00].

The *P_T* parameter allows filtering the transmission attempts. When, according to the standard protocol, a station is authorized to transmit (backoff counter is equal to zero and channel is idle) in the protocol extended with the Probability of Transmission a station will perform a real transmission with probability *P_T*, otherwise (i.e. with probability 1-*P_T*) the transmission is re-scheduled, since a collision would have occurred, i.e. a new backoff interval is sampled.

To better understand the relationship between the *P_T* definition and the network congestion level, we can observe Figure 2.

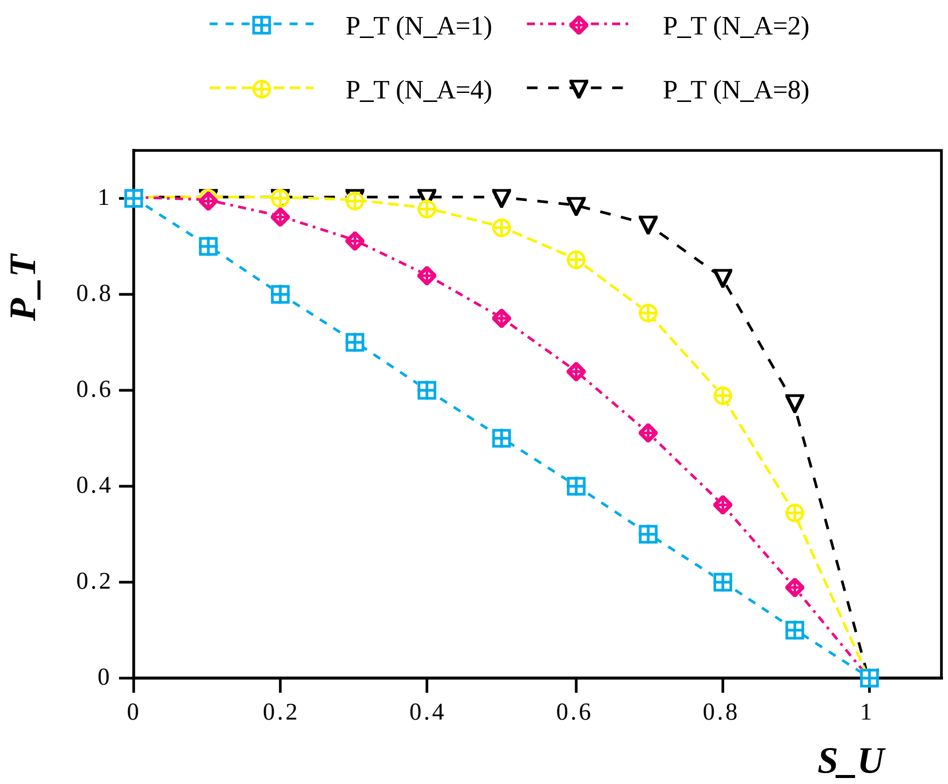

Figure 2: DCC Probability of Transmission

In Figure 2 we show the *P_T* curves (for users with different *N_A*), with respect to the estimated *S_U* values. Assuming *S_U* close to zero, we can observe that each station, independently of its number of performed attempts, obtains a Probability of Transmission (*P_T*) close to 1. This means that the proposed mechanism has no effect on the system, and each user performs its accesses as in the standard access scheme, without any additional contention control. This point is significant, as it implies the absence of overhead introduced in low-load conditions. The differences in the users' behavior as a function of their levels of privilege (related to the value of the *N_A* parameter) appear when the slot utilization grows. For example, assuming a slot utilization close to 1, say 0.8, we observe that the stations with the highest *N_A* value obtain a Probability of Transmission close to 1 while stations during the first transmission attempt transmit with a probability equal to 0.2.

It is worth noting a property of the DCC mechanism: the slot utilization of the channel never reaches the value 1. Assuming *S_U* close to or equal to 1, the DCC mechanism reduces the Probabilities of Transmission for all stations close to zero thus reducing the network contention level. This effect was due to the *P_T* definition, and in particular to the explicit presence of the upper bound 1 for the slot utilization estimate. The DCC choice to use 1 as the asymptotic limit for the *S_U* is heuristic and does not guarantee the maximum channel utilization. To achieve the maximum channel utilizatization we need to know the optimal congestion level, i.e. the optimal upper bound for the *S_U* value *(opt_S_U).* It is worth noting that, if *opt_S_U* is known, the *P_T* mechanism can be easily tuned to guarantee that maximum channel utilization is achieved. Intuitively, if the slot-utilization boundary value (i.e. the value one for DCC) is replaced by the *opt_S_U* value, we reduce all the probabilities of transmission to zero in correspondence with slot utilization values greater than or equal to the *opt_S_U*. This can be achieved by generalizing the definition for the Probability of Transmission:

$$P\_T(opt\_S\_U, S\_U, N\_A) = 1 - \min\left(1, \frac{S\_U}{opt\_S\_U}\right)^{N\_A} \qquad (1)$$

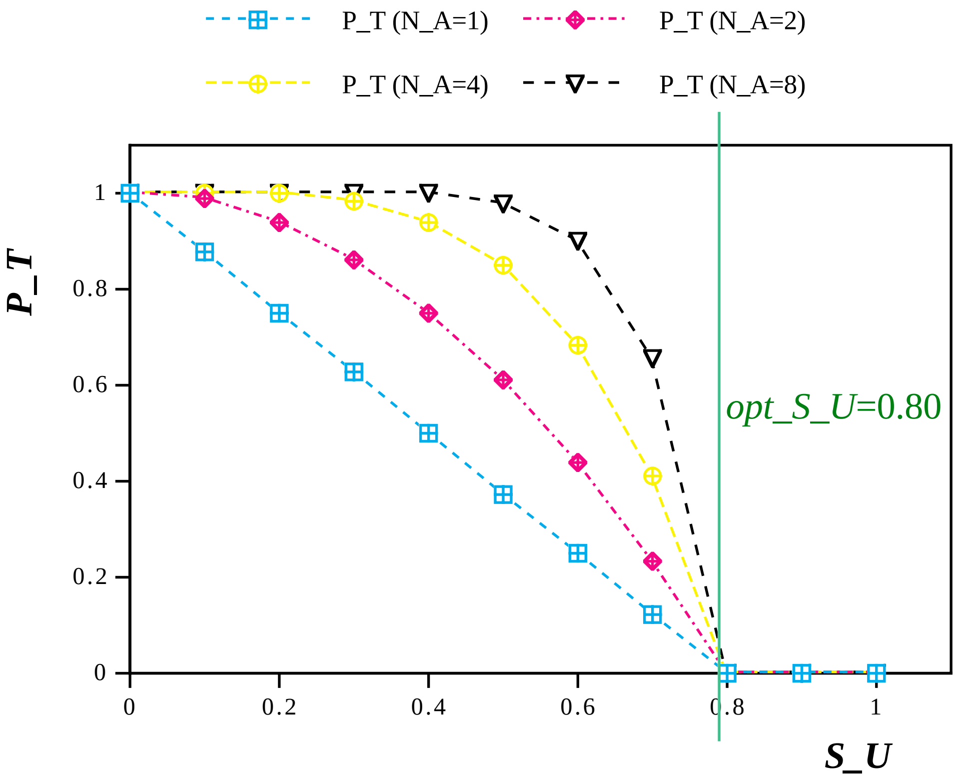

Figure 3: Generalized Probability of Transmission

Specifically, by applying this definition of the transmission probability we obtain the *P_T* curves shown in Figure 3. These curves were obtained by applying the generalized *P_T* definition with *opt_S_U*=0.80. As expected, the curves indicate the effectiveness of the generalized *P_T* definition to limit *S_U* to the *opt_S_U* value.

The generalized Probability of Transmission provides an effective tool for controlling the congestion inside an IEEE 802.11 WLAN in an optimal way, provided that the *opt_S_U* value is known.

In the following we will present a simple mechanism to set the *opt_S_U* value. Our mechanism is named Asymptotically Optimal Backoff as it guarantees that the optimal utilization is asymptotically achieved, i.e. for large *M* values.

4. Asymptotically Optimal Backoff (AOB) Mechanism

The aim of the AOB mechanism is to dynamically tune the backoff window size to achieve the theoretical capacity limit of the IEEE 802.11 protocol. The AOB mechanism is simpler, more robust and has lower costs and overhead introduced than the contention mechanisms proposed in ([Cal00a] and [Cal00b]). Specifically, the AOB mechanism requires no estimate of the number M of active stations. An accurate M estimate may be very difficult to obtain because M may be highly variable in WLANs.

In this section we exploit the results obtained from the analysis of the theoretical capacity limits of the IEEE 802.11 protocol to develop the AOB mechanism. For this reason, below we briefly summarize the results derived in [Cal00a].

In [Cal00a], to study the protocol capacity, it was defined a p-persistent IEEE 802.11 protocol. This protocol differs from the standard protocol only in the selection of the backoff interval. Instead of the binary exponential backoff used in the standard, the backoff interval of the p-persistent IEEE 802.11 protocol is sampled from a geometric distribution with parameter p. Specifically, at the beginning of an empty slot a station transmits (in that slot) with a probability p, while it defers the transmission with a probability 1-p, and then repeats the procedure at the next empty slot.[5] Hence, in this protocol the average backoff time is completely identified by the p value. By setting $p = 1/(E[B]+1)$ (where $E[B]$ is the average backoff time of the standard protocol[6]), the p-persistent IEEE 802.11 model provides an accurate approximation (at least from a capacity analysis standpoint) of the IEEE 802.11 protocol behavior [Cal00a].

The IEEE 802.11 p-persistent model is a useful and simple tool for analytically estimating the protocol capacity in a network with a finite number, M, of stations operating in *asymptotic conditions*. Furthermore, to simplify the discussion hereafter we assume that stations transmit messages whose lengths are a geometrically distributed (with parameter q) number of slots. By denoting with t_{slot} the length of a slot, the average message length, $\overline{m}$, is: $\overline{m} = t_{slot}/(1-q)$.

By exploiting the p-persistent model, in [Cal00a] it is derived a closed analytical formula for the channel utilization, ρ,

$$\rho = \overline{m}/f(M,p,q) \qquad (2)$$

By noting that $f(\;)$ is a function of the protocol and traffic parameters, it results that for a fixed network and traffic configuration (i.e., constant M and q), the maximum channel utilization corresponds to the p value, $p_{\min}$, that minimizes $f(\;)$.

Due to the correspondence (from the capacity standpoint) between the standard protocol, and the p-persistent one, the IEEE 802.11 maximum channel utilization is closely approximated by adopting in the standard protocol a contention window whose average size is identified by the optimal p value, i.e. $E[CW] = 2/p_{\min} - 1$.

The previous analysis shows that the IEEE 802.11 theoretical capacity is identified by $p_{\min}$. Hereafter, we will show the relationship between $p_{\min}$ and the *opt_S_U* value of the AOB mechanism. To this end we will further elaborate the capacity analysis presented in [Cal00a].

---

[5] On the other hand, in the standard protocol a station transmits in the empty slot selected uniformly inside the current contention window.

[6] Note that $E[B] = (E[CW]-1)/2$, where $E[CW]$ is the average contention window.

4.1 Theoretical capacity limits: an invariant figure

Results presented in this section (see Table 2) point out that the increase in the number of active stations has an almost negligible impact on the theoretical capacity bounds, while the average payload size (indicated as *MFS* in the following) greatly affects the optimal utilization level.

Results presented in Table 2 are numerically derived by computing the optimal p value, i.e. $p_{\min}$. according to formulas presented in [Cal00a] Specifically, in this table we report for various network and traffic configurations (defined by the (M, q) couples) the $p_{\min}$ values derived analytically as explained before. In this table we also report for each configuration the value $M{\cdot}p_{\min}$. It is worth noting that while $p_{\min}$ is highly affected by the M value, given a q-value, the product $M{\cdot}p_{\min}$ is almost constant. Specifically, results indicate that for a given message length, the product $M{\cdot}p_{\min}$ has an asymptotic value with respect to M. Furthermore, when M4, the $M{\cdot}p_{\min}$ values are very close to the asymptotic value. This is the reason for calling $M{\cdot}p_{\min}$ an *invariant figure*, i.e., for a given *MFS* it is almost constant.

Table 2: Optimal p values

q values	MFS (Slots)	$M = 2$		$M = 4$		$M = 10$		$M = 50$		$M = 100$	
		$p_{\min}$	$M \cdot p_{\min}$	$p_{\min}$	$M \cdot p_{\min}$	$p_{\min}$	$M \cdot p_{\min}$	$p_{\min}$	$M \cdot p_{\min}$	$p_{\min}$	$M \cdot p_{\min}$
0.5	2	.26160	.52321	.11679	.46715	.04430	.44304	.00864	.43206	.00431	.43076
0.9	10	.18260	.36521	.07880	.31520	.02945	.29448	.00570	.28518	.00284	.28409
0.96	25	.13293	.26586	.05638	.22552	.02091	.20914	.00404	.20186	.00201	.20101
0.98	50	.10053	.20106	.04221	.16883	.01559	.15591	.00300	.15018	.00149	.14952
0.99	100	.07434	.14868	.03097	.12388	.01140	.11403	.00219	.10968	.00109	.10918

Hereafter, we will analytically investigate the rational behind the $M{\cdot}p_{\min}$ quasi-constant value (for a given *MFS*). To perform this analysis, instead of the exact $p_{\min}$ derivation presented in [Cal00a] (it is too complex for our purpose), we approximate $p_{\min}$ with the p value that satisfies the following relationship:

$$E[Coll] = E[Idle\_p] \cdot t_{slot}\,, \qquad (3)$$

where $E[Coll]$ is the time the channel is busy due to a collision given that a transmission attempt occurs[7], and $E[Idle\_p]$ is the average number of consecutive idle slots observed on the channel. Equation (3) expresses the following condition: $p_{\min}$ is the p value that guarantees that the average time the channel is idle equals the average time the channel is busy due to the collisions.

Relationship (3) was proposed in[Gal85] for approximating the optimal operating point of CSMA protocols. In [Cal00b] this approximation was applied to IEEE 802.11. Recently, in [Con02b] it is analytically shown that (3) provides a very accurate approximation of $p_{\min}$.

By denoting with $p_{collision}$ the probability that a collision occurs given a transmission attempt, Equation (3) can be written as:

$$E[Coll]_{|collision} \cdot p_{collision} = E[Idle\_p] \cdot t_{slot} \qquad (4)$$

---

[7] *Coll* is equal to zero if the transmission attempt is successful otherwise it is equal to the collision length.

where $p_{collision}$ (i.e., the probability that two or more stations start transmitting at the same instant of time given that a transmission occurs) is given by

$$p_{collision} = \frac{1-(1-p)^M - Mp\cdot(1-p)^{M-1}}{1-(1-p)^M}$$

Closed expressions for $E[Coll]_{|collision}$ and $E[Idle\_p]$ are defined [Cal00a]. However, the $E[Coll]_{|collision}$ expression is quite involved, and hence we introduce the following approximation:

$$E[Coll]_{|collision} \approx E\left[\max\left\{L_x, L_y\right\}\right] \qquad (5)$$

where L_x and L_y denotes the length of two messages. To explain the above approximation, let us remember that, by denoting with N_{tr} the number of stations transmitting in the same slot, $E[Coll]_{|collision} = E\left[\max\left\{L_1, L_2, \ldots, L_{N_{tr}}\right\} \mid N_{tr} > 1\right]$. However, simulation results presented in [Cal00a] have shown that if the stations use *p*-values close to the optimal one, it is highly probable that a collision is caused by only two stations. It is also worth noting that (5) is exact if we have constant-length messages.

According to the approximation defined by (5), the average collision length is a function of the *q*-value, hence we can write $E\left[\max\left\{L_x, L_y\right\}\right] = l(q)\cdot t_{slot}$, where $l(q)$ is the average length (in slots) of a collision generated by two overlapping transmissions. Hence, if $p \neq 0$, Equation (4) can be written as:

$$l(q)\cdot\left[1-(1-p)^M - Mp\cdot(1-p)^{M-1}\right] = (1-p)^M \qquad (6.a)$$

By applying the Taylor formula, we have

$$\left[1-(1-p)^M - Mp\cdot(1-p)^{M-1}\right] \approx \frac{M\cdot(M-1)\cdot p^2}{2}, \text{ and}$$

$$(6.b)$$

$$(1-p)^M \approx 1 - Mp.$$

By substituting (6.b) in (6.a), and after simple algebraic manipulations, we obtain that the optimal *p* value is the solution of the following equation:

$$l(q)\cdot M\cdot(M-1)\cdot p^2 + 2\cdot Mp - 2 = 0 \qquad (6.c)$$

For large *M* values, $M\cdot(M-1) \approx M^2$, and (6.c) can be re-written as

$$l(q)\cdot(Mp)^2 + 2\cdot Mp - 2 = 0 \qquad (6.d)$$

Finally, by solving (6.d) we find that the maximum channel utilization is achieved if the following condition holds:

$$Mp_{\min}(q) = \frac{-1+\sqrt{1+2\cdot l(q)}}{l(q)} \qquad (6.e)$$

Equation (6.e) explains the behavior that we have observed by analyzing the numerical results of Table 2. Specifically, these results indicate that, for a given message length, the product $M\cdot p_{\min}$ has an asymptotic value with respect to *M*.

Equation (6.e) has been derived under some simplifying assumptions. Hereafter, we study how approximate $M \cdot p_{\min}(q)$ values obtained from (6.e) differ from the exact values reported in Table 2. To this end we need to derive $l(q)$

$$l(q) = \sum_{i_1=1}^{\infty} \sum_{i_2=1}^{\infty} \max\{i_1, i_2\} \cdot q^{i_1-1}(1-q) \cdot q^{i_2-1}(1-q) \quad .$$

After some algebraic manipulations $l(q)$ can be written as:

$$l(q) = \frac{1+2q}{1-q^2} \quad . \qquad (7)$$

Finally, by substituting (7) in (6.e) we obtain the results reported in Table 3.

Table 3 : Approximate optimal p values

q values	MFS (Slots)	$M \cdot p_{\min}$	$p_{\min}$				
			$M = 2$	$M = 4$	$M = 10$	$M = 50$	$M = 100$
0.50	2	0.5690	0.2845	0.14225	0.0569	0.0114	0.0057
0.90	10	0.3068	0.1534	0.0767	0.0306	0.0061	0.0031
0.96	25	0.2064	0.1032	0.0516	0.0206	0.0041	0.0021
0.98	50	0.1507	0.0753	0.0376	0.0151	0.0030	0.0015
0.99	100	0.1091	0.0545	0.0272	0.0101	0.0020	0.0011

Two main observations can be derived by comparing results in Tables 2 and 3:

1. The accuracy of the asymptotic estimation of $M \cdot p_{\min}(q)$ provided by Equation (6.e) increases with the increase of the message length. This can be expected since the main approximation in the estimate provided by (6.e) is related to the average collision length. As the message length increases, the collision cost becomes increasingly critical and to balance it with the idle-period length the optimal *p*-value decreases and this, in turn, reduces the probability of having more than 2 colliding stations.
2. Equation (6.e) is derived to provide an asymptotic (with respect to *M*) estimate of the optimal *p*-value. This means that $p_{\min}$ is derived by assuming a high-contention level. On the other hand, when there are few active stations (6.e) may provide a very conservative estimate of $p_{\min}$. For example with 2 active stations and messages with average length equal to 100 slots, the $p_{\min}$ obtained from (6.e) is 27% lower than the exact optimal *p*-value reported in Table 2. These errors are expected because for low *M* value the approximation $M \cdot (M-1) \approx M^2$ is very rough. The underestimation of the optimal *p*-value that may occur by adopting the asymptotic estimate of $M \cdot p_{\min}(q)$ can introduce an under-utilization of the system when only few stations are active. This does not seem to be a critical point because when there are few active stations the network bandwidth is not a critical resource.

We now investigate the relationship between $M \cdot p_{\min}(q)$ and the optimal S_U. As said before, $M \cdot p_{\min}(q)$ is derived assuming *M* active stations scheduling their transmission attempts in a slot selected according to a geometric distribution with parameter *p*. Furthermore, for each configuration an optimal value of parameter *p*, $p_{\min}$, exists that guarantees a balance on the channel idle periods and collisions. Furthermore, in Section 3 we introduce the *slot utilization* (S_U) parameter to estimate the network contention level. Let us now investigate the relationship between S_U and $M \cdot p_{\min}$.

To this end, let us consider a *p*-persistent IEEE 802.11 protocol in which each station uses the optimal value $p_{\min}$. 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 now observe that $M \cdot p_{\min}$ is the average number of stations which transmits in a slot:

$$M \cdot p_{\min} = \sum_{i=1}^{M} i \cdot P\{N_{tr} = i\} \geq \sum_{i=1}^{M} P\{N_{tr} = i\} = 1 - P\{N_{tr} = 0\} = S\_U \tag{7}$$

hence $M \cdot p_{\min}$ is an upper bound on the probability to observe a busy slot, i.e., $M \cdot p_{\min} \geq S\_U$.

Furthermore, by noting that

$$S\_U = 1 - P\{N_{tr} = 0\} = 1 - (1-p)^M = -\sum_{k=1}^{M} \binom{M}{k} (-p)^k \geq Mp - \frac{M \cdot (M-1)p}{2}$$

and by observing the optimal $M \cdot p_{\min}$ values reported in Table 3, we can conclude that $M \cdot p_{\min}$ is a tight upper bound of S_U. The accuracy of this approximation increases with the increase of the network congestion, i.e. number of active stations and/or message length.

4.2 The AOB mechanism

Results presented in Table 2 indicate that, for each *q*-value, the $M \cdot p_{\min}$ product results quasi-constant for *M* greater than 2, and hence it is possible to define a single quasi-optimal value for the $M \cdot p_{\min}$. To sum up, for each IEEE 802.11 physical layer parameters setting (e.g. see Table 1), it is possible to define a function of *q*, named *Asymptotic Contention Limit, ACL(q)*, such that $ACL(q) = M \cdot p_{\min}(q)$. This function would represent the optimal slot-utilization level the system should obtain to guarantee its optimal behavior from the channel utilization viewpoint. The *ACL(q)* function can be computed off-line using the analytical model presented in [Cal00a]. It is worth noting that *ACL(q)* identifies the optimal contention level without requiring any knowledge of the number of active stations in the system. This is important, because it is the basis for implementing an optimal window-tuning mechanism that does not require estimating the number of active stations in the system. The basic idea, as anticipated in Section 3, is *i*) to estimate *S_U*, and *ii*) to disable the stations' transmissions when *S_U* > *ACL(q)*. To this end, in the AOB, we use the generalized *P_T* mechanism (see Equation 1), and we set *opt_S_U(q)* equal to *ACL(q)*. Hence, in the AOB, the *P_T* formula is:

$$P\_T(ACL(q), S\_U, N\_A) = 1 - \min\left(1, \frac{S\_U}{ACL(q)}\right)^{N\_A} \tag{8}$$

Fixed a given *ACL(q)* value, the *P_T* values obtained fluctuates among 0 and 1. We named *Asymptotically Optimal Backoff* (AOB) a mechanism that, by using the *P_T* defined by Equation (8), guarantees a S_U value below the given *ACL(q)* value. The optimal slot utilization value (associated to ACL) can be only asymptotically achieved, for this reason the mechanism is named Asymptotically Optimal Backoff.

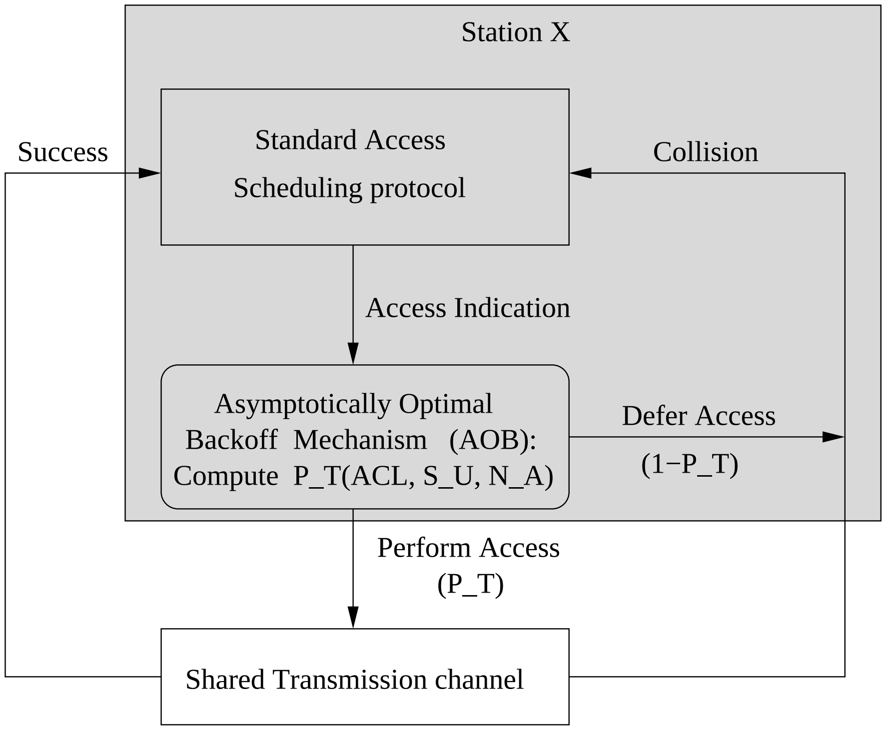

Figure 4: AOB and IEEE 802.11

To be effective, the AOB mechanism requires the knowledge of the *q* value to identify the *ACL(q)*. The *ACL(q)* value together with the current *S_U* estimate determines the transmission probability.

The *q* value depends on the characteristics of the traffic that is transmitted in the network. Two approaches exist to compute its value: static vs. dynamic approach. In the static approach the *q* value is computed by taking into consideration the characteristics of the Internet traffic [Ste 94]: on a byte count basis, 90% of the traffic is made up of maximum size packets (i.e. 512 bytes of user data) while the remaining 10% consists of very short packets (i.e. 10 bytes of user data). This approach is very simple but can introduce severe approximations on the real traffic that is transmitted in the network. Therefore, in this paper we prefer to adopt a dynamic approach: the *q* value is estimated by each station by observing the status of the channel through its carrier sensing mechanism. A dynamic approach, based on the channel status monitoring, is also used to obtain the current *S_U* estimate. The *q* and *S_U* estimation algorithms used hereafter to derive numerical results are reported in [Bon02]. In the that report we also discuss the *ACL(q)* computation.

It is worth noting that from a logical standpoint the AOB can be seen as a simple extension of the IEEE 802.11 mechanism (see Figure 4): each IEEE 802.11 transmission is deferred in a probabilistic way. However, this does not imply that AOB can be implemented on top of the standard protocol; indeed the mechanism is embedded within the standard protocol, since it requires information that is available inside the IEEE 802.11 network interface (backoff counter value, carrier sensing information, etc.). Hence its implementation is a simple extension of the IEEE 802.11 protocol implemented in existing products.

5. Effectiveness of the mechanism: steady-state analysis

In the remaining part of the paper, by means of the discrete event simulation, we extensively investigate the performance of the IEEE 802.11 protocol enhanced with the proposed AOB mechanism. Specifically, in this section we analyze the AOB behavior when the network operates under steady-state conditions. The protocol analysis in transient conditions and the protocol robustness are studied in the subsequent sections. The physical characteristics and parameter values of the investigated system are reported in Table 1.

The target of a MAC protocol is to share resources efficiently among several users. This efficiency is expressed by the protocol *capacity*. However, from the user standpoint, other performance figures are needed to measure the Quality of Service (QoS) that can be relied on. The most widely used performance measure is the delay, which can be defined in several forms, depending on the time instants considered during its measurement (access delay, queueing delay, propagation delay, etc.). A precise definition of the performance figures used to evaluate *capacity*, and user-requirements follows below.

5.1 Capacity analysis: the channel utilization level

The main target of this performance study is to investigate the relationship between the channel utilization level and the network contention.

Note that other interesting performance indices such as the Throughput and the Mean Access Delay are strongly correlated with the channel utilization level.

To perform this study we ran a set of simulation experiments with different M values. Active stations were assumed to operate in asymptotic conditions (i.e., with continuous transmission requirements). We used a maximum number of 200 active stations because the number of stations expected in the future could arrive at hundreds [Che94]. For example, a WLAN in a conference room in which the participants use mobile devices with a wireless interface.

The effectiveness of the proposed AOB mechanism is shown in Figure 5. This figure shows the channel utilization level achieved by adopting the AOB mechanism and compares this index with the analytically defined optimal utilization levels (OPT curves in the figure). The results show that the AOB mechanism drives an IEEE 802.11 network very close to its optimal behavior at least from the channel utilization viewpoint. Only a little overhead is introduced when only a few stations are active, as expected from the results presented in Section 4.1. It is worth noting that, with the AOB mechanism, the channel utilization remains close to its optimal value even in high-contention situations. In such cases, AOB almost doubles the channel utilization with respect to the standard protocol (compare results in Figure 1 with those in Figure 5).

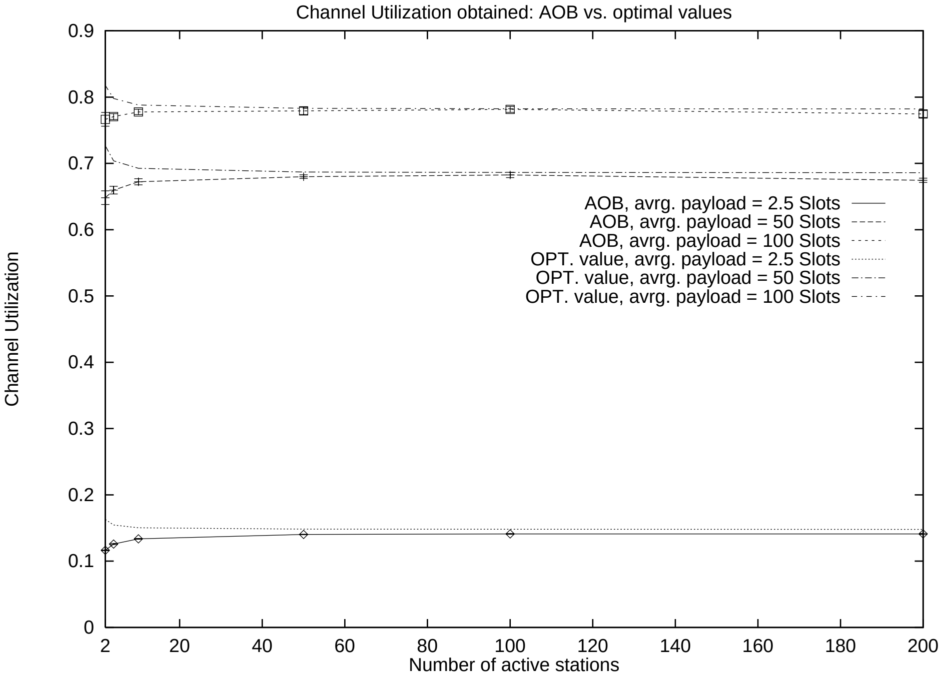

Figure 5: Channel utilization of the IEEE 802.11 protocol with the AOB mechanism vs. optimal value

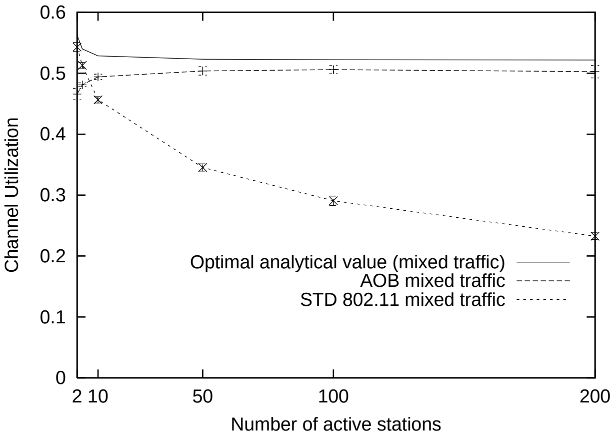

Figure 6: Channel utilization of the IEEE 802.11 protocol with and without the AOB mechanism vs. optimal value - mixed traffic conditions

The capacity analysis presented in Figure 5 was derived by assuming that the length of messages is sampled from a geometric distribution with parameter q. As previously stated before, studies of TCP traffic [Ste 94] show that, on a byte count basis, 90% of the traffic is made up of maximum size packets while the remaining 10% consists of very short packets. Hence, in a more realistic environment the message length distribution should be bimodal. We now evaluate the behavior of our protocol when the message length has a bimodal distribution. Specifically, we assume that “long messages” have an average length of 100 slots, while “short messages” have an average length of 2.5 slots, and a slot corresponds to 100 bits. The length of both classes of messages is geometrically distributed, and the percentage of long messages is denoted by π . Hereafter, we refer to this type of bimodal traffic as mixed traffic.

Figure 6 reports the protocol capacity of the IEEE 802.11 protocol with and without the AOB mechanism, when the message length has a bimodal distribution. To compare these results with theoretical bounds the average length of a message, $m(\pi)$, must be computed: $m(\pi) = 100 \cdot \pi + 2.5 \cdot (1 - \pi)$. Specifically, the analytical bounds are computed by assuming a single-class-message system in which the message length is geometrically distributed with average $m(\pi) = 20.401$ slots. These results confirm the results we obtained with the single-message-length traffic: *i*) the standard protocol becomes increasingly inefficient by increasing the network congestion (number of active stations), and *ii*) the AOB mechanism always maintains the IEEE 802.11 protocol close to its optimal behavior.

5.2 Performance analysis with On-off stations

The previous scenario analyzes the behavior of the AOB mechanism in an extreme situation in which all stations are always active. However, one may argue that in a more realistic situation each station alternates between active and idle periods, and hence:

i) the number of active-station changes in a continuous way;

ii) when idle, a station may not listen (e.g., for power-saving reason), and therefore, when it reactivates, it will not have a valid *S_U* estimate.

To analyze the AOB behavior in a more realistic scenario we modelled an IEEE 802.11 network in which each station alternates between idle and busy periods. Specifically, results presented in this section have been obtained by assuming that idle and busy periods have the same average length. A station consecutively transmits *K* frames (where *K* is geometrically distributed), and then enters an idle period during which it loses its memory of the previous estimations of the Slot Utilization and average message length.[8]

Results obtained with this on-off model are presented in Figure 7. The experiments were performed by assuming on-off periods with an average length of 10 or 20 frames. As no significant difference was observed for the two sets of experiments, in the figure we report only one curve tagged On/Off.

In the figure we have two sets of curves corresponding to short messages (average 2.5 slots) and long messages (average 100 slots), respectively. For each set of curves we plot: i) the theoretical optimal value (Optimum utilization), ii) the channel utilization with AOB and always on stations, iii) the channel utilization with AOB and on-off stations (On/Off), and *iv*) channel utilization with the standard protocol and On-Off sources (Std 802.11 On/Off).

---

[8] The length of the idle period is sampled from a geometric distribution whose average is equal to the length of the previous busy period.

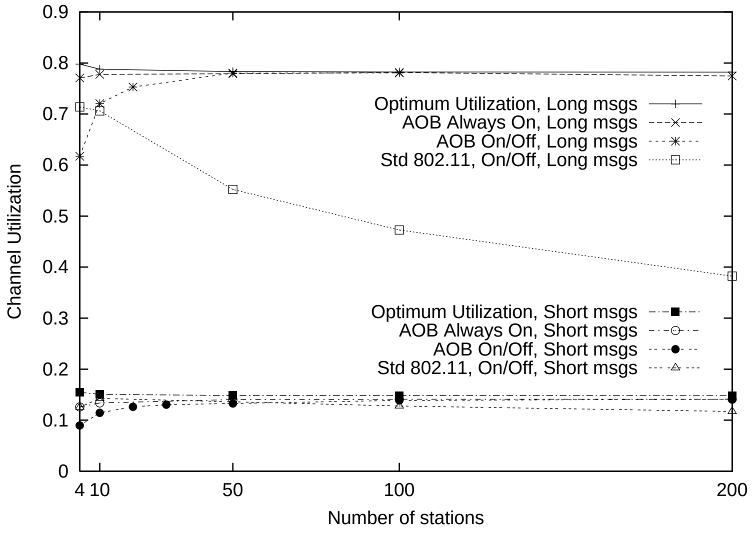

Figure 7: Channel utilization with on-off sources

Numerical results reported in the figure indicate that with 20 (or more) stations in the network the channel utilization with AOB is quasi-optimal. On the other hand, with few active stations we observe a small degradation in AOB efficiency. This is caused by two main reasons:

i. the AOB mechanism is tuned to asymptotically converge (i.e., M large) to the optimal value. Numerical results presented in the previous sections have indicated that with few (continuously) active stations a deviation from the optimal is expected. With on-off sources, on average, only half of the stations are active.
ii. when a station re-activates after an off period, it may have no estimate of the current slot utilization. In AOB we have adopted a conservative assumption: the station, when reactivates, assumes a slot utilization equal to the ACL(q) value, where q corresponds the length of the frame it has to transmit. This assumption helps to preserve the system's stability under highly congested conditions, but causes some possible bandwidth wastage with few active intermittent stations.

To summarize, the above results indicate that AOB is also effective with on-off sources. Slight deviations from the optimal channel utilization are possible when the network is not congested (i.e., few active stations).

5.3 The 99-th percentile of MAC access delay

The channel utilization provides information about the efficiency of a MAC protocol in sharing the channel among several stations. However, from the user standpoint other performance figures are needed to measure the Quality of Service (QoS) a user can rely on. The most widely used performance measure is the delay, which can be defined in several forms, depending on the time instants considered during its measurement (access delay, queuing delay, propagation delay, etc.). In computer networks the response time, defined as the time between the generation of a message at the sending station and its reception at the destination station, is the best figure to measure the QoS perceived by the users. However, it depends on the amount of buffering inside the network and it is not always meaningful to evaluate a LAN technology. For example, during congested periods, the buffers fill up and the response time is mainly a function of the buffer length. For this reason, in this paper, we will focus on the MAC delay. The MAC delay of a station in a LAN is the time between the instant in which a packet comes to the head of the station transmission queue and the end of the packet transmission [Con97].

In Figure 8 we report the 99-th percentile of the MAC delay vs. contention level (i.e. number of active stations) for various average sizes of the transmitted frames. By comparing AOB and the standard IEEE802.11, simulation results show that the AOB mechanism greatly reduces the tail of the MAC delay distribution.

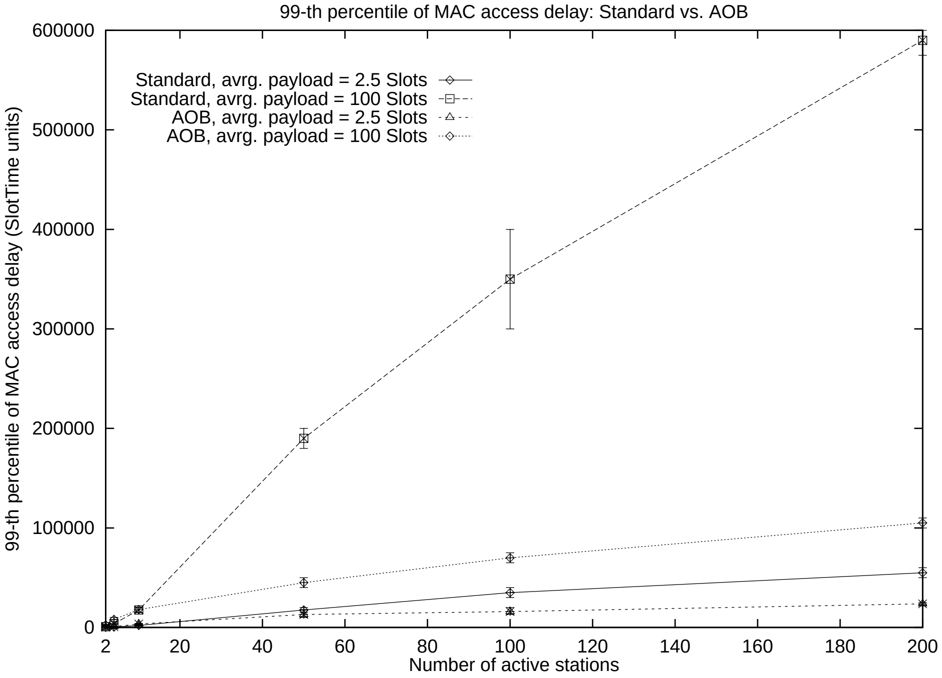

Figure 8: 99-th percentile of MAC delay

By noting that when the network operates in asymptotic conditions the average MAC delay is the inverse of the station throughput, we can verify that AOB is really effective in reducing the tail of the MAC Delay. For example, with 100-slot average payload, the ratio between the 99-th percentile of the MAC Delay with and without the AOB mechanism is about 6 while the ratio between the average MAC Delay is only about 2. This means that AOB enhances the fairness and reduces the risk of stations' starvation.

6. AOB behavior in transient situations

In this section we analyze the protocol promptness to re-tune when the state of the network sharply changes. Specifically, we investigate the *AOB* behavior when there is an upsurge in the number of active stations.

6.1 Change in the number of active stations

In this section, we analyze a network operating in steady-state conditions with 10 (100) active stations.

After 256 block units[9] (highlighted by the vertical bar “burst arrival time”), an additional 10 (100) stations become active. All stations transmit mixed traffic. Figures 9 and 10 show the effectiveness of the AOB mechanism. In the AOB case, the sharp increase in the number of active stations produces a negligible effect both in the slot utilization and in the channel utilization. Viceversa the standard is negatively affected by this change: the slot utilization increases sharply (i.e., the network congestion level increases) and as a consequence the channel utilization decreases.

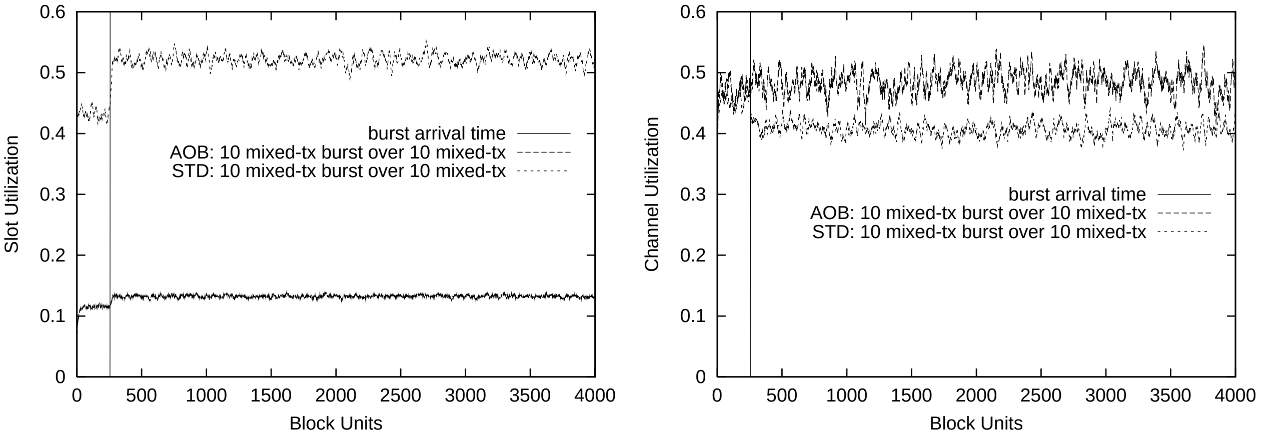

Figure 9: A burst of 10 new stations is activated when the network is operating in steady-state conditions with 10 active stations

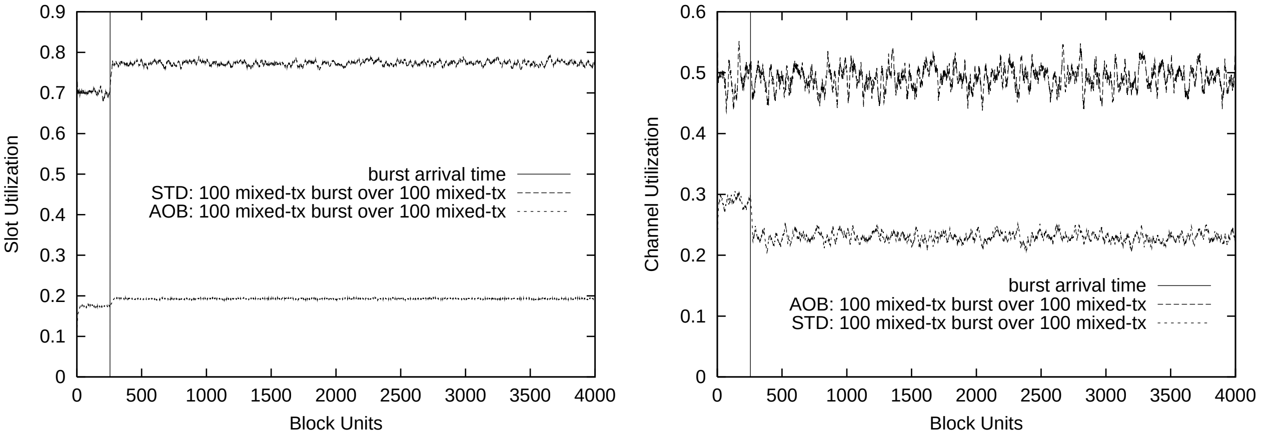

Figure 10: A burst of 100 new stations is activated when the network is operating in steady-state conditions with 100 active stations

6.2 Change in the number of active stations and in the network traffic

In this subsection, we investigate the AOB mechanism’s ability to react to sharp changes both in the M value and in the traffic characteristics. Specifically, we start from a system operating in steady-state conditions with M=100 (or M=10). The stations are homogeneous from the traffic standpoint: all stations transmit long (short) messages. Message length is sampled from a geometric distribution with average 2.5 and 100 slots for short and long messages, respectively.

In the following we use this notation: STND and AOB denote the standard protocol without and with the AOB mechanism, respectively. In addition, *N Long-tx* (*Short-tx*) indicates that there are *N* stations

---

[9] A block unit corresponds to 512 slots. The block unit is introduced to smooth the trace. The smoothing was introduced to reduce the fluctuations and thus increasing the figure’s readability.

that transmit only long (short) messages. For example, the legend "AOB: 100 Long-tx burst over 100 Short-tx" means that: *i*) the AOB mechanism is used, *ii*) the system is initially in a steady-state condition with 100 active stations all transmitting short messages, and *iii*) after 256 block units (highlighted by the vertical bar "burst arrival time"), 100 additional stations are activated and all the newly activated stations are transmitting long messages. Note that if we omit the type of messages transmitted by the active stations this means that results do not depend on message length.

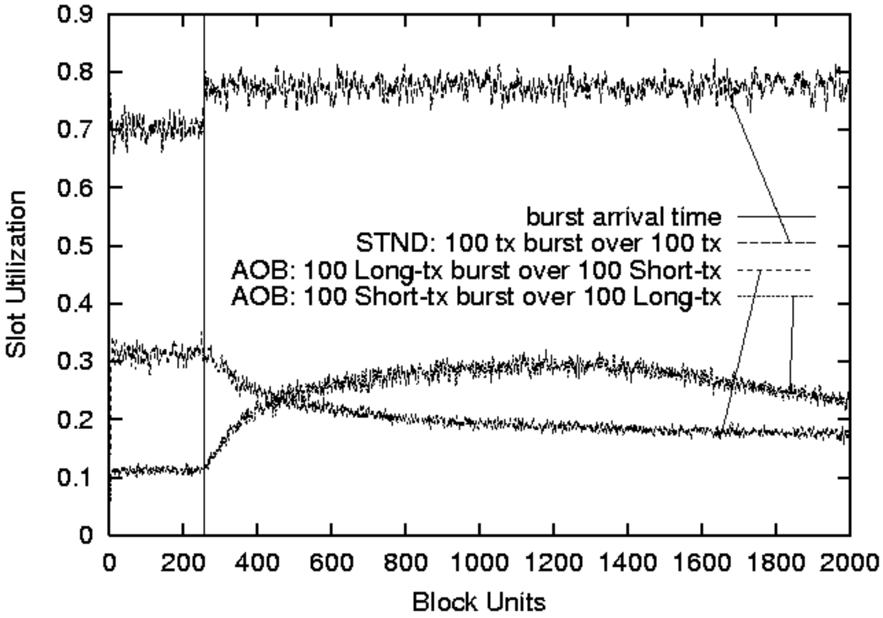

Figure 11: S_U evolution when the network traffic sharply changes (*M* changes from 100 to 200)

Figure 11 shows how a change in the number of active stations affects the slot utilization. In the period before the burst arrival time the protocol with the AOB mechanism is operating with a slot utilization value that depends on average message length, and in both cases it is very close to the boundary theoretical value (see Table 2). Without AOB, the network slot utilization is much higher and this means a highly congested network. Furthermore, without AOB, immediately after the burst arrival the slot utilization increases further. When AOB is used, the behavior is very different. Specifically, the slot utilization remains much lower with respect to the standard protocol, and after a transient period in both analyzed scenarios, the same steady-state condition is reached; the new steady-state is close to the ideal slot utilization value for a system with mixed traffic. Hence, the AOB curves show the effectiveness of this mechanism in controlling the slot utilization thus limiting network congestion. The apparently "strange" behavior, during the transient period, of the curve tagged "AOB: 100 Short-tx burst over 100 Long-tx" can be explained by looking at Figure 12. Specifically, the curves in Figure 12 indicate that the arrival of the burst sharply reduces the channel utilization. The reduced channel utilization is below that of the standard protocol. During this phase, when AOB is used, only short messages are transmitted. This is due to the *q* estimation algorithm in the newly activated stations (see [Bon02]). These stations do not have enough estimates of the network status, and hence they assume that the network traffic is homogeneous with their own, i.e., short traffic. As a consequence, the newly activated "short" stations adopt an ACL value that is higher than that of the already active "long" stations; in this way the short stations have a priority in accessing the channel. The use of a high ACL value by short stations also explains why in Figure 11 the *S_U* after the short-station arrival starts to increase. During the initial transient phase (up to 1200 block units, in Figure 12), only short messages are transmitted and the channel utilization is close to the optimal value for this class of traffic. After this initial phase, long messages start to be transmitted again and the channel utilization increases towards the optimal value for the mixed traffic conditions. The short-station priority effect disappears and a new steady-state condition is achieved when both classes of stations get the same view of the channel status (slot utilization, average message length, etc.).

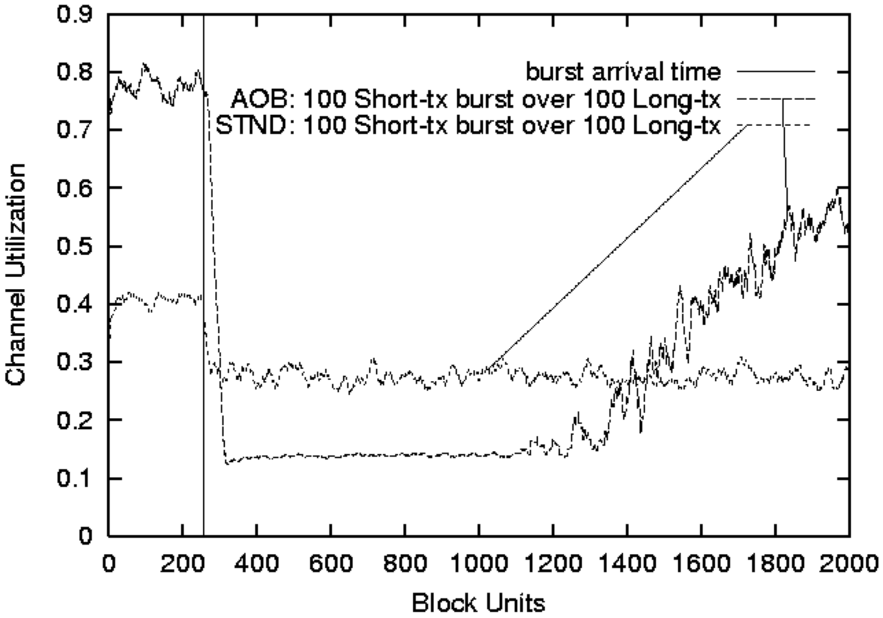

Figure 12: Sharp traffic change: 100 "short" stations over 100 "long" stations

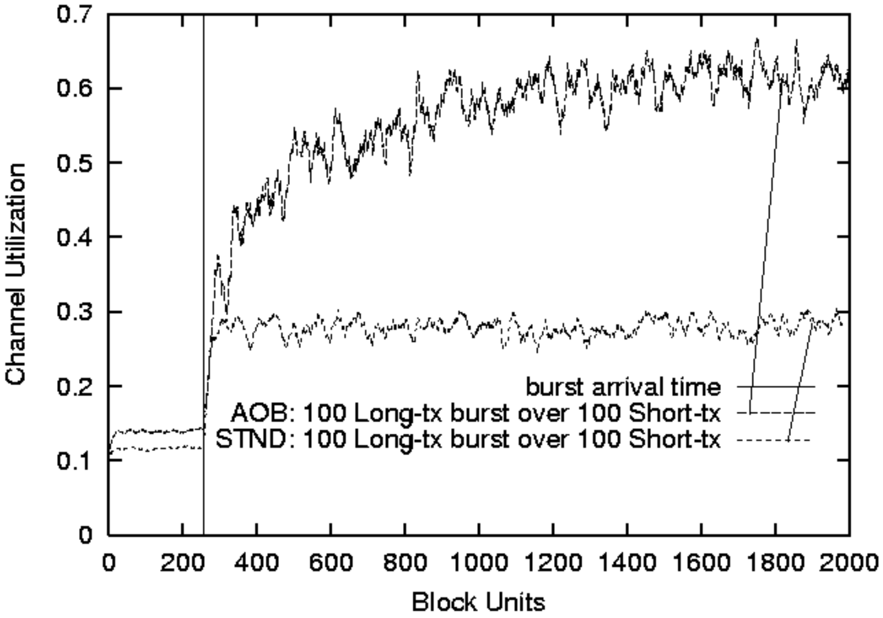

Figure 13: Sharp traffic change: 100 "long" stations over 100 "short" stations

The system behavior in the reverse case (in which a burst of long stations arrives when the system is in

a steady-state with short stations only) it is easier to explain, see Figure 13. In this case, long messages do not get priority with respect to short messages. Indeed long stations slowly start to transmit (and hence the channel utilization increases) when their view of the channel status becomes appropriate.
To summarize the AOB mechanism provides a temporary priority to short-messages bursts. This seems to be a good feature since short messages are typically generated by interactive applications (delay sensitive). These applications generate bursty traffic that rarely saturates the channel.

Previous results that were obtained by assuming 100 active stations are also confirmed by results presented in Figure 14, which were obtained by assuming a smaller set of active stations. Specifically, in Figure 14 we plot the S_U figures when the number of active stations changes from 10 to 20.

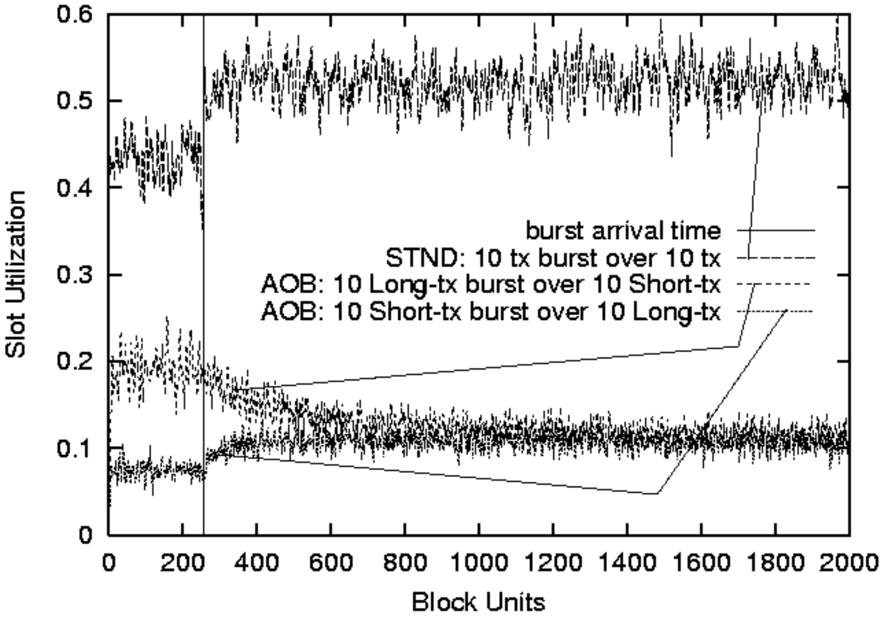

Figure 14: *S_U* evolution when the network traffic sharply changes (*M* changes from 10 to 20)

7. Protocol Robustness

In this section we discuss the robustness of the protocol by investigating the impact on the protocol performance of different types of errors. Specifically, in Section 7.1 we analyze the impact of the bit error rate of the channel , while in Section 7.2 we investigate the impact of the errors that may occur in the *q* and *S_U* estimates.

7.1 Sensitiveness to errors on the wireless medium

The protocol analysis presented so far assumes an ideal wireless channel: no channel errors. This assumption is unrealistic in wireless communications, in which (due to fading, interference, etc.) the probability that a bit is corrupted is randomly high and produces correlated losses [Cha00]. In this section we evaluate the impact of channel errors on our protocol. A Gilbert model (at the bit level) provides a simple and effective characterization of the wireless medium [Gil60]. This model has the advantage of analytical tractability, and the ability to capture the burstiness in the bit error rate. Specifically, the Gilbert model characterizes the channel status by a two-state (*Good* and *Bad*) continuous time Markov chain. When the Markov chain is in the *Good* state the Bit Error Rate (*BER*) is zero, while the BER significantly increases in the *Bad* periods. In *Bad* periods, if not explicitly specified, it is assumed $BER = 10E-4$. We denote with T_B and T_G the time spent by the Markov chain in the *Bad* and *Good* state, respectively. T_B and T_G are exponentially distributed random variables with average t_B and t_G. All the results presented in this section are obtained by assuming a constant value for t_B/t_G equal to 0.1.

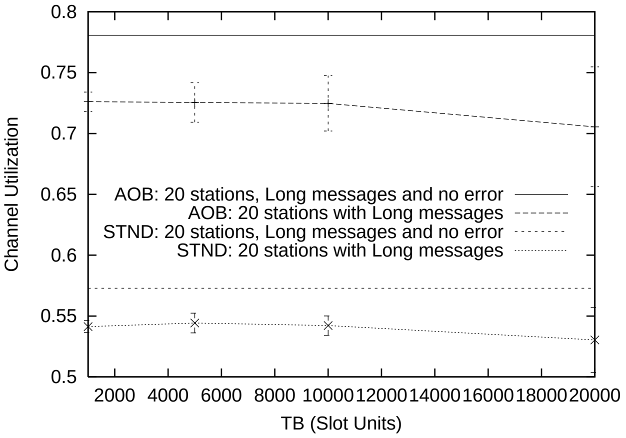

Figure 15: Impact of errors' burstiness

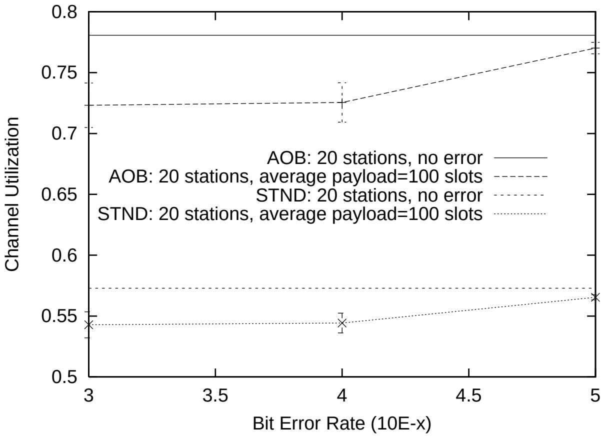

Figure 16: Impact of BER values

In Figure 15 we investigate the impact of the errors' burstiness on the channel utilization. The figure clearly indicates a low sensitivity to channel errors. Specifically, the figure shows that the standard protocol and the AOB protocol have the same percentage degradation in channel utilization that is about 10%. This figure can be easily explained because in the *Bad* periods there is a high probability of packets being lost. This explanation is also confirmed by results presented in Figure 16 in which we compare the channel utilization achieved with several BER values in the *Bad* periods (t_B is assumed equal to 5000 slots). As indicated by the figure, BER values higher than 10E-4 do not produce any further negative impact (with respect to BER=10E-4) because for BER values greater or equal to 10E-4 all packets are lost during the *Bad* periods. On the other hand, the impact of errors on the protocol capacity becomes negligible when the BER decreases of one order of magnitude down to 10E-5.

7.2 Estimation Errors

The AOB mechanism, to tune the backoff algorithm, requires a knowledge of the network status that is identified by two parameters: the average message length (or equivalently the *q*-parameter) and the slot utilization. As the values of these parameters are obtained through estimations some errors may occur. Hereafter, we discuss the sensitivity of AOB to these possible errors. Therefore, we compare the channel utilization in the ideal case (no estimation errors) with the channel utilization when an error is added/subtracted to the correct *q* and *S_U* estimate. Specifically, in the following figures, the curve tagged with +*x*% (-*x*%) error is obtained by multiplying by 1+*x*/100 (1-*x*/100) the real estimate of the parameter. Results obtained are summarized in Figures 17 (errors on *q* by assuming an average message length equal to 100 slots, i.e., *q*=0.99) and 18 (errors on *S_U*). These results indicate that the AOB channel utilization is scarcely affected by estimation errors. For example, assuming constant errors of 50%, the channel utilization fluctuates in a small interval (2-3%) around the no-error value. It is worth noting that due to the way AOB is defined: *i*) for large *M*, errors always have a negative impact (AOB is tuned to optimize asymptotic performance), *ii*) for few active stations, underestimation errors generate a channel utilization that is higher than that obtained in the no-error case. The latter behavior was expected because the ACL value is too conservative (i.e., it excessively limits the transmission rate) when there are few active stations (see Section 4.1). The underestimation of parameters produces the opposite effect, thus resulting in an increased channel utilization.

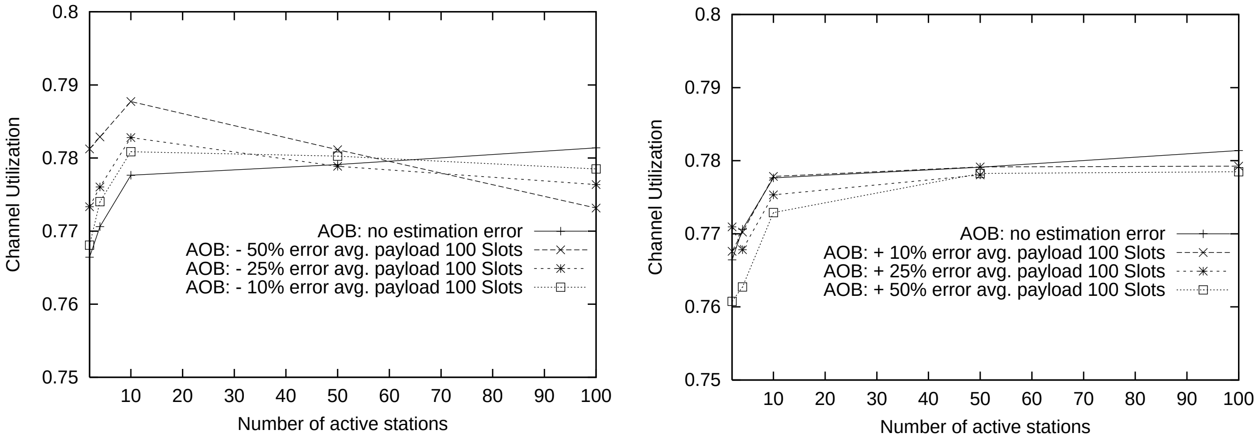

Figure 17: Sensitivity to errors in the estimation of the average message length

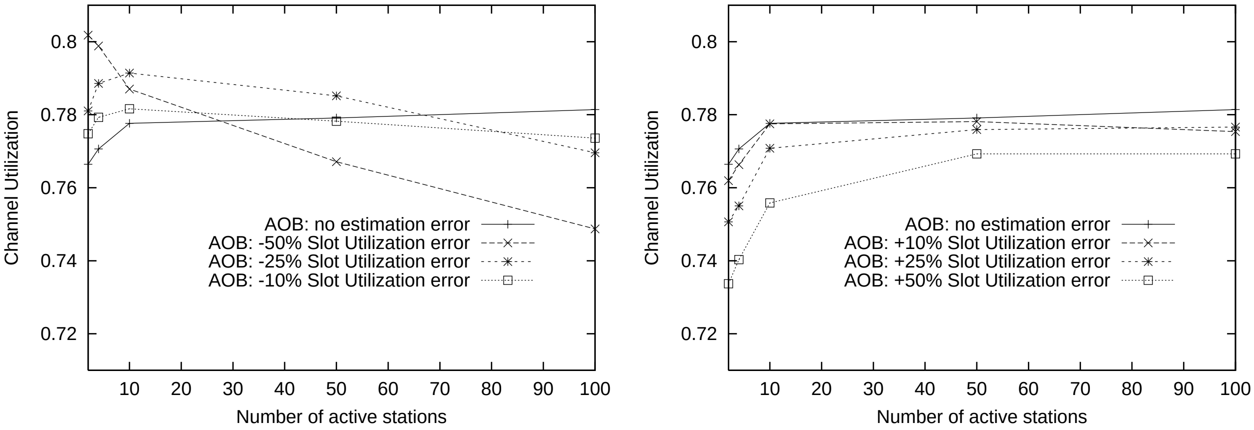

Figure 18: Sensitivity to errors in the estimation of the Slot Utilization

8. AOB potential additional features

The AOB mechanism can be extended to provide enhanced services to its users. These include power-saving features and supporting of differentiated services. AOB power-saving features are investigated in [Bon99]. Hereafter, we briefly discuss the ability of AOB to support traffic differentiation by introducing priorities in the access to the channel.

8.1 Traffic Differentiation

The Differentiated Services concept is currently the most promising solution to support better than best effort services. According to this concept, service differentiation must be provided by each hop with minimal control and signalling.

Wireless LANs are emerging as one of the most important technologies for the first hop in Internet access. Therefore, it is also important that they offer mechanisms for traffic differentiation.

Service differentiation in IEEE802.11 is currently a hot research area. Several proposals exist aimed at modifying the backoff algorithm for achieving differentiated quality of service on top of the DCF access method. One of the main directions for service differentiation is to adopt a backoff window size that depends on the traffic class. Specifically, in ([Ver00] and [Aad01]) it was proposed to use different ranges of the backoff window size, depending on the traffic class, to provide small backoff intervals for the high quality traffic classes. The decrease of the backoff interval corresponds to increasing a station priority. This effect can easily be obtained in AOB by extending it with a priority mechanism. Specifically, AOB extension with priority can be obtained with a simple change in the *Probability of transmission* definition (see Section 3). By adding a local parameter, named *Priority Level* (*Pr_Lev*), each station selects the priority level for each frame it transmits:

$$P\_T(opt\_S\_U, S\_U, N\_A, Pr\_Lev) = 1 - \min\left(1, \frac{S\_U}{opt\_S\_U}\right)^{N\_A \cdot Pr\_Lev} .$$

When the *Priority Level* parameter is greater than 1, the station's probability of transmission is higher than that it would have with the pure AOB mechanism.

As the mechanisms proposed in ([Ver00] and [Aad01]), the AOB mechanism guarantees that the higher the priority of a class, the smaller its window size. An advantage of AOB is the dynamic nature of the backoff tuning mechanism. This guarantees that, when only low priority traffic is present in the network, its performance is optimized. On the other hand, by adopting static window sizes (see, e.g., [Ver00]) the network performance cannot always achieve the optimal values.

In the following we present simulation results to confirm the effectiveness of the priority mechanism for improving the QoS experienced by high-priority traffic. As we have said before, the AOB priority mechanism is dynamic. Under light load conditions the priority effect is negligible, since in this case the slot utilization is low, and the *Probability of transmission* is always close to 1. The priority mechanism becomes effective in congested scenarios. For these reasons we have performed a set of simulation experiments with stations operating in asymptotic conditions. Figure 19 shows the ability of AOB priority mechanism to differentiate the throughput of each class. Several experiments have been performed by assuming a network with *X* stations transmitting only traffic at priority level 1, i.e. no priority. In addition, in the network there are 4 stations, all transmitting traffic with the priority level *h* (Pr_Lev=*h, h*=1, 2, 3, 5, 10). Specifically, the curve tagged Pr_Lev=*h* indicates the ratio between the average throughput of a priority-*h* station and that of a priority-1 station in a network with 4 stations with Pr_Lev=*h* and *X* stations with Pr_Lev=1 (*X* is the value on the *x*-axis). Numerical results show the throughput-differentiation effect of the Pr_Lev parameter: by increasing the priority level we obtain an increase of the station throughput. For example, for a Pr_Lev=10 the throughput is much higher than that achieved by stations with Pr_Lev=1 (the ratio is in the range [20, 50]).

It is worth pointing out that the AOB priority mechanism provides traffic differentiation without degrading the channel utilization. This is clearly shown in Figure 20 in which we compare the channel utilization achieved by adopting the AOB priority mechanisms with that achieved by the pure AOB mechanism with no priority (i.e., all stations transmitting with Pr_Lev=1). For completeness, in the same figure we also report the channel utilization of the standard 802.11 protocol. The efficiency of the priority mechanism (with long or short transmitted frames) is investigated in two configurations:

- 4 stations with priority level 10, 4 stations with priority level 5, and X stations with priority level 1 (curve tagged AOB: Pr_Lev=5 and 10);
- 4 stations with priority level 3, 4 stations with priority level 2, and X stations with priority level 1 (curve tagged AOB: Pr_Lev=2 and 3).

As clearly shown in the figure, the priority mechanism does not introduce any overhead as it is always very close to the pure AOB mechanism (curve tagged Pr_Lev=1)

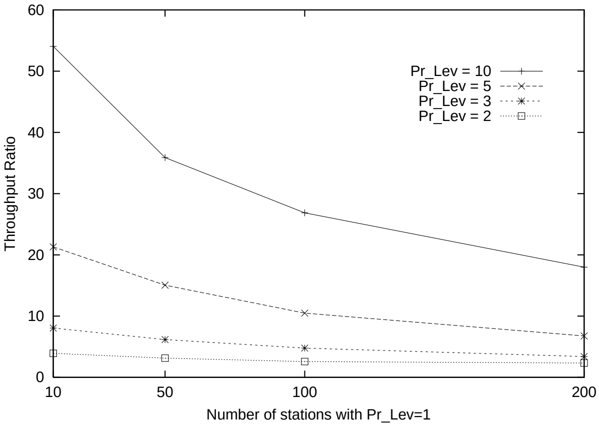

Figure 19: Throughput differentiation

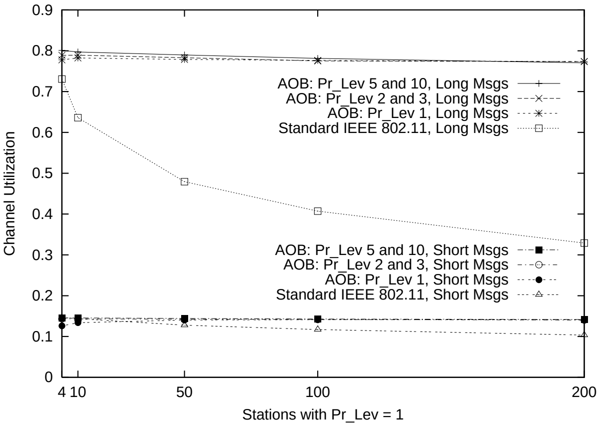

Figure 20: Impact on channel utilization

Service differentiation not only requires a differentiation of the throughput between traffic classes, but should be able to provide lower transfer delays to the higher priority classes. As we have said before, in this paper we use the MAC delay as the delay performance index. Results reported in Figures 21 and 22 point out the ability of the AOB priority mechanism to differentiate the MAC delays between priority classes. Specifically, in Figure 21 we considered a congested network with 200 stations, with priority level 1, continuously transmitting traffic; in addition we have 4 stations transmitting traffic with priority h. The curve tagged Pr_Lev=h represents the MAC delay distribution of the priority h traffic when in the network there are also 200 stations transmitting with priority level 1. For comparison, in the same figure we also plot the MAC delay distribution achieved in a network with 204 stations transmitting according to the standard (curve tagged Std 802.11), or to the pure AOB (curve tagged AOB, no priority). The curves show that priority mechanism significantly reduces the tail of the MAC delay distribution for the high priority classes.

In Figure 22 the MAC delay analysis is extended to a network configuration with three different traffic classes corresponding to Pr_Lev equal to 1 (200 stations), 5 (4 stations), and 10 (4 stations). The figure clearly shows that a significant improvement in the MAC delay of the high priority classes is achieved by increasing the delay experienced by the low priority class. Indeed, with respect to the no-priority case, the MAC delays of the high-priority classes (i.e., 5 and 10) are shorter than those achieved with pure AOB, while the MAC delay of the low priority class increases. It is also worth noting that the AOB mechanism is really effective in reducing the congestion and improving the quality of service, as the tail of the MAC delay distribution (also for the low priority class) is much shorter than that of the standard protocol.

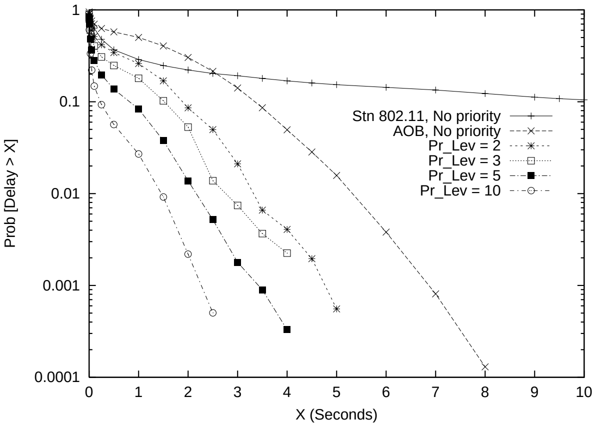

Figure 21: Tail of the MAC delay

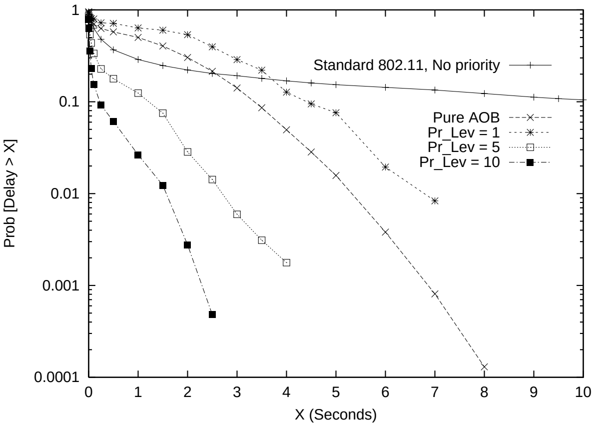

Figure 22: Tail of the MAC delay (three classes of traffic)

9. Conclusions and future research

In this paper we have proposed and evaluated the AOB mechanism that can be applied to dynamically control the network contention level in an IEEE 802.11 network. The network contention level is measured independently by each station, by an index that is simple to estimate: the slot utilization. The slot utilization estimate is used as a feedback signal to control the stations' behavior. This control is implemented through the computation, in each station, of a probability of transmission, *P_T*, which creates a filter in the transmission attempts. Specifically, when according to the standard protocol a station is authorized to transmit, in the protocol extended with AOB, a station will perform a real transmission with probability *P_T* otherwise (i.e., with probability 1-*P_T*) the transmission is re-scheduled as a collision occurs, i.e., a new backoff interval is sampled. In the paper we analytically derive the setting of the *P_T* parameter that leads to the optimal channel utilization level.

In this paper, via simulation, we have extensively evaluated the performance of the IEEE 802.11 access scheme with and without the AOB mechanism. The performance analysis was carried out both in steady-state and under transient conditions. Results obtained show that the dynamic tuning algorithm is very effective for the network and traffic configurations analyzed.

Furthermore, we have shown the robustness of the AOB mechanism to errors, and its potential for traffic differentiation. In this work we have only sketched the traffic differentiation potential of AOB. Further investigation is need on this topic: (i) to analytically characterize the relationship between the Pr_Lev parameter value and the QoS achieved by a class, and (ii) to use ACL(*q*) values that depend on the priority class to obtain a stronger traffic differentiation, e.g. low priority traffic is admitted only when the network is lightly loaded.

In this paper we mainly concentrated on infrastructure-based IEEE802.11 networks. An ongoing research activity is the extension of the AOB mechanism for the dynamic tuning of the backoff algorithm in ad hoc network configurations. As indicated also in [Bag94] we are currently investigating solutions for explicitly sharing the congestion information among neighbour nodes.

Bibliography.

[Aad01] I. Aad, C. Castelluccia, “Differentiation mechanisms for IEEE 802.11”, Proc. INFOCOM 2001, pp. 209 -218.

[Ana00] G. Anastasi, L. Lenzini, “QoS provided by the IEEE 802.11 wireless LAN to advanced data applications: a simulation analysis”, ACM Wireless Networks (WINET), Volume 6, Number 2, 2000, pp. 99-108.

[Bar94] V. Bharghavan, A. J. Demers, S. Shenker, L. Zhang, “MACAW: A Media Access Protocol for Wireless LAN's”, Proc. SIGCOMM 1994, pp. 212-225

[Bia96] Bianchi G., Fratta L., Olivieri M., “Performance Evaluation and Enhancement of the CSMA/CA MAC protocol for 802.11 Wireless LANs”, proceedings of PIMRC 1996, 10/1996, Taipei, Taiwan, pp. 392-396.

[Bia00] G. Bianchi, “Performance Analysis of the IEEE 802.11 Distributed Coordination Function”, *IEEE Journal on Selected Areas in Communications*, March 2000, Volume 18, Number 3

[Bon99] L. Bononi, M. Conti, L. Donatiello, “A Distributed Contention Control Mechanism for Power Saving in random-access Ad hoc Wireless Local Area Networks”, Proc. *MoMuC'99* Sixth International Workshop on Mobile Multimedia Communication, San Diego, CA, November 15-18, 1999.

[Bon00] L. Bononi, M. Conti, L. Donatiello, “Design and Performance Evaluation of a Distributed Contention Control (DCC) Mechanism for IEEE 802.11 Wireless Local Area Networks”, *Journal of Parallel and Distributed Computing*, Accademic Press Vol.60 N.4, April 2000.

[Bon02] L. Bononi, M. Conti, E. Gregori, “Run-Time Optimization of IEEE 802.11 Wireless LANs performance”, *IIT Internal report*, July 2002

[Bru01] R. Bruno, M. Conti, E. Gregori, “WLAN technologies for mobile ad hoc networks”, Proc. HICSS-34, Maui, Hawaii, January 3-6, 2001. An extended version can be found in the Chapter 4 of *Handbook of Wireless Networks and Mobile Computing* (I. Stojmenovic Editor), John Wiley & Sons, New York, 2001.

[Bru02a] R. Bruno, M. Conti, E. Gregori, "Traffic integration in personal, local and geograhical wireless networks", Chapter 7 of *Handbook of Wireless Networks and Mobile Computing* (I. Stojmenovic Editor), John Wiley & Sons, New York, 2002.

[Bru02b] R. Bruno, M. Conti, E. Gregori, “IEEE 802.11 Optimal Performances: RTS/CTS Mechanism vs. Basic Access”, Proc. 2002 International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2002), Lisboa Portugal September 15-18, 2002.

[Cal98] F. Cali', M. Conti, E. Gregori, “IEEE 802.11 Wireless LAN: Capacity Analysis and Protocol Enhancement”, Proc. INFOCOM'98, San Francisco, CA, March 29 - April 2, 1998, pp. 142-149.

[Cal00a] F. Cali' , Conti M., E. Gregori, "Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit”, *IEEE/ACM Transactions on Networking*, Volume 8 , No. 6 (Dec. 2000), pp. 785 - 799.

[Cal00b] F. Cali' , Conti M., E. Gregori, “Dynamic IEEE 802.11: design, modeling and performance evaluation”, *IEEE Journal on Selected Areas in Communications*, 18(9), September 2000. pp. 1774-1786.

[Cha00] A. Chandra V. Gumalla, J.O. Limb, “Wireless Medium Access Control Protocols”, IEEE Communications Surveys Second Quarter 2000.

[Che94] Chen K.C., “Medium Access Control of Wireless LANs for Mobile Computing”, IEEE Networks, 9-10/1994.

[Chh97] H.S. Chhaya, S. Gupta, "Performance Modeling of asynchronous data transfer methods in the IEEE 802.11 MAC protocol", *ACM/Balzer Wireless Networks*, Vol. 3, 1997, pp. 217-234.

[Con97] M. Conti, E. Gregori, L. Lenzini, *Metropolitan Area Network*”, Springer Verlag, London, 1997.

[Con02a] M. Conti, “Body, Personal, and Local Ad hoc Wireless Networks” in *Handbook of Ad Hoc Wireless Networks*, Mohammad Ilyas (Editor), CRC Press 2002.

[Con02b] M. Conti, E. Gregori, “Optimization of bandwidth and energy consumption in Wireless Local Area Networks”, Performance 2002 Tutorial paper, *Letcture Notes on Computer Science - Tutorial Lectures,* M. Calzarossa (Editor).

[Cor99] M. S. Corson, J.P. Maker, J.H. Cerincione, “Internet-based Mobile Ad Hoc Networking”, *Internet Computing*, July-August 1999, pp. 63-70.

[Cou00] Constantine Coutras, Sanjay Gupta and Ness B. Shroff, “Scheduling of realtime traffic in IEEE 802.11 wireless LANs”, ACM Wireless Networks (WINET) 6, 6 (Dec. 2000), pp. 457 - 466

[Cro97] B. P. Crow, I. Widjaja, J. G. Kim, P.T. Sakai, “IEEE 802.11 Wireless Local Area Networks”, *IEEE Communications Magazine*, Sept. 97, pp.116-126.

[For 94] G.H. Forman, J. Zahorjan, “ The challenges of mobile computing”, *IEEE Computer,* April 94, pp.38-47.

[Ful97] Chane L. Fullmer, J.J. Garcia-Luna-Aceves, ``Solutions to Hidden Terminal Problems in Wireless Networks," Proc. ACM SIGCOMM 97, Cannes, France, September 14-18, 1997.

[Gal85] Gallagher R.G., “A perspective on multiaccess channels”, IEEE Trans. Information Theory, vol. IT-31, No.2, 3/1985, pp. 124-142.

[Gar96] R. Garcés, J. J. Garcia-Luna-Aceves, “Floor Acquisition Multiple Access with Collision Resolution”, Proc. MOBICOM 1996, pp. 187-197

[Gar99] J.J. Garcia-Luna-Aceves and C. L. Fullmer, "Floor Acquisition Multiple Access (FAMA) in Single-Channel Packet-Radio Networks," MONET, Vol 4, Number 3, 1999.

[Geo85] Georgiadis L., Papantoni-Kazakos P., “Limited Feedback Sensing Algorithms for the Packet Broadcast channel”, IEEE Trans. on Info. Theory, Vol IT-31, No.2, 3/1985, pp. 280-294.

[Ger77] M. Gerla, L. Kleinrock, “Closed loop stability control for S-Aloha satellite communications”, *Proc. Fifth Data Communications Symp., Sept. 1977,* pp. 2.10-2.19.

[Gil60] E.N. Gilbert “Capacity of a burst-noise channel”, Bell Syst. Tech. J., Vol. 39, pp 1253-1265, 1960.

[Goo85] Goodman J., Greenberg A.G., Madras N., March P., “Stability of Binary Exponential Backoff”, app. in the Proc. of the 17-th Annual ACM Symp. on Theory of Comp., Providence, May 1985.

[Haj 82] B. Hajek, T. Van Loon, “Decentralized dynamic control of a multiaccess broadcast channel”, *IEEE Trans Automat. Control,* Vol.27, 1982, pp. 559-569.

[Ham88] Hammond J.L., O'Reilly P.J.P., Performance Analysis of Local Computer Networks, Addison-Wesley 1988.

[Has96] Hastad J., Leighton T., Rogoff B., “Analysis of Backoff Protocols for Multiple Access Channels”, Siam J. Computing vol. 25, No. 4, 8/1996, pp. 740-774.

[Hey82] D. P. Heyman, M. J. Sobel, "Stochastic models in operations research" Vol. I, McGraw-Hill Book Company, 1982.

[IEE802] http://grouper.ieee.org/groups/802/11/main.html

[IEE97] IEEE standard for Wireless LAN- Medium Access Control and Physical Layer Specification, P802.11, November 1997.

[Imi 94] T. Imielinsky, B.R. Badrinath, “Mobile Computing: Solutions and Challenges in Data Management”, *Communications of ACM* , Oct. 94.

[Jun02] Eun-Sun Jung, Nitin Vaidya “An Energy Efficient MAC Protocol for Wireless LANs”, Proc. IEEE INFOCOM, June 2002.

[Kel 85] F. Kelly, “Sthocastic Models of computer communications systems”, *J. Royal Statist. Soc.*, Series B, Vol. 47, 1985, pp. 379-395.

[Kra98] R. Kravets, P. Krishnan, “Power Management Techniques for Mobile Communication”, Proceedings of The Fourth Annual *ACM/IEEE International Conference on Mobile Computing and Networking* (MOBICOM'98).

[Qia02] Daji Qiao and Kang G. Shin, "Achieving Efficient Channel Utilization and Weighted Fairness for Data Communications in IEEE 802.11 WLAN under the DCF", in Proc. Tenth International Workshop on Quality of Service (IWQoS'02), Miami Beach, Florida, May 2002.

[Riv87] R.L. Rivest, “Network Control by Bayesian Broadcast”, IEEE Trans. on Info. Theory, Vol IT-33, No.3, 5/1987, pp. 323-328.

[Sob99] J. L. Sobrinho, A. S. Krishnakumar, "Quality of service in ad hoc carrier sense multiple access wireless networks," *IEEE Journal on Selected Areas in Communications*, pp. 1353-1368, August 1999.

[Sta96] Stallings W., Local & Metropolitan Area Networks, Fifth Edition, Prentice Hall 1996, pp. 356-383.

[Sta01] Stallings W., “IEEE802.11: Moving Closer to Practical Wireless LANs”, IT Pro, May-June 2001 pp. 17-23.

[Ste96] M. Stemm , R.H. Katz, “Measuring and Reducing Energy Consumption of Network Interfaces .in Hand-Held Devices”, Proc. 3rd International workshop on Mobile Multimedia Communications (MoMuC-3), Princeton, NJ, September 1996.

[Ste94] W.R.Stevens. TCP/IP Illustrated, Volume 1: The Protocols, Addison-Wesley, Reading, MA, 1994.

[Tas86] Tasaka S., Performance Analysis of Multiple Access Protocols, MIT Press 1986.

[Tob 75] F.A. Tobagi, L. Kleinrock, “Packet Switching in Radio Channels: Part II”, IEEE Trans on Comm., Vol. 23, 1975, pp. 1417-1433.

[Tsi87] Tsitsiklis J.N., “Analysis on a multiaccess Control Scheme”, IEEE Trans. on Auto. Contr., Vol AC-32, No.

11, 11/1987, pp. 1017-1020.

[Van02] V. Vanni, “Misure di prestazioni del protocollo TCP in reti locali Ad Hoc”, Computer Engineering Laurea Thesis, Pisa, February 2002 (in Italian)

[Vee01] M. Veeraraghavan, N. Cocker, T. Moors, “Support of voice services in IEEE 802.11 wireless LANs”, Proc. INFOCOM 2001 2001 Page(s): 488 -497 vol.1

[Ver00] Veres, Campbell, A.T, Barry, M. and L-H. Sun, "Supporting Service Differentiation in Wireless Packet Networks Using Distributed Control", IEEE Journal of Selected Areas in Communications (JSAC), Vol. 19, No. 10, pp. 2094-2104, October 2001.

[Vis02a] V.M. Vishnevsky and A.I.Lyakhov, “802.11 LANs: Saturation Throughput in the Presence of Noise,” Proc. of 2nd Int. IFIP TC6 Networking Conf. (Networking 2002), Pisa, Italy, May 19-24, 2002. - Lecture Notes in Computer Science, vol.2345, pp.1008-1019, Springer-Verlag, 2002.

[Vis02b] V.M. Vishnevsky and A.I.Lyakhov, “IEEE 802.11 Wireless LAN: Saturation Throughput Analysis with Seizing Effect Consideration,” Cluster Computing, vol.5, no.2, April 2002, pp.133-144.

[Wei96] Weinmiller J., Woesner H., Ebert J.P., Wolisz A., “Analyzing and tuning the Distributed Coordination Function in the IEEE 802.11 DFWMAC Draft Standard”, Proc. Int. Workshop on Modeling, MASCOT 96, San Jose, CA.

[Wei 97] J. Weinmiller, M. Schläger, A. Festag, A. Wolisz, " Performance Study of Access control in Wireless LANs-IEEE 802.11 DFWMAC and ETSI RES 10 HIPERLAN", *Mobile Networks and Applications,* Vol. 2, 1997, pp.55-67.

[Xu01] S. Xu, T. Saadawi, “Does IEEE 802.11 MAC Protocol Work Well in Multi-hop Wireless Ad Hoc Networks?”, IEEE Communication Magazine, June 2001.

[Xu02] S. Xu, T. Saadawi, “Revealing the Problems with 802.11 MAC Protocol in Multi-hop Wireless Ad Hoc Networks”, Journal of Computer Networks, Vol. 38, No. 4, March 2002.