

Providing service guarantee in 802.11e EDCA WLANs with legacy stations

Albert Banchs, *Member, IEEE*, Pablo Serrano, *Member, IEEE*, and Luca Vollero, *Member, IEEE*

Abstract—Although the EDCA access mechanism of the 802.11e standard supports legacy DCF stations, the presence of DCF stations in the WLAN jeopardizes the provisioning of the service guarantees committed to the EDCA stations. The reason is that DCF stations compete with Contention Windows (CW 's) that are predefined and cannot be modified, and as a result the impact of the DCF stations on the service received by the EDCA stations cannot be controlled. In this paper, we address the problem of providing throughput guarantees to EDCA stations in a WLAN in which EDCA and DCF stations coexist. To this aim, we propose a technique that, implemented at the Access Point (AP), mitigates the impact of DCF stations on EDCA by skipping with a certain probability the Ack reply to a frame from a DCF station. When missing the Ack, the DCF station increases its CW and thus our technique allows us to have some control over the CW 's of the legacy DCF stations. In our approach, the probability of skipping an Ack frame is dynamically adjusted by means of an adaptive algorithm. This algorithm is based on a widely used controller from classical control theory, namely a Proportional Controller. In order to find an adequate configuration of the controller, we conduct a control theoretic analysis of the system. Simulation results show that the proposed approach is effective in providing throughput guarantees to EDCA stations in presence of DCF stations.

Index Terms—WLAN, 802.11, 802.11e, EDCA, DCF, ACKS, legacy stations, throughput guarantees, control theory

1 INTRODUCTION

THE Wireless LAN (WLAN) technology is nowadays widely used for Internet access. One of the shortcomings of traditional WLANs, based on the 802.11 standard [1], is that they provide no means to offer service guarantees to users. This is a significant drawback, in particular due to the inherent resource limitation in radio systems. This shortcoming has been identified by the research community, who has devoted considerable effort over the last decade to the design of wireless local area networks (WLAN's) with Quality of Service (QoS) support. Along this effort, the Enhancements Task Group (TGe) was formed under the IEEE 802.11 WG to recommend an international WLAN standard with QoS support. This standard is called 802.11e [2] and will be included in the ongoing new revision of the 802.11 standard [3].

The 802.11e standard defines two different access mechanisms: the *Enhanced Distributed Channel Access* (EDCA) and the *HCF Controlled Channel Access* (HCCA). This paper focuses on the former. The EDCA mechanism of 802.11e was designed as an extension of the DCF (*Distributed Coordination Function*) mechanism of the legacy 802.11 standard. One of the key design goals of the EDCA mechanism was the backwards compatibility with the legacy DCF mechanism. Following this goal, EDCA was designed such that legacy

stations using DCF could operate in an 802.11e WLAN under EDCA.

One of the main problems of the EDCA mechanism is that, although legacy DCF stations can interoperate in a WLAN under EDCA, they substantially degrade the performance of the WLAN and preclude the provisioning of service guarantees to the EDCA stations. Indeed, as we have noted in [4], [5], the fact that DCF (in contrast to EDCA) competes with predefined contention parameters that cannot be modified prevents controlling the aggressiveness of DCF stations. As a result, if EDCA stations competing against aggressive DCF stations are to receive service guarantees, they will need to behave aggressively as well, and this will severely degrade the overall WLAN performance.

Some effort in the literature has been devoted to the analysis of WLANs in which EDCA and DCF stations coexist (see e.g. [6], [7], [8], [9]). Additionally, a number of proposals have been made to improve the performance of EDCA in presence of DCF stations, namely [10], [11], [12] in addition to our previous works of [4], [5]¹. The main drawback of [10], [11], [12] is that they require introducing modifications into the DCF or the EDCA stations. In contrast, our proposal of [4], [5] leaves the EDCA and DCF stations untouched, which represents a major advantage from a deployment perspective.

Following our previous works of [4], [5], in this paper we address the problem of providing throughput guarantees to EDCA stations in a WLAN with legacy DCF stations. To tackle this, we propose the *Dynamic ACK Skipping* (DACKS) technique, which mitigates the impact of legacy stations on an 802.11e WLAN under the EDCA mechanism by implement-

- A. Banchs and P. Serrano are with the Department of Telematics Engineering, Univ. Carlos III de Madrid, 28911 Leganés, Spain
E-mail: {banchs,pablo}@it.uc3m.es
- A. Banchs is also with IMDEA Networks, 28912 Leganés, Spain
- L. Vollero is with the Università Campus Bio-Medico di Roma, 00155 Rome, Italy
E-mail: l.vollero@unicampus.it.

1. In [13] the authors used a similar idea to that of [4], [5] for a different purpose; namely, to provide service differentiation in a WLAN with DCF stations only.

ing a small modification in the 802.11e Access Point (AP). The main contributions of the paper are summarized in the following points:

- We propose the DACKS technique. The key feature of the approach (as compared to our previous works of [4], [5]) is that the system is dynamically controlled based on the observed behavior of the WLAN. In particular, the proposed DACKS system is based on a commonly used controller from classical control theory.
- We develop a model of a WLAN with DACKS under stationary conditions. Based on this model, we determine the optimal configuration of the EDCA parameters in order to provide EDCA stations with throughput guarantees.
- We develop a model for the transient response of a WLAN controlled by DACKS. With this model, we analyze the dynamics of our system from a control theoretic standpoint and, based on this analysis, we tune the DACKS parameters following classical control theory considerations.
- We thoroughly evaluate our proposal by means of an exhaustive simulation study. In particular, we evaluate the system dynamics as well as stationary conditions.

The rest of the paper is structured as follows. In Section 2 we describe the 802.11 DCF and 802.11e EDCA mechanisms. In Section 3 we present the *Dynamic ACK Skipping* (DACKS) technique. In Section 4 we analyze the throughput performance of a WLAN with DACKS under stationary conditions and, from this analysis, we derive the configuration of the EDCA parameters. In Section 5 we propose a system based on control theory to dynamically adjust DACKS; we analyze the performance of the system under transient conditions and determine the configuration of the various system parameters based on this analysis. In Section 6 we evaluate the performance of DACKS under a variety of scenarios including stationary and transient conditions. Finally, the paper closes with some final remarks in Section 7.

2 802.11 DCF AND 802.11E EDCA

DCF and EDCA execute a similar algorithm to transmit their frames. In the following, we first present the 802.11e EDCA mechanism and then we describe the differences between 802.11e EDCA and 802.11 DCF.

EDCA regulates the access to the wireless channel on the basis of the *channel access functions* (CAF's). A station may run up to 4 CAF's, and each of the frames generated by the station is mapped to one of these CAF's. Then, each CAF executes an independent backoff process to transmit its frames. A CAF i with a new frame to transmit monitors the channel activity. If the channel is idle for a period of time equal to the arbitration interframe space parameter ($AIFS_i$), the CAF transmits. Otherwise, if the channel is sensed busy (either immediately or during the $AIFS_i$ period), the CAF starts a backoff process. The arbitration interframe space ($AIFS_i$) takes a value of the form $DIFS + nT_e$, where $DIFS$ is the DCF interframe space, T_e is the duration of an empty slot time and n is a nonnegative integer.

Upon starting the backoff process, the CAF computes a random integer value uniformly distributed in the range $(0, CW_i - 1)$, and initializes its backoff time counter with this value. The CW_i value is called the contention window, and depends on the number of transmissions failed for the frame. At the first transmission attempt, CW_i is set equal to the minimum contention window parameter (CW_i^{min}). As long as the channel is sensed idle the backoff time counter is decremented once every time interval T_e , and "frozen" when a transmission is detected on the channel.

When the backoff time counter reaches zero, the CAF transmits. A collision occurs when two or more CAF's start transmission simultaneously. An acknowledgement (Ack) frame is used to notify the transmitting CAF that the frame has been successfully received. The Ack is immediately transmitted at the end of the frame, after a period of time equal to the SIFS (the short interframe space). If the Ack is not received within a timeout given by the $Ack_Timeout$, the CAF assumes that the frame was not received successfully and reschedules the transmission by reentering the backoff process. The CAF then doubles CW_i (up to a maximum value given by the CW_i^{max} parameter), computes a new backoff time and starts decrementing the backoff time counter at an $AIFS_i$ time following the timeout expiry. If the number of failed attempts reaches a predetermined retry limit R , the frame is discarded.

After a (successful or unsuccessful) frame transmission, before transmitting the next frame the CAF must execute a new backoff process. As an exception to this rule, the protocol allows the continuation of an EDCA transmission opportunity (TXOP). A continuation of an EDCA TXOP occurs when a CAF retains the right to access the channel following the completion of a transmission and transmits several frames back-to-back. The period of time a CAF is allowed to retain the right to access the channel is limited by the transmission opportunity limit parameter ($TXOP_limit_i$).

In the case of a single station running more than one CAF, if the backoff time counters of two or more CAF's of the station reach zero at the same time, a scheduler inside the station avoids the *internal collision* by granting the access to the channel to the highest priority CAF. The other CAF's of the station involved in the internal collision react as if there had been a collision on the channel, doubling their CW_i and restarting the backoff process.

As it can be seen from the description of EDCA given in this section, the behavior of a CAF depends on a number of parameters, namely CW_i^{min} , CW_i^{max} , $AIFS_i$ and $TXOP_limit_i$. These are configurable parameters that can be set to different values for different CAF's. The standard draft groups CAF's by Access Categories (AC's), all the CAF's of an AC having the same configuration, and limits the maximum number of AC's in the WLAN to 4. An EDCA station that wants to enter the WLAN must issue a signalling request indicating the AC that it wants to join. If admitted, the EDCA station can join the WLAN with a CAF configured according to the parameters of the corresponding AC. The parameters of each AC are announced periodically by means of beacon frames.

A DCF station executes a very similar backoff process to the one described above for an EDCA CAF, albeit with some

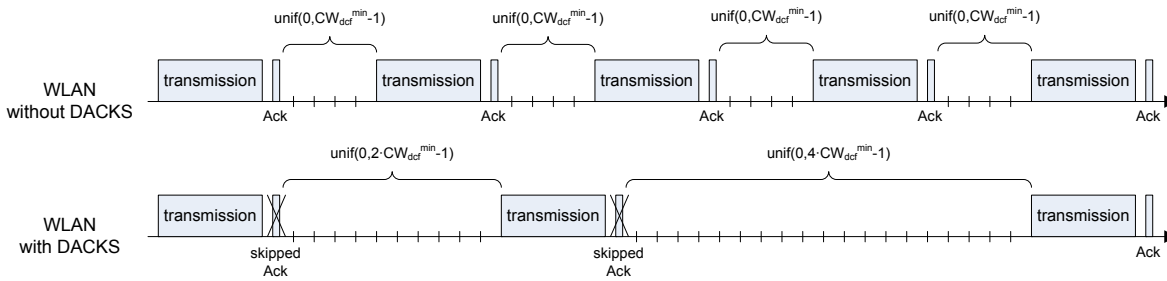


Fig. 1. DACKS Technique.

differences. One difference is the way the backoff counter is managed. In EDCA, the backoff counter is resumed one slot time before the AIFS expiration, while in DCF it is resumed after the expiration. Moreover, in DCF a station transmits immediately when the counter decrements to 0, while in EDCA it transmits in the next slot time².

Another key difference between DCF and EDCA is that, while in 802.11e EDCA the contention parameters are configurable and can be set to different values for different Access Categories (AC's), in DCF the values of these parameters are fixed by the standard as follows:

- The $AIFS_i$ parameter in DCF is set equal to $DIFS$.
- The configuration of the CW_i^{min} and CW_i^{max} parameters is predefined by the 802.11 DCF standard. We refer to the values given by the standard as CW_{dcf}^{min} and CW_{dcf}^{max} , respectively.
- Upon accessing the medium, DCF stations transmit a single packet and hence do not use the $TXOP_limit_i$ parameter.

While EDCA has been designed to allow coexistence with legacy DCF stations, the fact that the contention parameters with which DCF stations compete are fixed jeopardizes the provisioning of service guarantees to EDCA stations. The rest of the paper is devoted to overcoming this limitation.

3 DACKS TECHNIQUE

As we have seen in the previous section, legacy DCF stations start the backoff process with a CW equal to CW_{dcf}^{min} . This initial CW is fixed by the standard to a small value, and it only doubles after each failed attempt. These small CW values of DCF stations raise problems in a WLAN in which EDCA stations are to receive service guarantees. Indeed, no matter whether the CW of the EDCA stations are configured with small or large values, the following drawbacks are observed when there is a non-small number of stations in the WLAN:

- If EDCA stations were configured with small CW values in order to give them a higher priority than DCF stations, we would have both DCF and EDCA stations with small CW 's and the resulting overall efficiency of the WLAN will be low, due to the fact that small CW values result in a high collision rate.

- If EDCA stations were configured with large CW values in order to avoid the above problem, DCF stations would compete with smaller CW 's than EDCA and would consume most of the WLAN resources, leaving EDCA stations with little resources and thus failing to meet their service guarantees.

It is obvious that none of the above two alternatives is desirable, as in both cases the service received by the EDCA stations is seriously degraded as a consequence of the impact of legacy stations. Instead, it would be desirable to increase the CW of legacy stations; in this way, EDCA stations could receive service guarantees without compromising the overall efficiency. The *Dynamic ACK Skipping* (DACKS) technique achieves this goal without modifying the legacy DCF stations.

DACKS is based on the following behavior of DCF: after sending a packet, a DCF station waits for an Ack frame, and, if the frame is not received within an Ack timeout, it assumes a collision and increases its CW . The central idea is then the following: if the AP skips the Ack reply to legacy DCF stations with a certain probability (hereafter referred to as P_{skip}), these stations will 'see' a collision rate higher than the actual one, and will contend with larger CW 's, resulting this in a smaller impact on the EDCA stations.

The above behavior of DACKS is illustrated in Figure 1. In this figure, the behavior of a DCF station in a WLAN without DACKS is compared against the behavior of a DCF station in a WLAN that uses the DACKS technique. It can be observed that in the latter case, by skipping the Ack reply with some probability, DACKS achieves the objective of increasing the average CW with which the DCF station contends for channel access, and hence reduces the number of times that the DCF station transmits.

The challenge with the DACKS technique is the configuration of the probability P_{skip} . This adds to the inherent difficulty in 802.11e of configuring the EDCA contention parameters in order to provide the desired behavior. In [4], [5] we proposed some algorithms to compute P_{skip} statically. The main drawbacks of a static configuration are:

- A static configuration has to compute the configuration assuming the worst case in which all DCF stations are constantly active. This requires a much more aggressive behavior than needed against DCF stations. In particular, when all DCF stations are active, Ack frames need to be skipped with a high probability to ensure the desired throughput guarantees for EDCA. In contrast, if some

². The reader is referred to [7] for further details about the backoff behavior of EDCA and DCF.

DCF stations are not active, a smaller skipping probability is enough to provide EDCA stations with the desired service.

- Similarly to the above, a static configuration has to assume that all admitted EDCA stations are active, since this is the worst case to ensure the desired guarantees. This assumption forces a high probability of skipping Ack frames, degrading thus DCF performance. In the case some EDCA stations are not active, the desired service could be provided while reducing the degradation suffered by DCF.

We conclude from the above that a static configuration degrades the performance of DCF stations unnecessarily when not all the (EDCA and DCF) stations are active. In this paper we propose an alternative scheme that, by dynamically adjusting the skipping probability to the current behavior of the WLAN, minimizes the disruption suffered by the DCF stations.

4 EDCA CONFIGURATION

It follows from the above explanations that a major challenge for an EDCA WLAN with DACKS is the configuration of both the EDCA parameters and the DACKS skipping probability. In this section we analyze the EDCA configuration, while the DACKS configuration is analyzed in the next section.

In the analysis of the EDCA configuration, we start by describing our scenario and assumptions. Then, we present a model for a DCF station. Based on this model, we analyze the throughput performance of a WLAN with DCF and EDCA stations. Finally, we use this analysis to propose the optimal configuration of the parameters of the EDCA stations for throughput guarantees.

4.1 Scenario and Assumptions

In the following we describe the scenario considered in this paper as well as the assumptions upon which our analysis is based:

- Our scenario consists of a WLAN where EDCA and DCF stations coexist. Our goal is to provide EDCA stations in this scenario with throughput guarantees.
- We consider that each EDCA station executes only one CAF and joins a given AC i depending on its throughput requirements. We denote by R_i the throughput guarantee given to the EDCA stations of AC i .
- We assume that, over a time period, a station is either constantly backlogged³ or does not transmit any traffic. We refer to the former as an *active* station and the latter as *inactive*.
- We denote by N_{dcf} the number of active DCF stations in the WLAN and by N_i the number of active EDCA stations that belong to AC i .
- Following our previous results of [15], we use the following configuration for the EDCA stations: $AIFS_i =$

3. [14] refers to constantly backlogged stations as *saturated*. In the rest of the paper, we use the terms ‘constantly backlogged’ and ‘saturated’ indistinctly.

$DIFS$ and $CW_i^{min} = CW_i^{max}$, since [15] shows (both analytically and via simulation) that no other configuration provides better throughput performance. We denote $CW_i = CW_i^{min} = CW_i^{max}$.

- Following [16], we assume that backoff times are geometrically distributed, i.e. a station at a given backoff stage transmits with a constant and independent probability in each slot time.
- Upon accessing the channel, both EDCA and DCF stations transmit a single packet of length l .

4.2 DCF Station Model

We start our analysis by computing the probability that a DCF station transmits at a randomly chosen slot time, τ_{dcf} , as a function of the probability that a transmission attempt of a DCF station collides, c_{dcf} .

Figure 2 illustrates our model of a DCF station. The states represent the backoff stage of the station, i.e. the number of collisions suffered by the current frame. At state 0, the station’s CW is equal to CW_{dcf}^{min} , yielding the following transmission probability [14]

$$\tau_{dcf,0} = \frac{2}{CW_{dcf}^{min} + 1} \quad (1)$$

Let m be the maximum backoff stage defined by $CW_{dcf}^{max} = 2^m CW_{dcf}^{min}$. Note that in DCF we have $m < R$ [1]. At state $i \leq m$, the CW has been doubled i times, yielding the following transmission probability

$$\tau_{dcf,i} = \frac{2}{2^i CW_{dcf}^{min} + 1} \quad (2)$$

At state $i > m$, the CW has already reached CW_{dcf}^{max} , yielding

$$\tau_{dcf,i} = \frac{2}{2^m CW_{dcf}^{min} + 1} \quad (3)$$

In the rest of the paper, we use the following simplifying approximation for $\tau_{dcf,i}$:

$$\tau_{dcf,i} \approx \frac{2}{2^{\min(i,m)}(CW_{dcf}^{min} + 1)} = \frac{\tau_{dcf,0}}{2^{\min(i,m)}} \quad (4)$$

Following the above, we have that at state i the station transmits in each slot time with probability $\tau_{dcf,i}$. If the transmission collides (which occurs with probability c_{dcf}), the station moves to the next state, and doubles its CW if $i < m$. If it succeeds, the station goes back to the initial state 0, and sets the CW equal to CW_{dcf}^{min} . When the station reaches the maximum retry limit at state R , it moves back to state 0 no matter if the transmission succeeds or collides. This leads to the state transition probabilities given in Figure 2.

Let us denote by P_i the probability that the station is at state i . The probability of entering state i is equal to the probability of being at state $i - 1$ and performing a failed transmission. The probability of leaving this state is equal to the probability of performing a (failed or successful) transmission. By forcing equilibrium between these two probabilities we have

$$P_{i-1}\tau_{dcf,i-1}c_{dcf} = P_i\tau_{dcf,i} \quad (5)$$

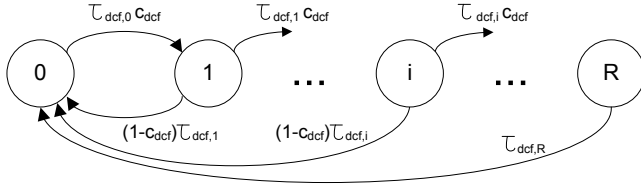


Fig. 2. Markov chain model of a DCF station.

Since, following Eq. (4), we have

$$\tau_{dcf,i} = \begin{cases} \tau_{dcf,i-1}/2, & i \leq m \\ \tau_{dcf,i-1}, & i > m \end{cases} \quad (6)$$

which yields

$$P_i = \begin{cases} P_{i-1}2c_{dcf}, & i \leq m \\ P_{i-1}c_{dcf}, & i > m \end{cases} \quad (7)$$

Applying the above recursively leads to

$$P_i = \begin{cases} P_0(2c_{dcf})^i, & i \leq m \\ P_02^m c_{dcf}^i, & i > m \end{cases} \quad (8)$$

By forcing

$$\sum_{i=0}^{\infty} P_i = P_0 \left(\sum_{i=0}^m (2c_{dcf})^i + \sum_{i=m+1}^R 2^m c_{dcf}^i \right) = 1 \quad (9)$$

we obtain

$$\begin{aligned} P_0 &= \frac{1}{\sum_{i=0}^m (2c_{dcf})^i + \sum_{i=m+1}^R 2^m c_{dcf}^i} \\ &= \frac{1}{\frac{1-(2c_{dcf})^{m+1}}{1-2c_{dcf}} + \frac{2^m c_{dcf}^m (1-c_{dcf}^{R-m})}{1-c_{dcf}}} \end{aligned} \quad (10)$$

With the above, we can compute the transmission probability of a DCF station as follows

$$\begin{aligned} \tau_{dcf} &= \sum_{i=0}^R P_i \tau_{dcf,i} \\ &= \sum_{i=0}^m P_0 (2c_{dcf})^i \frac{\tau_{dcf,0}}{2^i} + \sum_{i=m+1}^R P_0 2^m c_{dcf}^i \frac{\tau_{dcf,0}}{2^m} \end{aligned} \quad (11)$$

from which

$$\tau_{dcf} = \frac{(1-2c_{dcf})(1-c_{dcf}^{m+1}) + (1-c_{dcf})(1-(2c_{dcf})^{m+1}) + (1-2c_{dcf})c_{dcf}^{m+1}(1-c_{dcf}^{R-m})}{(1-2c_{dcf})2^m c_{dcf}^{m+1}(1-c_{dcf}^{R-m})} \tau_{dcf,0} \quad (12)$$

which terminates our model of a DCF station.

Remark 1: We note that Bianchi's analysis [14], which has been widely used to analyze the performance of 802.11 DCF, reaches a result very similar to ours although it uses a different model. Indeed, if we take Bianchi's formula to compute the transmission probability:

$$\tau_{dcf} = \frac{2(1-2c)}{(1-2c)(CW+1) + c \cdot CW [1-(2c)^m]} \quad (13)$$

where $c = c_{dcf}$ and $CW = CW_{dcf}^{min}$, and we make the approximation $CW \approx CW + 1$, we obtain

$$\tau_{dcf} = \frac{1-2c}{1-c-2^m c^{m+1}} \left(\frac{2}{CW+1} \right) \quad (14)$$

which is equal to the result we have obtained in Eq. (12) under the assumption $R = \infty$ that Bianchi used in his analysis.

Remark 2: In a properly configured WLAN, stations rarely reach the maximum CW . Under these conditions, an accurate approximation of the behavior of the DCF stations can be obtained by assuming that the CW_{dcf}^{max} and the retransmission limit are infinite, i.e. $R = m = \infty$. With this assumption, the following simplified expressions for Eqs. (8) and (12) are derived:

$$P_i = P_0 (2c_{dcf})^i \quad (15)$$

$$\tau_{dcf} = \frac{(1-2c_{dcf})}{(1-c_{dcf})} \tau_{dcf,0} \quad (16)$$

The transient analysis of Section 5.3 is based on the above simplified expressions, while the throughput analysis and CW_i configuration of Sections 4.3 and 4.4 are based on the exact expressions. The reason for using these approximations in the transient analysis only is that this analysis is much more complex and the approximations are necessary to make it tractable. Instead, in the throughput analysis it is possible to use the exact expression which allows being more accurate and ensures that there will be no errors (not even small ones) in the committed throughputs.

4.3 Throughput Analysis

Based on the model of a DCF station presented above, we now analyze the throughput performance of DCF and EDCA stations in the WLAN. Our analysis is based on the following: *i*) after each transmission, there is a slot time in which DCF stations have not yet decremented their backoff counter and only EDCA stations may transmit, *ii*) we assume that EDCA and DCF stations transmit with a constant and independent probability in those slot times where they are allowed, and *iii*) when computing their transmission probabilities, we account for the fact that EDCA stations wait for one extra slot time after the backoff counter reaches 0.

Eq. (12) gives the transmission probability of a DCF station as a function of the collision probability. The transmission probability of the EDCA stations, whose configuration satisfies $CW_i = CW_i^{min} = CW_i^{max}$, can be easily computed as follows⁴:

$$\tau_i = \frac{2}{CW_i + 3} \quad (17)$$

Further, the collision probability of the DCF stations can be expressed as⁵:

$$c_{dcf} = 1 - P_{ack}(1-\tau_{dcf})^{N_{dcf}-1} \left(\prod_i (1-\tau_i)^{N_i} \right) \quad (18)$$

4. Note that Eq. (17) differs from Eq. (1) as it takes into account that an EDCA station transmits at the next slot time when its backoff counter reaches 0.

5. Note that by collision here we understand both the case when the transmission actually collides and the case when, even if there is not a real collision, the Ack is omitted by the DACKS technique

where P_{ack} is the probability that, upon successfully receiving a packet from a DCF station, the AP sends the corresponding Ack – i.e., the probability that the DACKS technique does not skip this Ack:

$$P_{ack} = 1 - P_{skip} \quad (19)$$

With the above, we can compute the transmission probability of all the station of the WLAN as follows:

- The transmission probability of the EDCA stations, τ_i , can be computed from their configured CW_i with Eq. (17).
- Given all τ_i 's, we can compute τ_{dcf} by solving the nonlinear equation formed by Eqs. (12) and (18)⁶.

Once all transmission probabilities have been obtained, we can compute the probability P_t that a given slot time contains a transmission (either a success or a collision) as follows. If the previous slot time was empty all stations may transmit, and otherwise only EDCA stations may transmit. Thus,

$$1 - P_t = (1 - P_t)(1 - \tau_{dcf})^{N_{dcf}} \prod_i (1 - \tau_i)^{N_i} + P_t \prod_i (1 - \tau_i)^{N_i} \quad (20)$$

which yields

$$P_t = \frac{1 - (1 - \tau_{dcf})^{N_{dcf}} \prod_i (1 - \tau_i)^{N_i}}{1 + \prod_i (1 - \tau_i)^{N_i} - (1 - \tau_{dcf})^{N_{dcf}} \prod_i (1 - \tau_i)^{N_i}} \quad (21)$$

With the above, we can proceed to compute the throughput experienced by an EDCA station of AC i , r_i , and the throughput experienced by a DCF station, r_{dcf} , as follows:

$$r_i = \frac{\tau_i c_i l}{(1 - P_t)T_e + P_t T_t} \quad (22)$$

and

$$r_{dcf} = \frac{P_{ack} \tau_{dcf} (1 - \tau_{dcf})^{N_{dcf} - 1} \left(\prod_j (1 - \tau_j)^{N_j} \right) l}{(1 - P_t)T_e + P_t T_t} \quad (23)$$

where T_e is the duration of an empty slot time, T_t is the duration of a slot time with a transmission, and c_i is the probability that a transmission attempt of an EDCA station of AC i collides,

$$c_i = (1 - P_t)(1 - \tau_i)^{N_i - 1} (1 - \tau_{dcf})^{N_{dcf}} \prod_{j \neq i} (1 - \tau_j)^{N_j} + P_t (1 - \tau_i)^{N_i - 1} \prod_{j \neq i} (1 - \tau_j)^{N_j} \quad (24)$$

The duration of an empty slot time (T_e) is fixed by the standard, while the duration of a slot time that contains a success and a collision is equal to, respectively⁷:

$$T_s = T_{PLCP} + \frac{H}{C} + \frac{l}{C} + SIFS + T_{PLCP} + \frac{Ack}{C} + DIFS \quad (25)$$

$$T_c = T_{PLCP} + \frac{H}{C} + \frac{l}{C} + EIFS \quad (26)$$

6. The reader is referred to [17] for a discussion on the uniqueness of the solution.

7. Note that, in case of a skipped Ack, the slot time duration is given by T_s , since stations update their NAV to the duration of a successful transmission, and defer channel access during this time.

where T_{PLCP} is the PLCP (Physical Layer Convergence Protocol) preamble and header transmission time, H is the MAC overhead (header and FCS), l is the size of the acknowledgement frame and C is the channel bit rate.

Since the standard fixes the value of $EIFS$ equal to the time required to send an Ack, we have that the duration of a collision and a success are equal, and we can thus compute the duration of a slot time with a transmission as

$$T_t = T_s = T_c \quad (27)$$

With the above, we can compute, given the configuration of the CW_i and P_{ack} parameters, the throughput of each of the DCF and EDCA stations in the WLAN, which terminates the throughput analysis. In the following sections we address the configuration of these parameters.

4.4 CW_i Configuration

We now address the issue of calculating the optimal configuration of the WLAN. The goal of the optimal configuration is to provide the desired throughput guarantees while maximizing the overall throughput performance.

Upon changing the CW_i configuration, the AP needs to distribute the new configuration to the stations by means of signaling. This signaling limits the frequency with which the CW_i 's values can be updated. In contrast to the CW_i 's, the P_{ack} parameter is local and its value needs not be sent to the stations. As a result, P_{ack} can be updated as frequently as needed with no associated signaling cost. Following this, in this paper we make the following choices:

- The CW_i parameters are statically set based on information that does not change frequently and therefore does not trigger frequent updates of their values.
- The P_{ack} parameter is configured based on a dynamic algorithm that constantly updates its value following the observed behavior of the WLAN.

In the remaining of this section we address the configuration of the CW_i parameters, while the dynamic algorithm that updates P_{ack} is presented in the next section.

Following the above argumentation, the computation of the CW_i configuration needs to be based on data that do not change frequently. In particular, we use the following data:

- The number of EDCA stations admitted in the WLAN and their required throughputs. These data are available at the AP since EDCA stations, prior to entering the WLAN, have to issue an admission control request with this information.
- The number of DCF stations present in the WLAN. This information is available as DCF stations need to go through an authentication/association process before they enter the WLAN.

In contrast to the above data, P_{ack} is constantly updated, and therefore cannot be taken into account in the computation of the CW_i 's. This raises an issue since the optimal CW_i configuration actually depends on the setting of this parameter. In order to overcome this problem, the approach that we take in this paper is to compute the configuration of the CW_i 's

considering that P_{ack} is set to 0. This suboptimal solution has the following advantages:

- The first advantage is that the solution becomes optimal when the WLAN is stressed with many throughput guarantee requests from the EDCA stations. This is due to the fact that, when the WLAN is stressed, the DACKS technique forces DCF stations to reduce drastically their transmission rate by setting $P_{ack} = 0$, thereby making the computed CW_i configuration optimal.
- The other advantage of the proposed configuration is that it allows maximizing the number of throughput guarantee requests that can be admitted. Indeed, if a request cannot be admitted when P_{ack} is set to 0, this means that the request can never be admitted.

To compute the optimal configuration, we start by imposing the following condition, which ensures that the throughput will be distributed among stations proportionally to their requests [18]:

$$\frac{\tau_i(1 - \tau_j)}{\tau_j(1 - \tau_i)} = \frac{R_i}{R_j} \quad (28)$$

where R_i is the throughput guarantee of AC i .

We note that, with the above equation, if we assume that the value of a given CW_i is known, we can compute the value of all the other CW_i 's. From the throughput analysis of Section 4.3 and taking $P_{ack} = 0$, we can then compute all the throughputs.

With the above, we proceed as follows to find the optimal CW_i configuration. We conduct a numerical search using the *golden section search* method over the CW_i of the AC with the lowest throughput guarantee (without loss of generality, we assume it is AC 1). For each CW_1 value evaluated in the search, we compute the other CW_i 's from Eq. (28), and from these, we compute r_1 . With the numerical search we find thus the CW_1 value that leads to the largest r_1 . In order to avoid a large degree of unfairness with DCF, we impose in the search that CW_1 cannot be smaller than CW_{dcf}^{min} . Once the search finds CW_1 , we then compute all the other CW_i 's, which terminates the algorithm.

Note that a requirement that must be met by the CW_i configuration given by the above algorithm is that the resulting r_i 's are larger than the corresponding R_i 's. If this condition is not satisfied, this means that there exists no set of CW_i values that meets the desired throughput guarantees even when P_{ack} is set to 0. In this case, the requested guarantees cannot be satisfied and the request that triggered this computation must therefore be rejected⁸.

4.5 Best-Effort EDCA stations

So far we have assumed that all EDCA stations require throughput guarantees. In the following we address the case when one of the AC's does not require any throughput

guarantee. We refer to this AC as the *Best-Effort* AC. In the configuration of this AC we aim at the following objectives:

- We want to ensure that the committed throughput guarantees of the other AC's are met.
- We want to share the extra throughput between the DCF and the *Best-Effort* (BE) stations fairly.

In order to meet the above objectives, we proceed as follows. We first check if we can support DCF and BE stations when they transmit with the same probability and DCF stations are not disrupted (i.e., $P_{ack} = 1$). We do this by solving the analysis of Section 4.3 with $\tau_{dcf} = \tau_{be}$ (where τ_{be} is the τ_i of the BE stations) and comparing the resulting throughputs r_i 's against the requirements R_i 's. If the guarantees are met, this means that this setting of τ_{be} preserves the desired guarantees while providing fairness between DCF and BE. We therefore take this setting and compute CW_{be} by applying Eq. (17) to τ_{be} .

If the desired guarantees are not met, this means that we need to reduce the probability with which BE and DCF stations transmit. The only option for the DCF stations, since their contention parameters cannot be modified, is to skip some of the Ack frames by reducing P_{ack} . For the BE stations, however, we can directly modify their configuration instead of skipping their Ack frames. We compute the configuration of the BE stations as follows. From Eq. (22), we can express the throughput of AC i as a function of P_t . From this, we compute the maximum allowed value of P_t that satisfies $r_i \geq R_i$ for all AC's, which guarantees that the throughput commitments of all EDCA stations are met. Once we have obtained this value, we then compute τ_{be} by solving the nonlinear equation formed by

$$1 - P_t = (1 - P_t)(1 - \tau_i)^{N_i}(1 - \tau_{be})^{N_{be}}(1 - \tau_{dcf})^{N_{dcf}} + P_t(1 - \tau_i)^{N_i}(1 - \tau_{be})^{N_{be}} \quad (29)$$

and

$$\tau_{be} = (1 - P_t)\tau_{dcf} \quad (30)$$

Note that the Eq. (30) imposes that BE and DCF stations transmit with the same probability to ensure that they will obtain approximately the same throughput. Once we have computed τ_{be} , we obtain CW_{be} , which terminates the configuration of the BE stations.

5 DACKS CONFIGURATION

The remaining challenge from the previous section is the configuration of the DACKS technique, namely the parameter P_{ack} . In this section we present an algorithm that updates this parameter dynamically. We start by analyzing the conditions that must be met by the setting of P_{ack} . Next, we propose a system based on control theory that, following these conditions, dynamically adjusts P_{ack} . In order to analyze the overall controlled system, we develop a linearized model of the system. Based on this linearized model, we conduct a stability analysis to determine the region of the system parameters that guarantees a stable behavior. Finally, we obtain the setting of the parameters of the controlled system within the stability region.

8. Note that this request can come either from an EDCA or a DCF station. In the latter case, the AP can reject the request by not completing the association process initiated by the station. Note that many of today's APs already apply similar policies to deny association of stations based e.g. on their MAC address or on the AP's current load.

5.1 P_{ack} Configuration

Our goals for the setting of the P_{ack} parameter are the following ones:

- Given the CW_i configuration obtained in the previous section, we want to ensure that backlogged EDCA stations see their throughput guarantees satisfied.
- As long as the throughput guarantees for EDCA stations are met, we want to minimize the throughput degradation of the DCF stations by setting P_{ack} as large as possible.

Following the above, the main goal for the dynamic algorithm that computes P_{ack} is to set it to the largest possible value that satisfies the throughput requirements of the EDCA stations. We build the algorithm around the probability P_t that a randomly chosen slot time contains a transmission. Note that Eq. (22) can be rewritten as a function of P_t as follows

$$r_i = \frac{\tau_i(1 - P_t)l}{(1 - \tau_i)((1 - P_t)T_e + P_t T_r)} \quad (31)$$

Our algorithm is based on the following two observations:

- Given the CW_i configuration of AC i , there exists a maximum $P_{t,max,i}$ value such that, as long as $P_t \leq P_{t,max,i}$, the throughput guarantee of AC i is met. This can be seen from Eq. (31).
- The larger the P_t we allow, the smaller the probability of skipping an Ack frame needs to be. One of the goals that we have stated above was precisely to make the probability of skipping an Ack frame as small as possible, in order to minimize the disruption suffered by the DCF stations.

With the above observations, our objective can be formulated as to finding the P_{ack} configuration that yields a transmission probability equal to

$$P_{t,max} = \min_i \{P_{t,max,i}\} \quad (32)$$

since this is the P_t value that minimizes the degradation suffered by the DCF stations while meeting the throughput guarantees of all EDCA stations.

$P_{t,max,i}$ can be obtained by imposing $r_i \geq R_i$ and isolating P_t from Eq. (31). Given the $P_{t,max,i}$'s we can then compute from Eq. (32) the value of $P_{t,max}$. Note that this value is a constant that depends only on the CW_i configuration obtained in the previous section.

The remaining challenge is to design an adaptive algorithm that, by observing the transmission probability P_t in the channel, adjusts P_{ack} such that the channel's transmission probability is equal to $P_{t,max}$. Note that the key advantage of the proposed algorithm is that, by monitoring the WLAN's behavior, we can adjust the probability of skipping an Ack to the minimum value that current conditions allow, and thus we disrupt legacy stations as little as possible. Specifically, note the following:

- With our algorithm, P_{ack} is adjusted dynamically to the behavior of the DCF stations. Indeed, as only the DCF stations currently active contribute to P_t , these are the only ones taken into account when adjusting P_{ack} .
- P_{ack} is also dynamically adjusted to the behavior of the EDCA stations. Indeed, if some of the EDCA stations are

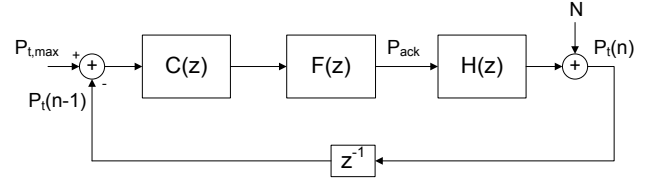


Fig. 3. Block diagram of the controlled system.

not active, those do not contribute to P_t and therefore the setting of P_{ack} is not unnecessarily penalized because of them.

Following the above, we next design an algorithm based on control theory that adjusts P_{ack} as a function of the P_t observed in the channel with the goal of forcing that this P_t equals the target $P_{t,max}$.

5.2 DACKS Control System

Based on the above, our goal is to design a control law that drives the transmission probability P_t to the desired target value $P_{t,max}$ computed in Eq. (32). To this aim, we build the closed loop control system illustrated in Figure 3, which consists of the following blocks:

- $H(z)$ represents the WLAN system. The system is controlled by P_{ack} and its output is the occupation of each slot time (where an output of '1' means that a slot time is occupied and '0' that it is empty). We consider that this occupation function is given by the average transmission probability of the WLAN system, P_t , added to some noise of zero mean, which we represent by N .
- $C(z)$ is the controller module. It takes the error, given by $P_{t,max} - P_t$, as input, and computes from this error the control signal.
- In order to eliminate the noise fed from N into the control signal, we introduce (following the design guidelines of [19]) a low-pass filter $F(z)$ to eliminate this undesired noise. The resulting control signal free from noise is the probability of replying a frame from a DCF station with an Ack, P_{ack} .

For the transfer function of the controller $C(z)$, in this paper we focus on a very simple controller from classical control theory, namely the Proportional Controller [20]:

$$C(z) = K_p \quad (33)$$

For the low-pass filter $F(z)$, we use a simple exponential smoothing algorithm of parameter α [21],

$$F_{out}[n] = \alpha F_{in}[n] + (1 - \alpha)F_{out}[n - 1] \quad (34)$$

where F_{in} and F_{out} are the input and output signals of the filter, respectively.

Since the output of the filter $F(z)$ is the probability P_{ack} , we need to enforce that it stays between 0 and 1. We do this by setting

$$P_{ack}[n] = \max(0, \min(1, F_{out}[n])) \quad (35)$$

which generates the following clipping error

$$e[n] = \max(0, \min(1, F_{out}[n])) - F_{out}[n] \quad (36)$$

In order to eliminate this error, we follow the strategy of [22] of subtracting the error of the previous sample into the input of the following one. With this, Eq. (34) is rewritten as

$$F_{out}[n] = \alpha(F_{in}[n] - e[n-1]) + (1 - \alpha)F_{out}[n-1] \quad (37)$$

In the analysis of the rest of this section, we assume that F_{out} keeps always in the range $(0, 1)$ and neglect the effect of the clipping error. With this assumption, $F(z)$ behaves as a first order filter with the following transfer function:

$$F(z) = \frac{\alpha}{1 - (1 - \alpha)z^{-1}} \quad (38)$$

It can be seen from the above that our control system relies on two parameters, namely K_p and α . The rest of this section is devoted to analyzing the system with the goal of finding an appropriate setting for these parameters.

5.3 Transient Analysis of 802.11

In the system illustrated in Figure 3, we need to characterize the WLAN transfer function $H(z)$. To this aim, the transient response of an 802.11 WLAN system has to be studied. While 802.11 has been widely analyzed under stationary conditions (including our analysis presented in Section 4), its transient response to changing conditions has received much less attention. Indeed, although a number of papers have studied different aspects of the transient response of 802.11 [23], [24], [25], to the knowledge of the authors ours is the first attempt to analyze the transient response of the complete 802.11 protocol under general conditions⁹.

In our analysis, we will assume that the number of active DCF stations and the number of active EDCA stations are constant. Note that, with this assumption, the effect of all EDCA stations can be captured with the probability that a slot time contains the transmission of at least one EDCA station. We denote this probability by P_{edca} .

To model the transient behavior of the WLAN our goal is to compute the probability that a DCF station transmits at a slot time n , $\tau_{dcf}[n]$, given the transmission probability of the DCF station in the previous slot time, $\tau_{dcf}[n-1]$, and the probability P_{ack} . Note that in stationary conditions we will have $\tau_{dcf}[n-1] = \tau_{dcf}[n]$.

The key approximation upon which we base our transient analysis is the following. We assume that the relationship between the state probability P_i and the transmission probability τ_{dcf} given by Eqs. (15) and (16), which has been derived under stationary conditions, also holds during transients. Specifically, we assume that a given slot time $n-1$ we have

$$P_i[n-1] = \left(1 - 2 \frac{\tau_{dcf}[n-1] - \tau_{dcf,0}}{\tau_{dcf}[n-1] - 2\tau_{dcf,0}}\right) \cdot \left(2 \frac{\tau_{dcf}[n-1] - \tau_{dcf,0}}{\tau_{dcf}[n-1] - 2\tau_{dcf,0}}\right)^i \quad (39)$$

9. In particular, [23] analyzes a dynamic 802.11 protocol which is different from the standard one, [24] analyzes the start-up of a simplified version of the protocol in which $CW_{min} = CW_{max}$ and [25] analyzes the recovery time under a disaster scenario. None of these analyses models the transient behavior with a transfer function that can be used for a control theory study.

where $\tau_{dcf}[n-1]$ is the transmission probability at this slot time.

Given $P_i[n-1]$, the state probabilities at the next slot time n can be computed as follows: if the station does not transmit at time $n-1$, it stays in the same state at time n ; if it transmits successfully, it moves to state 0; if it collides it moves to state $i+1$. This yields

$$P_i[n] = P_i[n-1](1 - \tau_{dcf,i}) + P_{i-1}[n-1]\tau_{dcf,i-1}c_{dcf}, i > 0 \quad (40)$$

and

$$P_0[n] = P_0[n-1](1 - \tau_{dcf,0}) + \sum_{i=0}^{\infty} P_i[n-1]\tau_{dcf,i}(1 - c_{dcf}) \quad (41)$$

where c_{dcf} , the probability that a transmission at slot time $n-1$ collides, is given by

$$1 - c_{dcf} = (1 - P_{edca})(1 - \tau_{dcf}[n-1])^{N_{dcf}-1}(1 - P_{ack}) \quad (42)$$

With the above, we can compute $\tau_{dcf}[n]$ as follows. By definition,

$$\tau_{dcf}[n] = \sum_{i=0}^{\infty} P_i[n]\tau_{dcf,i} \quad (43)$$

Applying Eqs. (41) and (40) to $P_i[n]$ in the above equation we have

$$\begin{aligned} \tau_{dcf}[n] &= P_0[n-1](1 - \tau_{dcf,0})\tau_{dcf,0} \quad (44) \\ &+ \sum_{i=0}^{\infty} P_i[n-1]\tau_{dcf,i}(1 - c_{dcf})\tau_{dcf,0} \\ &+ \sum_{i=1}^{\infty} P_i[n-1](1 - \tau_{dcf,i})\tau_{dcf,i} \\ &+ \sum_{i=1}^{\infty} P_{i-1}[n-1]\tau_{dcf,i-1}c_{dcf}\tau_{dcf,i} \end{aligned}$$

Recombining the above terms and considering that $\tau_{dcf,i} = \tau_{dcf,i-1}/2$ we obtain

$$\begin{aligned} \tau_{dcf}[n] &= \sum_{i=0}^{\infty} P_i[n-1]\tau_{dcf,i} - \sum_{i=0}^{\infty} P_i[n-1]\tau_{dcf,i}^2 \\ &+ (1 - c_{dcf})\tau_{dcf,0} \sum_{i=0}^{\infty} P_i[n-1]\tau_{dcf,i} \\ &+ \frac{c_{dcf}}{2} \sum_{i=0}^{\infty} P_i[n-1]\tau_{dcf,i}^2 \quad (45) \end{aligned}$$

where the first term of Eq. (44) has been integrated into the first two sums of the above equation.

The term $\sum P_i[n-1]\tau_{dcf,i}$ is by definition equal to $\tau_{dcf}[n-1]$. The term $\sum P_i[n-1]\tau_{dcf,i}^2$ can be expressed as follows:

$$\begin{aligned} \sum_{i=0}^{\infty} P_i[n-1]\tau_{dcf,i}^2 &= \sum_{i=0}^{\infty} \left(1 - 2 \frac{\tau_{dcf}[n-1] - \tau_{dcf,0}}{\tau_{dcf}[n-1] - 2\tau_{dcf,0}}\right) \\ &\cdot \left(2 \frac{\tau_{dcf}[n-1] - \tau_{dcf,0}}{\tau_{dcf}[n-1] - 2\tau_{dcf,0}}\right)^i \left(\frac{\tau_{dcf,0}}{2^i}\right)^2 \quad (46) \end{aligned}$$

which, solving the series, yields

$$\sum_{i=0}^{\infty} P_i[n-1]\tau_{dcf,i}^2 = \frac{2\tau_{dcf}[n-1]\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \quad (47)$$

Finally, combining all the above we obtain the following equation which describes the system behavior under transient conditions

$$\begin{aligned} \tau_{dcf}[n] &= \tau_{dcf}[n-1] + (1 - c_{dcf})\tau_{dcf,0}\tau_{dcf}[n-1] \\ &\quad - (1 - c_{dcf}/2)\frac{2\tau_{dcf}[n-1]\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \end{aligned} \quad (48)$$

where c_{dcf} is a function of P_{ack} given by Eq. (42).

Note that by imposing stationary conditions (i.e., $\tau_{dcf}[n-1] = \tau_{dcf}[n]$) the above equation results in Eq. (16), which we have obtained with the stationary analysis of Section 4.2.

5.4 Linearized Model

The above transient analysis has resulted in a nonlinear relationship between τ_{dcf} and P_{ack} . In order to analyze the problem from a control theoretic standpoint, we need to obtain a linear relationship that can be captured by a transfer function. To achieve this, we linearize Eq. (48) around the stable point of operation of the system¹⁰.

The stable point of operation of the WLAN can be obtained from forcing $\tau_{dcf}[n-1] = \tau_{dcf}[n]$ in Eq. (48) and isolating τ_{dcf} . We express the perturbations around this point as $\tau_{dcf} + \Delta\tau_{dcf}$. When these perturbations are small, they can be approximated by:

$$\Delta\tau_{dcf}[n] \approx \frac{\partial\tau_{dcf}[n]}{\partial\tau_{dcf}[n-1]}\Delta\tau_{dcf}[n-1] + \frac{\partial\tau_{dcf}[n]}{\partial P_{ack}}\Delta P_{ack} \quad (49)$$

where $\tau_{dcf}[n]$ is the right hand side expression of Eq. (48).

The above expression provides a linear relationship between $\tau_{dcf}[n]$ and P_{ack} ; however, in order to obtain $H(z)$ we need to find a linear relationship between $P_t[n]$ and P_{ack} . We do this as follows:

$$\Delta P_t[n] \approx \frac{\partial P_t[n]}{\partial P_t[n-1]}\Delta P_t[n-1] + \frac{\partial P_t[n]}{\partial P_{ack}}\Delta P_{ack} \quad (50)$$

where

$$\begin{aligned} \frac{\partial P_t[n]}{\partial P_t[n-1]} &= \frac{\partial P_t[n]}{\partial\tau_{dcf}[n]} \frac{\partial\tau_{dcf}[n]}{\partial\tau_{dcf}[n-1]} \frac{\partial\tau_{dcf}[n-1]}{\partial P_t[n-1]} = \\ &= \frac{\partial\tau_{dcf}[n]}{\partial\tau_{dcf}[n-1]} \end{aligned} \quad (51)$$

and

$$\frac{\partial P_t[n]}{\partial P_{ack}} = \frac{\partial P_t[n]}{\partial\tau_{dcf}[n]} \frac{\partial\tau_{dcf}[n]}{\partial P_{ack}} \quad (52)$$

With the above, we have the following expression for the relationship between ΔP_t and ΔP_{ack} :

$$\Delta P_t[n] = H_1\Delta P_t[n-1] + H_2\Delta P_{ack} \quad (53)$$

where the expressions for the coefficients H_1 and H_2 are computed from Eqs. (51) and (52) in Appendix I.

10. A similar approach was used in [26] to analyze RED from a control theoretic standpoint.

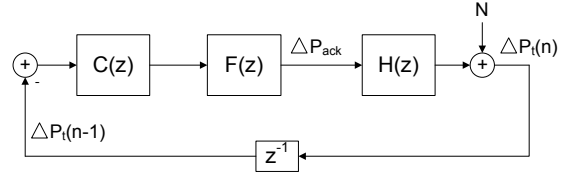


Fig. 4. Block diagram of the linearized system.

By doing the Z -transform of the above equation we obtain

$$\Delta P_t(z) = H_1\Delta P_t(z)z^{-1} + H_2\Delta P_{ack}(z) \quad (54)$$

from where, by isolating $\Delta P_t(z)/\Delta P_{ack}(z)$, we finally obtain $H(z)$:

$$H(z) = \frac{H_2}{1 - H_1z^{-1}} \quad (55)$$

5.5 Stability Analysis

We now study the system when it suffers perturbations around its point of operation and analyze the conditions that guarantee local stability.

Figure 4 illustrates the linearized model when working around the stable operation point:

$$P_t = P_t + \Delta P_t \quad (56)$$

$$P_{ack} = P_{ack} + \Delta P_{ack} \quad (57)$$

Note that, as compared to the model of Figure 3, in Figure 4 only perturbations around the stable operation point are considered.

The closed-loop transfer function of the system of Figure 4 is given by:

$$T(z) = \frac{C(z)H(z)F(z)}{1 + z^{-1}C(z)H(z)F(z)} \quad (58)$$

Substituting Eqs. (33), (38) and (55) into the above yields

$$T(z) = \frac{K_p\alpha H_2}{(1 - (1 - \alpha)z^{-1})(1 - H_1z^{-1}) + z^{-1}K_p\alpha H_2} \quad (59)$$

which can be rewritten as

$$T(z) = \frac{K_p\alpha H_2 z^2}{z^2 + a_1 z + a_2} \quad (60)$$

with

$$a_1 = K_p\alpha H_2 - H_1 - (1 - \alpha) \quad (61)$$

$$a_2 = H_1(1 - \alpha) \quad (62)$$

A sufficient condition for stability is that the poles of the above polynomial fall within the unit circle $|z| < 1$. This can be ensured by choosing coefficients $\{a_1, a_2\}$ of the characteristic polynomial that belong to the stability triangle [27]:

$$a_2 < 1 \quad (63)$$

$$a_1 < a_2 + 1 \quad (64)$$

$$a_1 > -1 - a_2 \quad (65)$$

Eq. (63) is met given that $1 - \alpha < 1$ and $H_1 < 1$. Eq. (65) is met given that

$$-1 - a_2 = -1 - H_1 + H_1\alpha < 1 - H_1 + \alpha < a_1 \quad (66)$$

Eq. (63) imposes the following restriction

$$K_p\alpha H_2 - H_1 - (1 - \alpha) < H_1(1 - \alpha) + 1 \quad (67)$$

from which we obtain the following restriction on K_p

$$K_p < \left(\frac{2 - \alpha}{\alpha} \right) \frac{1 + H_1}{H_2} \quad (68)$$

As long as the configuration of K_p is smaller than the above expression, the system is guaranteed to be stable. However, H_1 and H_2 in the above expression are a function of the number of active DCF stations, N_{dcf} , and the behavior of the EDCA stations, given by P_{edca} . These values are not known a priori and may vary with time.

In order to assure stability, we need to find some upper bound for K_p that guarantees stability independent of N_{dcf} and P_{edca} . This bound is given by Theorem 1 (in Appendix II), which shows that as long as K_p is configured smaller than K_p^{max} the system will be stable, K_p^{max} being a constant value given by the following expression

$$K_p^{max} = \left(\frac{2 - \alpha}{\alpha} \right) \frac{1 + H_1^{min}}{H_2^{max}} \quad (69)$$

where the expressions for H_1^{min} and H_2^{max} are given in Appendix II. This terminates the stability analysis.

5.6 Parameter Setting

The stability analysis conducted in the previous section provides a range for the parameters values where the system is guaranteed to be stable. In this section we propose specific rules for setting the parameters α and K_p within this range. The proposed rules aim at *i*) ensuring that the system behaves stably while reacting quickly to changes, and *ii*) eliminating from the system the noise caused by the oscillations of P_t . In the following, we first fix α and then, with the given value of α , we set K_p such that these two objectives are met.

The parameter α of the low-pass filter is fixed based on the following criterion. The goal of the low-pass filter is to eliminate the fluctuations introduced to the system by P_t . Since, with a transmission probability of $P_{t,max}$, there is approximately one transmission every $P_{t,max}$ samples, the frequency that needs to be filtered out is approximately equal to $2\pi/P_{t,max}$. Following this reasoning, we impose as design criterion that the low-pass filter reduces this frequency by a factor G_F :

$$|F(2\pi/P_{t,max})| = G_F \quad (70)$$

With the above, the problem of configuring α is reformulated as to finding the value that satisfies Eq. (70). Combining this with Eq. (38) yields

$$\left| \frac{\alpha}{1 - (1 - \alpha)[\cos w + j \sin w]} \right|^2 = G_F^2 \quad (71)$$

where

$$w = \frac{2\pi}{P_{t,max}} \quad (72)$$

Operating on the above equation we obtain

$$(1 - (1 - \alpha) \cos w)^2 + (1 - \alpha)^2 \sin^2 w = \alpha^2 G_F^{-2} \quad (73)$$

which is a second order equation from which we can isolate α :

$$\alpha = \frac{-(1 - \cos w) + \sqrt{(1 - \cos w)^2 + 2(G_F^{-2} - 1)(1 - \cos w)}}{G_F^{-2} - 1} \quad (74)$$

which terminates the setting of α .

Given the above α setting, we next address the configuration of the parameter K_p in order to meet the two goals set at the beginning of this section. We start by analyzing the setting of K_p following stability considerations.

From a stability standpoint, we have a tradeoff between system stability and speed of reaction to changes. The larger K_p , the fastest the system reacts to changes; however, if K_p is chosen too large the system becomes unstable (as we have seen in the previous section). In order to determine the right tradeoff between these two effects in the setting of the K_p parameter, we follow the Ziegler-Nichols rules [20] which are widely used to configure proportional controllers. According to these rules, we impose that this parameter cannot be larger than one half of the maximum value that guarantees stability,

$$K_p \leq K_p^{stability} = \frac{K_p^{max}}{2} \quad (75)$$

In addition to the above, K_p also needs to be set according to the objective of eliminating the noise from the system. The noise caused by the fluctuations of P_t around frequency w is amplified into the input signal P_{ack} by $|C(w)F(w)|$. In order to avoid that this noise causes too large oscillations on the input signal, we impose as a design criterion that this gain is no larger than G_{CF} ,

$$|C(w)F(w)| = K_p G_F \leq G_{CF} \quad (76)$$

Isolating K_p from the above equation, we obtain the largest K_p allowed by the considerations on noise,

$$K_p \leq K_p^{noise} = \frac{G_{CF}}{G_F} \quad (77)$$

Finally, based on the above, we configure K_p as follows to guarantee that the two objectives set at the beginning of this section on stability and noise are met:

$$K_p = \min(K_p^{stability}, K_p^{noise}) \quad (78)$$

Note that the configuration proposed above depends on the setting of two parameters, G_F and G_{CF} . To provide appropriate filtering and attenuate noise, these parameters should take small values. Furthermore, to allow sufficiently large K_p^{noise} values, Eq. (77) imposes $G_{CF} \gg G_F$. Following these considerations, in this paper we take $G_{CF} = 10^{-2}$ and $G_F = 10^{-4}$.

6 PERFORMANCE EVALUATION

In order to evaluate the performance of DACKS, we have performed an exhaustive set of simulation experiments. For the simulations, we have extended the simulator used in [15], [28]; this is an event-driven simulator that closely follows the details of the MAC protocol of 802.11 EDCA. For all tests, we have taken a fixed frame payload size of 1000 bytes and the system parameters of the IEEE 802.11b physical layer [29]. For the simulation results, average and 95% confidence interval values are given (note that in many cases confidence intervals are too small to be appreciated in the graphs). Analytical results have been obtained by conducting an exhaustive search over P_{ack} to find the largest value that meets the requirements of EDCA stations and then computing the throughputs resulting from the analysis of Section 4 with this P_{ack} . Unless otherwise stated, we assume that all stations are saturated, i.e. they always have a packet ready for transmission. The experiments from Sections 6.1 to 6.13 focus on a single EDCA Access Category (AC 1), while the experiments from Sections 6.17 to 6.19 extend the evaluation to more than one AC.

6.1 Throughput Guarantees

In our first experiment, we evaluated the ability of DACKS to provide throughput guarantees to the EDCA stations. To this aim, we considered a scenario with N_{edca} EDCA stations, all belonging to the same AC (AC 1), and N_{dcf} DCF stations. The EDCA stations were given a throughput guarantee of 300 Kbps. We took $N_{edca} = N_{dcf} = N$ and varied N from 2 to the maximum number of stations allowed by our admission control algorithm. The results of this experiment are illustrated in Figure 5. Analytical results are represented with lines, and simulations with points with errorbars. An horizontal line is used to show the guaranteed throughput. We can observe from the figure that

- i) The proposed DACKS technique is effective in providing throughput guarantees. Indeed, we observe that for all N values, EDCA stations never have a throughput below 300 Kbps.
- ii) The throughput experienced by the DCF stations decreases as N increases. Indeed, as the load in the WLAN increases, DACKS forces DCF stations to decrease their transmission probability in order to preserve the committed guarantees to the EDCA stations.
- iii) Analytical results follow simulations closely, which validates our analytical model.

We conclude from this experiment that our goal of providing throughput guarantees to EDCA in presence of DCF stations is achieved by the proposed solution.

6.2 Number of DCF stations

In the experiment of the previous section, the number of EDCA stations has been taken equal to the number of DCF stations. In order to evaluate the performance of DACKS in scenarios with different numbers of EDCA and DCF stations, we performed the following experiment. We fixed the number of EDCA stations (N_{edca}) to 5 (low load), 10 (medium

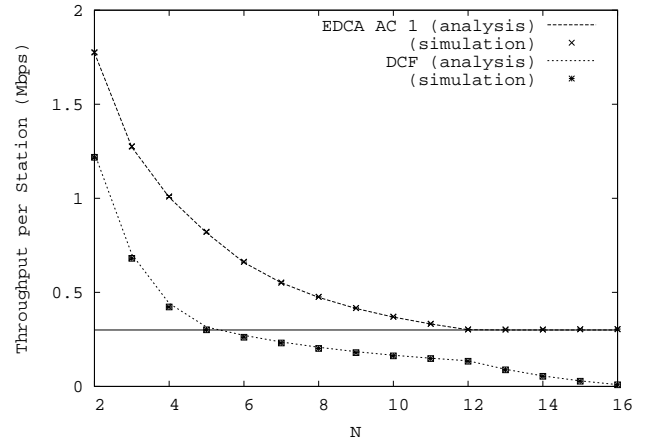


Fig. 5. Throughput Guarantees.

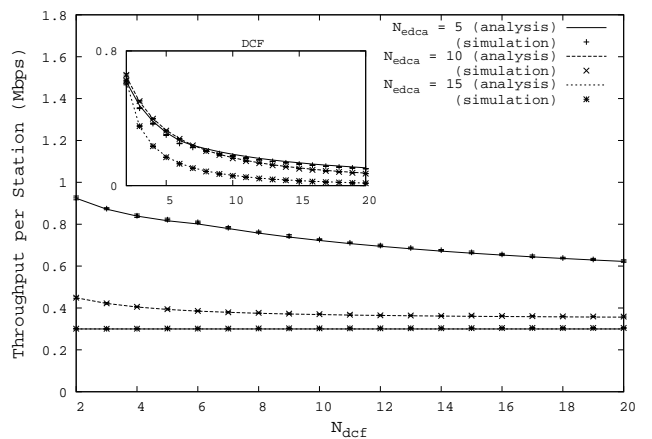


Fig. 6. Number of DCF stations.

load) and 15 (high load) stations, and varied the number of DCF stations (N_{dcf}) from 2 to 20. The resulting throughputs obtained analytically and via simulation for EDCA and DCF stations are given in the main plot and subplot of Figure 6, respectively. Results confirm the effectiveness of DACKS in providing throughput guarantees to EDCA stations while minimizing the disruption suffered by DCF stations. Furthermore, results validate our analytical model also for this case.

6.3 Total throughput

In addition to providing throughput guarantees, one of our goals is also to optimize the overall throughput performance. In order to assess the performance of the CW_i configuration proposed in Section 4.4, we compared the total throughput obtained with our CW_i setting against the result of performing an exhaustive search over CW_i and choosing the best configuration. Specifically, in the exhaustive search we evaluated all possible CW_i values, choosing for each one the largest P_{ack} that ensured the desired throughput guarantees, and took the CW_i value that provided the largest total throughput.

The results of the above experiment are depicted in Figure 7 as a function of $N_{edca} = N_{dcf} = N$. We can see that the total performance achieved by our configuration (points) follows closely the one resulting from the exhaustive search

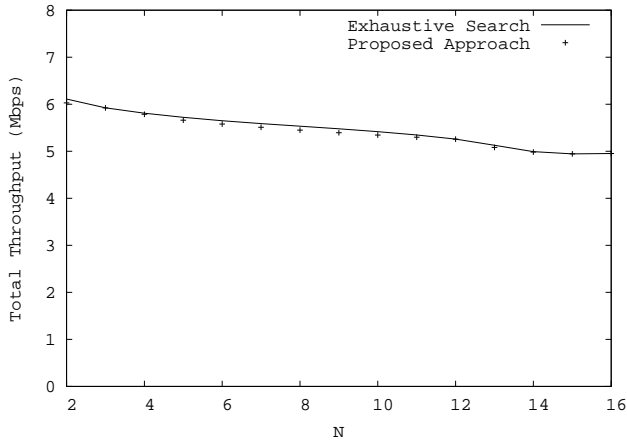


Fig. 7. Total throughput.

(line). In particular, for large N values the total throughput with our configuration is almost identical to the one obtained with the exhaustive search. Note that efficiency is particularly critical in this situation, since it is when stations receive smaller throughputs. We therefore conclude that, in addition to providing throughput guarantees, our scheme is also effective in optimizing the overall throughput performance in the region of interest.

6.4 Admissibility region

According to the results of Figure 5, the maximum number of stations that can be admitted by our algorithm with a throughput guarantee of 300 Kbps is $N = 16$. In order to see whether some setting exists that could possibly admit more stations, we performed the following experiment. We took $N = 17$ stations, and ran an exhaustive search over the CW_i configuration. In order to minimize the disruption introduced by the DCF stations, we fixed $P_{ack} = 0$. Figure 8 shows the throughputs as a function of CW_i (obtained analytically and via simulation). We can see that there is no CW_i value that provides EDCA with the desired throughput, which confirms that there is no way of admitting $N = 17$ stations in the system. We conclude that our system admits as many stations as possible maximizing thus the admissibility region.

6.5 WLAN without DACKS

In order to assess the benefits gained from DACKS, we compared its performance against a WLAN without DACKS configured according to the two following strategies:

- *Standard configuration:* EDCA stations are configured with the CW_i setting recommended by the standard [2] for voice traffic, which is the one that gives the highest priority to EDCA over DCF.
- *Optimal configuration:* For each N value, we configure EDCA stations with the CW_i setting that maximizes their throughput; note that this setting has the advantage of maximizing the admissibility region.

Results on the total throughput and the throughput of EDCA and DCF stations are given in Figure 9. We first observe that

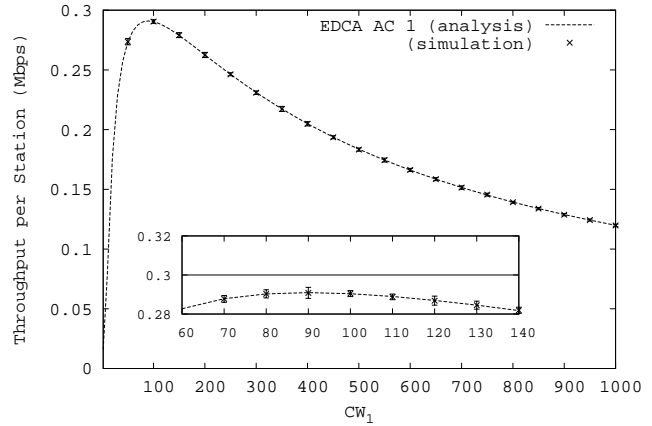


Fig. 8. Admissibility region.

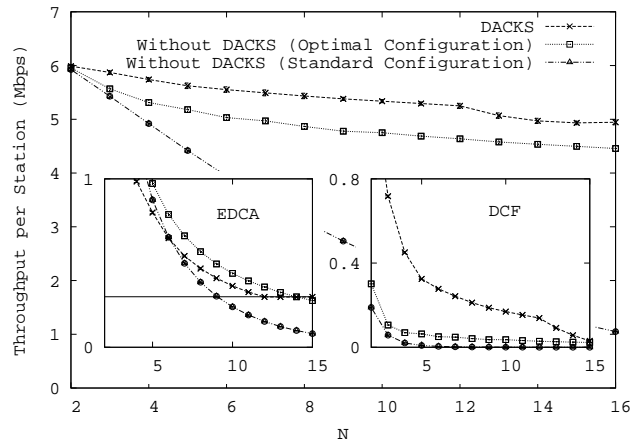


Fig. 9. WLAN without DACKS.

DACKS outperforms the strategies without DACKS in terms of total throughput. Looking at the per station throughputs, we see that the three approaches give similar throughput to EDCA stations, while DACKS provides a substantial larger throughput to DCF stations. The reasons for this improvement are further analyzed in the next experiment.

We further observe that DACKS allows admitting more EDCA stations while meeting the throughput guarantees. Indeed, up to 16 stations can be admitted with DACKS, while only 13 and 9 stations can be admitted with the optimal and standard configurations, respectively. We conclude that DACKS benefits both DCF stations (by providing them with more throughput) and EDCA stations (by increasing the number of stations that can be admitted).

6.6 Collision rate

The reason for the performance improvement achieved with DACKS is that, although DACKS wastes some time in the retransmission of successful frames whose Acks are skipped, a WLAN without DACKS wastes much more time in collisions. Indeed, in a WLAN without DACKS, the aggressiveness of DCF stations cannot be controlled and, as a consequence, EDCA stations need to behave aggressively as well, which results in many collisions. In order to illustrate this behavior,

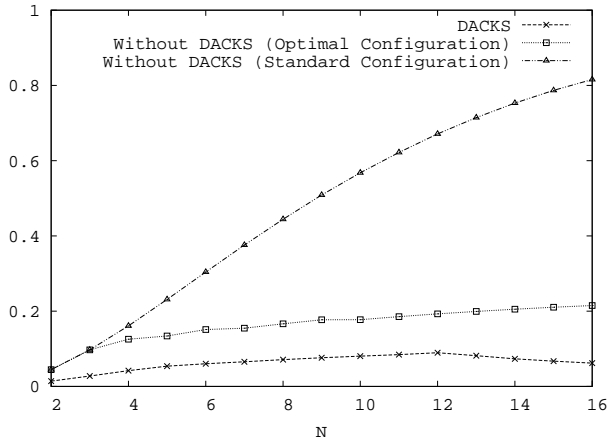


Fig. 10. Collision rate.

Figure 10 shows the collision rate with DACKS for the same scenario as the previous experiment and compares it against the collision rate for the strategies without DACKS. This result confirms that the collision rate with DACKS is indeed much smaller than with the other approaches.

6.7 P_{ack} tuning

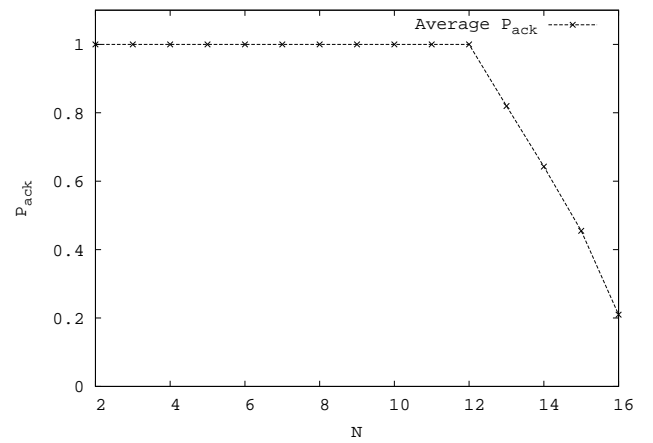
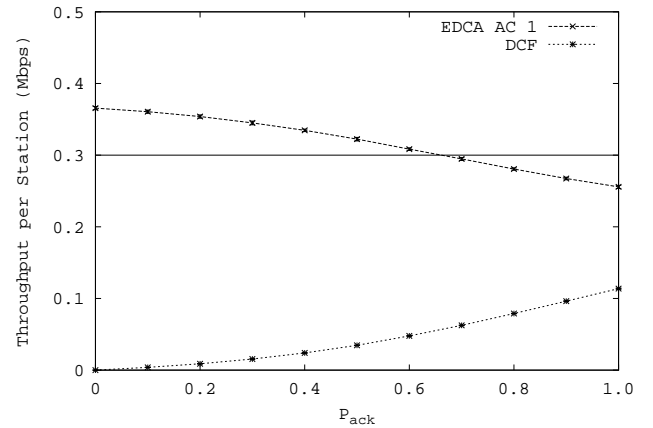
In our system, the probability P_{ack} of replying a DCF transmission with an Ack is automatically adjusted by the DACKS controller. Figure 11 depicts the average P_{ack} probabilities measured for the different scenarios considered in Figure 5. We observe that (as expected) P_{ack} decreases as the number of stations increases, which is necessary in order to provide EDCA stations with the desired throughput guarantees.

In DACKS, the algorithm that adjusts P_{ack} dynamically has been designed with the following goals: *i*) provide EDCA stations with the committed throughputs, and *ii*) minimize the disruption suffered by the DCF stations. In order to validate the ability of our system to achieve these goals, we performed the following experiment for the scenario $N = 14$. We swept along all possible values of P_{ack} in steps of 0.1. In each step, we set P_{ack} statically to this value and evaluated the system performance in terms of the throughput of the EDCA and the DCF stations.

The results of the above experiment are given in Figure 12. We can observe from these results that the P_{ack} value that provides the desired throughput guarantees to EDCA while minimizing the disruption of DCF is $P_{ack} = 0.65$, which is approximately the same P_{ack} value that we have in Figure 11 for $N = 14$. The resulting throughput performance for this setting in Figure 11 is of about 300 Kbps for the EDCA stations and 65 Kbps for the DCF ones, which is about the same performance as the provided by our system according to the results of Figure 5. This confirms the ability of our system to optimally adjust P_{ack} .

6.8 Stability

One of the objectives of the configuration setting computed in Section 5 is to ensure that the system is stable. In order to evaluate the stability of our configuration, we analyzed the

Fig. 11. Average P_{ack} .Fig. 12. P_{ack} tuning.

evolution of the control signal (P_{ack}) over time and compared it against a configuration with K_p set to a value 100 times larger. Figure 13 depicts the time plots for our configuration (straight line) and for the configuration with larger K_p (dotted line) for the scenario with $N = 15$. We observe from the figure that with our configuration P_{ack} oscillates stably around the average value, while the configuration with larger K_p shows an unstable behavior with large oscillations of P_{ack} that go from 0 (where DCF stations are starved) to 1 (where DCF stations are uncontrolled). These results confirm the effectiveness of our configuration to ensure stability.

6.9 Instantaneous throughput

From the perspective of the service delivered to the stations, system's stability is important in order to avoid oscillations in the instantaneous throughput experienced by the stations. In order to assess the impact of our closed-loop system onto instantaneous throughput, we analyzed the evolution (averaged over 1 second intervals) of the throughput experienced by an EDCA station. To distinguish the oscillations in throughput caused by our closed-loop system from the inherent oscillations resulting from the random nature of the WLAN channel, we compared our system against an open-loop system in which P_{ack} was set to a constant value (in particular, to the largest

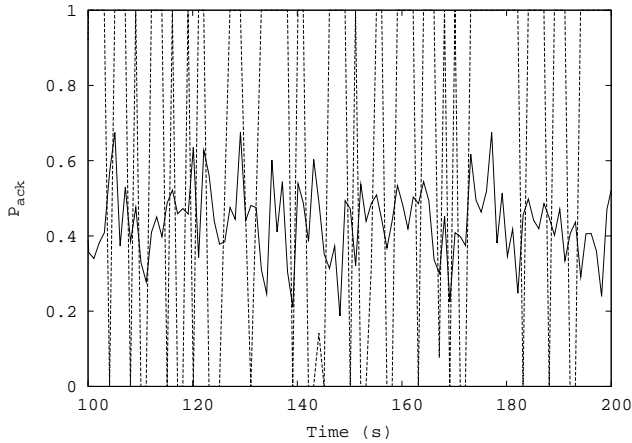


Fig. 13. Stability.

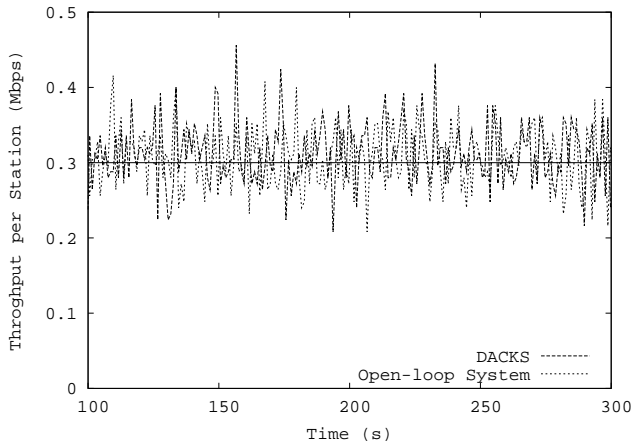


Fig. 14. Instantaneous throughput.

value that guarantees the desired throughput for EDCA). Note that in the open-loop system, as the input variable P_{ack} is fixed, oscillations are caused only by the random nature of the MAC algorithm.

Figure 14 shows the instantaneous throughput of the above closed and open-loop systems for $N = 15$. We observe that both systems suffer similar oscillations in the instantaneous throughput. Indeed, if we compare the standard deviation around the average, we see that they are almost identical: 0.0334 Mbps for DACKS and 0.0337 for the open-loop. This confirms the stability of DACKS since no additional oscillations (other than the ones resulting from the random channel access) are created by the closed-loop.

6.10 Changing conditions

In addition to stability, another objective of the configuration setting computed in Section 5 is to ensure that the system reacts quickly upon changes. In order to study the system’s transient response to changes, we performed the following experiment. Initially, we had the system operating with $N_{edca} = N_{dcf} = 5$. At some time instant ($t = 200$ seconds) we introduced 10 additional DCF stations in the system ($N_{dcf} = 15$). At some later instant ($t = 300$ seconds) we introduced 10 further additional EDCA stations

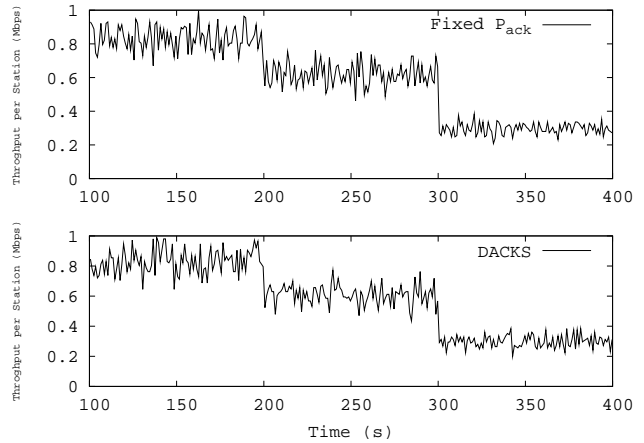


Fig. 15. Changing conditions.

($N_{edca} = 15$) which (in contrast to the previous case) triggered the corresponding configuration update. Figure 15 depicts the time plot of the throughput of one EDCA station. As a benchmark to assess the response of our system, we compare the instantaneous throughput with DACKS against that of a system where P_{ack} is immediately changed to a fixed new value upon the stations’ arrival. We observe from the figure that DACKS reacts quickly and smoothly to the changes. This and the previous experiments confirm the proposed configuration setting in terms of stability and response to changes.

6.11 Noisy channel

Our analysis and simulations so far have assumed an error-free channel in which transmissions only fail due to collisions¹¹. In order to gain insight into the impact of a noisy channel on DACKS, we ran the following experiment. We took $N = 5, 10$ and 15 , respectively, and varied the packet error rate (PER) from 0 to 0.1. Figure 16 illustrates the throughputs resulting from this experiment for EDCA and DCF stations as well as the average P_{ack} values. Results show that EDCA stations see a small throughput degradation (proportional to PER) while DCF stations see a slightly larger degradation when the WLAN is not stressed and an imperceptible degradation when it is stressed. We further observe that the average P_{ack} keeps approximately constant independent of the PER. Figure 17 further illustrates the EDCA and DCF throughputs for the standard configuration. We observe a similar behavior to DACKS.

The above experiment raises the question of whether the desired throughput guarantees will be met in case of noisy channels. Note that this is an inherent problem of throughput guarantees in EDCA independent of the presence of DCF stations. Based on our results, we argue that under typical error rates the throughput decrease is not significant. In case of large error rates, one possible strategy for a station may be to request

11. Another nonideal effect that could possibly happen is that a collision is not distinguished from noise if the signal strength is below the carrier sense threshold. Note, however, that a stations transmitting at such a low signal strength is unlikely to send successful frames or even associate to the AP [30]. Following this argument, in this paper we have not considered this effect.

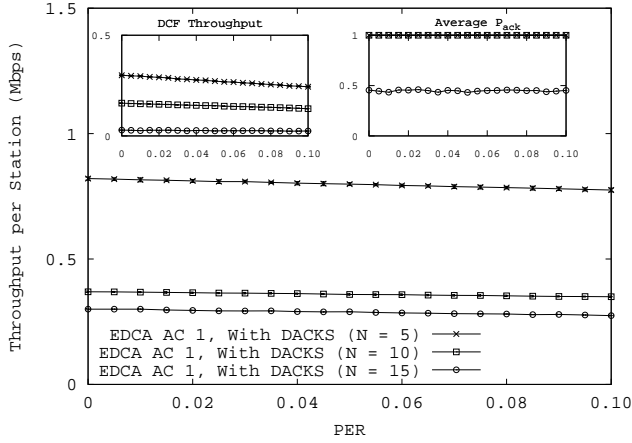


Fig. 16. Noisy channel.

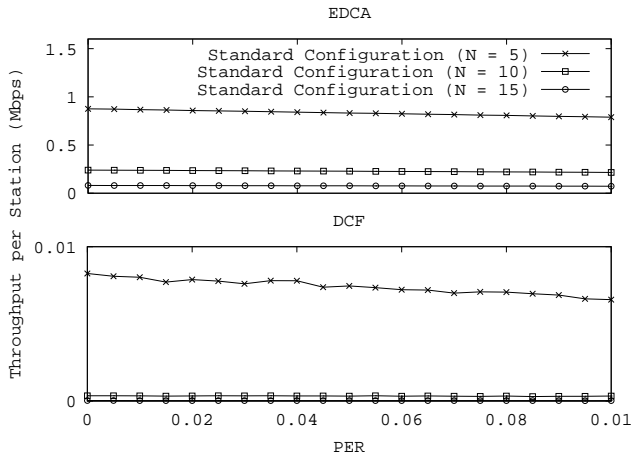


Fig. 17. Noisy channel for the standard configuration.

a larger throughput on account of the expected/measured error rate.

6.12 Validation of the transient model

One of the main contributions of this paper is the transient analysis of 802.11 presented in Section 5.3. In order to validate the model proposed, we performed the following experiment. We had ten DCF stations in the WLAN and at slot time 200, five of the stations left. Figure 18 illustrates the evolution of the total transmission probability in the channel, P_t , according to our transient model and to simulations. For the simulations, the total probability is computed by taking into account the backoff stage of each station and the corresponding transmission probability at this backoff stage as given by Eq. (3).

It can be seen from the figure that, when 5 of the stations leave, P_t drops to a smaller value as only half of the stations contribute to it. From this point on, stations suffer less collisions since they compete with fewer stations, and as a result their transmission probability increases gradually. We observe that simulation results follow our model; although there is a large degree of variability in the simulations, caused by the inherent randomness of P_t , the results given by our model fall within the confidence intervals of simulation results. This confirms the validity of the model.

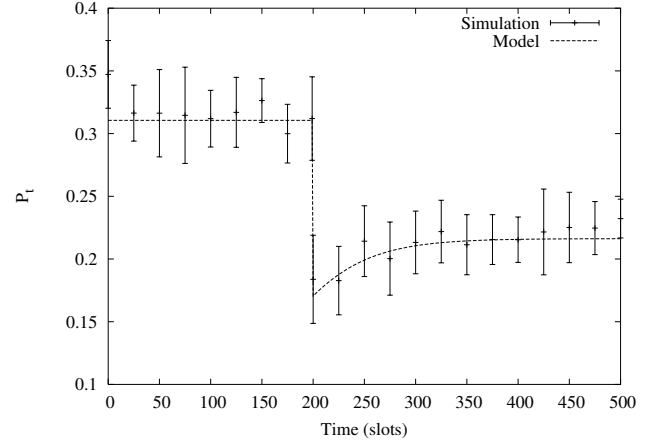


Fig. 18. Validation of the transient model.

6.13 Inactive stations

One of the design goals of the proposed DACKS scheme is its ability to dynamically adapt to the number of active DCF and EDCA stations. Specifically, the proposed scheme automatically adjusts P_{ack} to the traffic actually transmitted in the WLAN, in order to avoid degrading unnecessarily the throughput experienced by DCF stations.

In order to evaluate the above feature of the algorithm, we performed the following experiment. We had the WLAN configured to support $N_{edca} = N_{dcf} = 16$ stations, with and a throughput request of 300 Kbps for each EDCA station. Then, we had that out of the admitted EDCA stations, only N_{active} were active. Furthermore, we had a number of active DCF stations also equal to N_{active} . To understand the benefit of adjusting P_{ack} dynamically, we compared DACKS against a static configuration where P_{ack} was computed in order to provide the desired throughput guarantees with $N_{edca} = N_{dcf} = 16$.

Figure 19 illustrates the throughput of a DCF station resulting from the above experiment with DACKS and with the static configuration. We observe that DACKS achieves the objective of minimizing the disruption suffered by the DCF stations by avoiding skipping Ack frames when the actual WLAN conditions do not require it. In contrast, with the static configuration, Ack frames are still skipped with a high probability even when the actual number of active stations is very small, which severely degrades the DCF throughput. We conclude that the proposed adaptive DACKS approach outperforms very significantly the static approach proposed in [4].

6.14 Support for Best-Effort traffic

In order to evaluate the configuration for *Best-Effort* stations proposed in Section 4.5, we repeated the experiment of Figure 5 but with $\lceil N/2 \rceil$ BE stations and $\lfloor N/2 \rfloor$ DCF stations instead of N DCF stations. Results are given in Figure 20. We can observe from these results that the objectives set in Section 4.5 are met. In particular, the EDCA stations with throughput guarantees see their commitments satisfied, while EDCA BE and DCF stations share the remaining bandwidth fairly, with

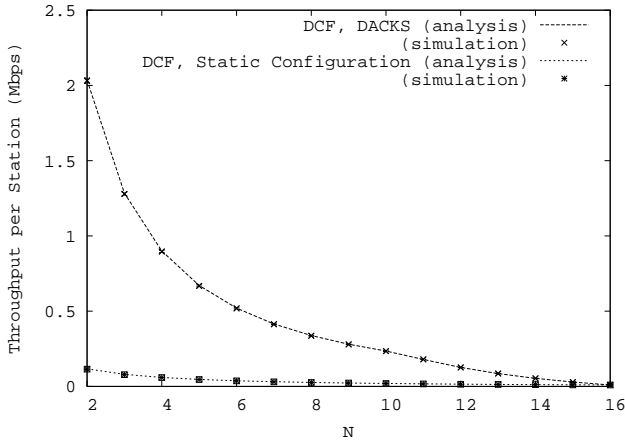


Fig. 19. Inactive stations.

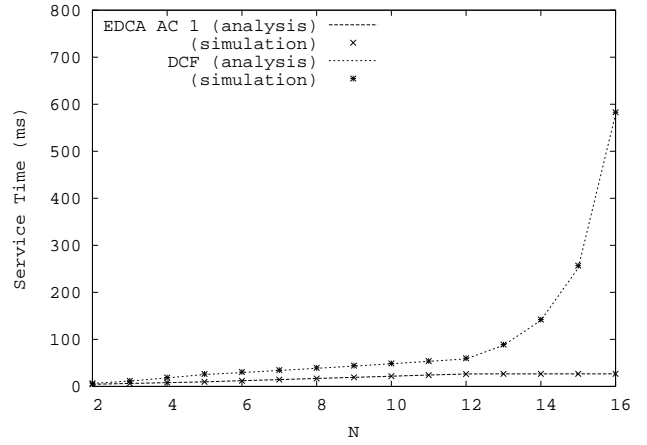


Fig. 21. Delay Performance.

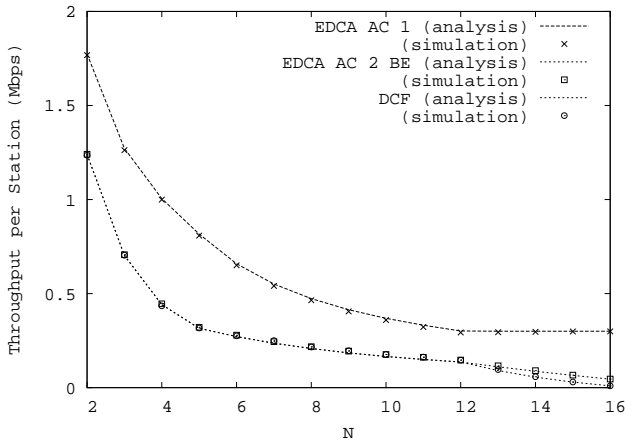


Fig. 20. Support for Best-Effort traffic.

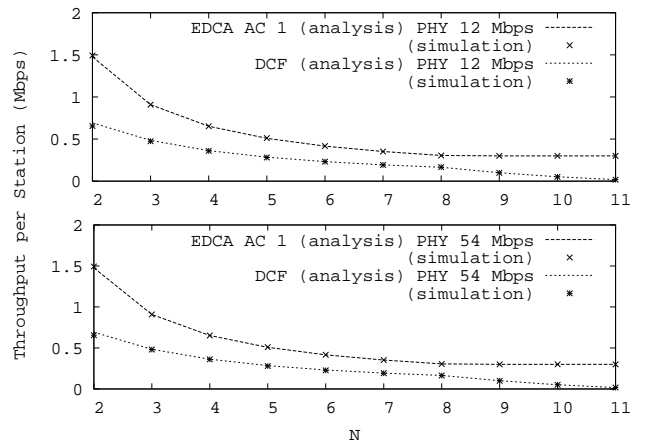


Fig. 22. Multirate WLAN.

only a small bias towards BE stations for large N values. This confirms the effectiveness of the proposed configuration for BE stations.

6.15 Delay Performance

In order to assess the delay performance resulting from DACKS, Figure 21 shows the service delays resulting from the experiment of Figure 5. We observe from the figure that the delays of EDCA stations always keep small regardless of the number of stations, while the delays of DCF stations keep small until $N = 12$ and grow sharply for larger N values. We conclude that *i*) DACKS is effective not only in giving throughput guarantees to EDCA stations but also in providing them with small delays, and *ii*) DCF stations only suffer from large delays when this is the only option to preserve the EDCA throughput guarantees.

6.16 Multirate WLAN

All the experiments performed so far considered that all stations are transmitting at the same physical rate. We note, however, that our approach can be used for any combination of physical rates in the WLAN, by simply taking into account the different rates into the equations that compute $P_{t,max}$. We

further note that, in case of rate adaptation, when a station changes its physical rates, the AP needs to be update $P_{t,max}$ to reflect the new physical rates in the WLAN.

In order to show that DACKS also works when there are stations transmitting at different physical rates in the WLAN, we performed the following experiment. We had:

- N 802.11g EDCA stations transmitting at the nominal rate (54 Mbps).
- N 802.11g EDCA stations trasmitting at a lower rate (12 Mbps).
- N 802.11g DCF stations transmitting at 54 Mbps.
- N 802.11g DCF stations transmitting at 12 Mbps.

Figure 22 depicts the throughput obtained by each station type. We observe that: *i*) the throughput guarantee of 300 Kbps is always met by the EDCA stations, independent of their physical rate, and *ii*) throughput is fairly shared between the 54 and the 12 Mbps stations. We conclude that DACKS is also effective in a multirate scenario.

6.17 Two AC's

The experiments performed so far involve one single EDCA Access Category with throughput guarantees. To gain insight into the performance of DACKS with more than one AC, we

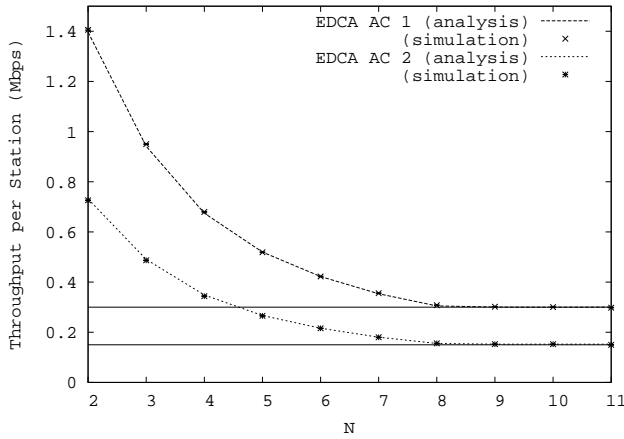


Fig. 23. Two AC's.

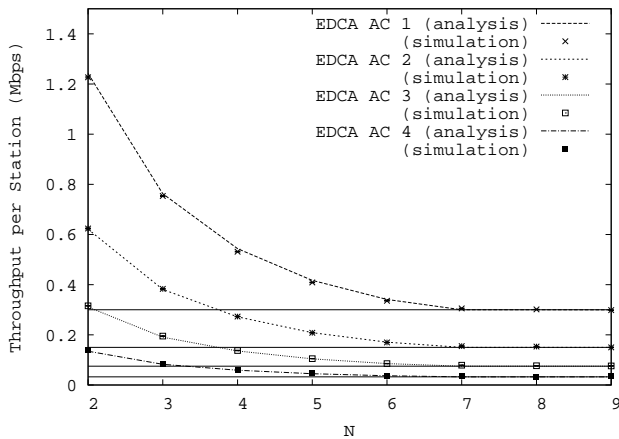


Fig. 24. Multiple AC's.

conducted the following experiment. We had two AC's, the first one with a throughput guarantee of 300 Kbps and the second one with 150 Kbps. The number of stations of each AC and of DCF stations was taken equal to $N_{edca,AC1} = N_{edca,AC2} = N_{dcf} = N$, with N being varied from 2 to the maximum number of stations that could be admitted. Figure 23 illustrates the throughput obtained by the EDCA stations of AC 1 and 2. We observe that the desired throughput guarantees are met in all cases, which confirms the effectiveness of DACKS when there are two AC's present in the WLAN.

6.18 Multiple AC's

To gain further insight into the behavior of DACKS under multiple AC's, we repeated the above experiment with 4 AC's, which is the maximum number of AC's allowed by the 802.11e standard. The throughput guarantees provided to the different AC's was of 300 Kbps, 150 Kbps, 75 Kbps and 37.5 Kbps to AC 1, AC 2, AC 3 and AC 4, respectively. The results, depicted in Figure 24, confirm the effectiveness of DACKS under multiple AC's. In particular, the desired throughput guarantees are always met for all AC's.

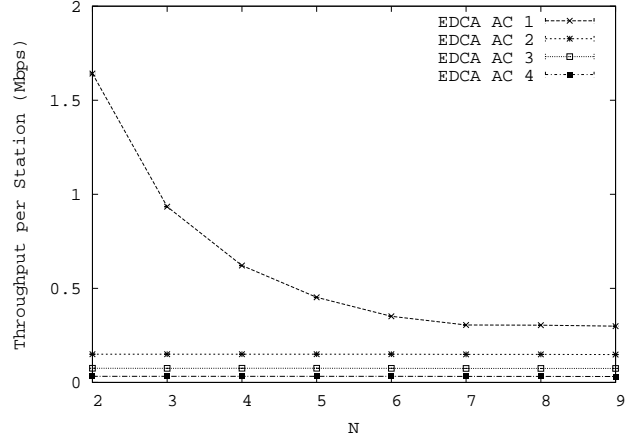


Fig. 25. Nonsaturated traffic.

6.19 Nonsaturated traffic

All previous experiments have been performed with all stations saturated. In order to evaluate DACKS under different traffic conditions, we repeated the experiment of the previous section under nonsaturation. Specifically, we considered the following traffic models:

- EDCA stations of AC 1 and DCF stations were saturated.
- EDCA stations of AC 2 generated traffic at a constant rate. The average sending rate was equal to the guaranteed rate.
- EDCA stations of AC 3 generated traffic following a Poisson process with an average rate equal to its guaranteed rate.
- EDCA stations of AC 4 generated traffic following a Pareto process of shape 2. The average rate was equal to the guaranteed rate also in this case.

The results obtained, illustrated in Figure 25, show that our technique is also effective under nonsaturated conditions. In particular, all the AC's see their desired throughput guarantees satisfied independent of their arrival process.

7 SUMMARY AND FINAL REMARKS

The EDCA mechanism of the IEEE 802.11e standard is backwards compatible thereby allowing legacy DCF stations to interoperate in a WLAN working under the EDCA mechanism. However, the coexistence of EDCA and DCF stations in the same WLAN stations degrades performance substantially. In particular, the presence of DCF stations jeopardizes the service guarantees committed to the EDCA stations and degrades the overall efficiency of the WLAN. The reason for this performance degradation is that DCF stations compete with overly small CW 's values, and these values cannot be modified since they are predefined by the standard.

In this paper, we have proposed the DACKS technique to overcome the above problem. With DACKS, upon receiving a frame from a DCF station, the AP skips the Ack reply with some probability. When missing the Ack reply, DCF stations assume that the transmitted frame collided and double their CW . This allows having some control on the average CW 's used by the DCF stations and thereby overcoming the above

problem which was caused by the lack of control on the CW 's of the DCF stations.

One of the major challenges with the DACKS scheme is the configuration of the probability of skipping the Ack reply. This probability should be configured in order to preserve the committed service guarantees to the EDCA stations while minimizing the disruption suffered by the DCF stations. We argue that these goals require the skipping probability to be dynamically configured. Indeed, if the skipping probability was statically set, we would have to choose a conservative configuration to avoid failing to meet EDCA service guarantees when all stations are active. As a result, when some of the stations were inactive, the skipping probability would be too high and DCF stations would see their throughput performance unnecessarily reduced.

The system proposed to dynamically tune the skipping probability is based on the observation that, as long as the overall transmission probability in the WLAN does not exceed a certain threshold, EDCA stations are guaranteed to receive the committed service. Following this observation, the controller used by our system takes as input the observed transmission probability and provides as output the skipping probability. The algorithm that we have chosen in this paper to compute the output control signal based on the measured input is a very simple controller from classical control theory, namely the Proportional Controller.

One of the challenges of our DACKS system is the configuration of the gain of the proportional controller. This adds to the inherent challenge of computing the EDCA parameters of the different AC's present in the WLAN. The configuration of all these parameters has been addressed in the paper in the following two steps:

- We have first conducted a performance analysis of our system under stationary conditions. Based on this analysis, we have determined *i*) the configuration of the EDCA parameters, and *ii*) the maximum transmission probability in the WLAN that guarantees EDCA stations receive the committed throughputs. The latter has been used as the reference signal of the DACKS controller, whose goal is to achieve that the measured transmission probability does not exceed the reference value.
- In a second step, we have conducted an analysis of our system under transient conditions. Based on this analysis, we have studied our system from a control theoretic standpoint and found the conditions that need to be met in order to guarantee that our system is stable. Following considerations from control theory, we have then set the gain of the Proportional Controller as a tradeoff between stability and speed of reaction.

The proposed scheme has been exhaustively evaluated by means of simulations. The performance evaluation conducted has shown that:

- i*) DACKS is effective in providing throughput guarantees to EDCA stations, independent of *a*) the number of (EDCA and DCF) stations, *b*) the number of EDCA AC's, *c*) whether stations are saturated or not, and *d*) whether they are active or not.

- ii*) The chosen configuration maximizes the overall efficiency; in particular, there is no other configuration that provides a (noticeably) larger total throughput.
- iii*) A WLAN with DACKS is more efficient than a WLAN that does not use the DACKS technique; specifically, the former provides a substantially larger total throughput.
- iv*) Our technique avoids disrupting DCF stations in case some of the (EDCA or DCF) stations are not active; in contrast, with a static configuration DCF stations are unnecessarily starved.
- v*) Our closed-loop system behaves stably (the instantaneous throughput does not suffer more oscillations than an open-loop system) while reacting quickly upon changing conditions.

Although the focus of this paper has been on providing EDCA stations with throughput guarantees, the proposed scheme can also be used to provide delay guarantees. Indeed, the key idea of DACKS is to regulate the DCF stations to ensure that the transmission probability in the channel does not exceed a given value. Following this, the value of the transmission probability that ensures the desired delay guarantees can be computed based on the model of [31], and then DACKS can be used to provide these guarantees.

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APPENDIX I

In this appendix we compute the expressions for the parameters H_1 and H_2 introduced in Section 5.4. Let us start with H_1 . According to Section 5.4, H_1 is computed as the following partial derivative evaluated at the stable point of operation:

$$H_1 = \frac{\partial \tau_{dcf}[n]}{\partial \tau_{dcf}[n-1]} \quad (79)$$

From Section 5.3 we have

$$\begin{aligned} \tau_{dcf}[n] &= \tau_{dcf}[n-1] + (1 - c_{dcf})\tau_{dcf,0}\tau_{dcf}[n-1] \\ &\quad - (1 - c_{dcf}/2) \frac{2\tau_{dcf}[n-1]\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \end{aligned} \quad (80)$$

which can be rewritten as

$$\begin{aligned} \tau_{dcf}[n] &= \tau_{dcf}[n-1] \left(1 - \frac{\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \right) \\ &\quad + \left(\tau_{dcf,0}\tau_{dcf}[n-1] - \frac{\tau_{dcf,0}^2\tau_{dcf}[n-1]}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \right) \\ &\quad \cdot (1 - c_{dcf}) \end{aligned} \quad (81)$$

Applying the partial derivative to the above equation yields

$$\begin{aligned} \frac{\partial \tau_{dcf}[n]}{\partial \tau_{dcf}[n-1]} &= 1 - \frac{\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \\ &\quad - \frac{\tau_{dcf}[n-1]\tau_{dcf,0}^2}{(3\tau_{dcf,0} - \tau_{dcf}[n-1])^2} \\ &\quad + \frac{\partial(1 - c_{dcf})}{\partial \tau_{dcf}[n-1]} \left(\tau_{dcf,0}\tau_{dcf}[n-1] \right. \\ &\quad \left. - \frac{\tau_{dcf,0}^2\tau_{dcf}[n-1]}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \right) \\ &\quad + (1 - c_{dcf}) \left(\tau_{dcf,0} - \frac{\tau_{dcf,0}^2\tau_{dcf}[n-1]}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \right. \\ &\quad \left. - \frac{\tau_{dcf,0}^2\tau_{dcf}[n-1]}{(3\tau_{dcf,0} - \tau_{dcf}[n-1])^2} \right) \end{aligned} \quad (82)$$

Note that in the stable point of operation of the system the following equation, obtained from imposing $\tau_{dcf}[n] = \tau_{dcf}[n-1]$ in Eq. (81), holds

$$\begin{aligned} \frac{\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} &= (1 - c_{dcf}) \left(\tau_{dcf,0} \right. \\ &\quad \left. - \frac{\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \right) \end{aligned} \quad (83)$$

Substituting the above in Eq. (82) we obtain

$$\begin{aligned} \frac{\partial \tau_{dcf}[n]}{\partial \tau_{dcf}[n-1]} &= 1 - (1 - c_{dcf}) \frac{\tau_{dcf,0} \tau_{dcf}[n-1]}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \\ &+ \frac{\partial(1 - c_{dcf})}{\partial \tau_{dcf}[n-1]} \left(\tau_{dcf,0} \tau_{dcf}[n-1] \right. \\ &\left. - \frac{\tau_{dcf,0}^2 \tau_{dcf}[n-1]}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \right) \end{aligned} \quad (84)$$

From Eq. (42) we have

$$\frac{\partial(1 - c_{dcf})}{\partial \tau_{dcf}[n-1]} = -(N_{dcf} - 1) \frac{1 - c_{dcf}}{1 - \tau_{dcf}[n-1]} \quad (85)$$

Combining all the above we finally obtain the following expression for H_1 :

$$\begin{aligned} H_1 &= 1 - (1 - c_{dcf}) \frac{\tau_{dcf,0} \tau_{dcf}}{3\tau_{dcf,0} - \tau_{dcf}} \\ &- (N_{dcf} - 1) \frac{1 - c_{dcf}}{1 - \tau_{dcf}} \left(\tau_{dcf,0} \tau_{dcf} \right. \\ &\left. - \frac{\tau_{dcf,0}^2 \tau_{dcf}}{3\tau_{dcf,0} - \tau_{dcf}} \right) \end{aligned} \quad (86)$$

which, applying again Eq. (83), can be rewritten as

$$\begin{aligned} H_1 &= 1 - (1 - c_{dcf}) \frac{\tau_{dcf,0} \tau_{dcf}}{3\tau_{dcf,0} - \tau_{dcf}} \\ &- (N_{dcf} - 1) \frac{\tau_{dcf}}{1 - \tau_{dcf}} \left(\frac{\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}} \right) \end{aligned} \quad (87)$$

where τ_{dcf} is the transmission probability of a DCF station at the stable point of operation.

Next, we address the computation of an expression for the parameter H_2 :

$$H_2 = \frac{\partial P_t[n]}{\partial \tau_{dcf}[n]} \frac{\partial \tau_{dcf}[n]}{\partial P_{ack}} \quad (88)$$

From Eq. (21) we have

$$\frac{\partial P_t[n]}{\partial \tau_{dcf}[n]} = N_{dcf} \frac{(1 - P_t[n])^2}{1 - \tau_{dcf}[n]} (1 - \tau_{dcf}[n])^{N_{dcf}} \quad (89)$$

On the other hand,

$$\begin{aligned} \frac{\partial \tau_{dcf}[n]}{\partial P_{ack}} &= - \frac{\partial c_{dcf}}{\partial P_{ack}} \left(\tau_{dcf,0} \tau_{dcf}[n-1] \right. \\ &\left. - \frac{\tau_{dcf,0}^2 \tau_{dcf}[n-1]}{3\tau_{dcf,0} - \tau_{dcf}[n-1]} \right) \end{aligned} \quad (90)$$

where, from Eq. (42),

$$\begin{aligned} \frac{\partial c_{dcf}}{\partial P_{ack}} &= -(1 - P_{edca})(1 - \tau_{dcf}[n-1])^{N_{dcf}-1} \\ &= - \frac{1 - P_{edca}}{1 - \tau_{dcf}[n-1]} (1 - \tau_{dcf}[n-1])^{N_{dcf}} \end{aligned} \quad (91)$$

Combining all the above we finally obtain the following expression for H_2 :

$$\begin{aligned} H_2 &= N_{dcf} \frac{(1 - P_t)^2}{(1 - \tau_{dcf})^2} \tau_{dcf} \tau_{dcf,0} \left(1 - \frac{\tau_{dcf,0}}{3\tau_{dcf,0} - \tau_{dcf}} \right) \\ &(1 - P_{edca})(1 - \tau_{dcf})^{2N_{dcf}} \end{aligned} \quad (92)$$

where P_t , τ_{dcf} and P_{edca} are the overall transmission probability, the transmission probability of a DCF station, and the probability that a slot time contains a transmission of an EDCA station, respectively, at the stable point of operation.

Given the following equality, derived from Eq. (21),

$$(1 - \tau_{dcf})^{N_{dcf}} = \frac{1 - P_t - P_t(1 - P_{edca})}{(1 - P_t)(1 - P_{edca})} \quad (93)$$

H_2 can be rewritten as

$$\begin{aligned} H_2 &= N_{dcf} \frac{\tau_{dcf} \tau_{dcf,0}}{(1 - \tau_{dcf})^2} \left(1 - \frac{\tau_{dcf,0}}{3\tau_{dcf,0} - \tau_{dcf}} \right) \\ &\frac{(1 - P_t - P_t(1 - P_{edca}))^2}{1 - P_{edca}} \end{aligned} \quad (94)$$

APPENDIX II

Eq. (68) provides a bound for the configuration of K_p that guarantees the system is stable. However, this bound is a function of N_{dcf} and P_{edca} , which are not known a priori and may vary with time. In order to assure stability, we need to find an upper bound for K_p that is independent of N_{dcf} and P_{edca} and depends only on known (constant) values. In this appendix we find a bound that meets this requirement.

If we find a lower bound for H_1 and an upper bound for H_2 that is satisfied by all possible P_{edca} and N_{dcf} values, the resulting upper bound on K_p is conservative and surely meets Eq. (68). Specifically, the resulting bound is the following:

$$K_p < \left(\frac{2 - \alpha}{\alpha} \right) \frac{1 + H_1^{min}}{H_2^{max}} \quad (95)$$

In the following, we first provide a lower and upper bound for H_1 and H_2 , H_1^{min} and H_2^{max} , that are functions P_{edca} and N_{dcf} , and then we find the values of P_{edca} and N_{dcf} that minimize H_1^{min} and maximize H_2^{max} , respectively.

Lemma 1: H_1 is bounded below by

$$\begin{aligned} H_1^{min} &= 1 - (1 - c_{dcf}) \frac{\tau_{dcf,0} \tau_{dcf}}{3\tau_{dcf,0} - \tau_{dcf}} \\ &- N_{dcf} \frac{\tau_{dcf}}{1 - \tau_{dcf}} \left(\frac{\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}} \right) \end{aligned} \quad (96)$$

Proof: Since $N_{dcf} - 1$, contained in a negative term, been substituted by N_{dcf} , the resulting expression is smaller and therefore a lower bound. \square

Lemma 2: H_2 is bounded above by

$$H_2^{max} = N_{dcf} \frac{(1 - P_t)^2}{(1 - \tau_{dcf})^2} (1 - P_{edca}) \tau_{dcf} \tau_{dcf,0} \left(\frac{2}{3} \right) \quad (97)$$

Proof: The expression of H_2 given by Eq. (92) can be rewritten as

$$\begin{aligned} H_2 &= N_{dcf} \frac{\tau_{dcf} \tau_{dcf,0}}{(1 - \tau_{dcf})^2} \left(\frac{2\tau_{dcf,0} - \tau_{dcf}}{3\tau_{dcf,0} - \tau_{dcf}} \right) \\ &\frac{(1 - P_t - P_t(1 - P_{edca}))^2}{1 - P_{edca}} \end{aligned} \quad (98)$$

From observing that

$$\frac{2\tau_{dcf,0} - \tau_{dcf}}{3\tau_{dcf,0} - \tau_{dcf}} \leq \frac{2}{3} \quad (99)$$

and

$$1 - P_t - P_t(1 - P_{edca}) \leq (1 - P_t)(1 - P_{edca}) \quad (100)$$

the proof follows. \square

We next address the behavior of H_1^{min} and H_2^{max} with respect P_{edca} by finding the values of P_{edca} that minimize H_1^{min} and maximize H_2^{max} .

Lemma 3: H_1^{min} is minimized for $P_{edca} = 0$.

Proof: From Eq. (96) we have that H_1^{min} is a decreasing function of τ_{dcf} and an increasing function of c_{dcf} .

The point of stable conditions at which H_1^{min} is evaluated, we have that the overall transmission probability P_t is driven to the desired $P_{t,max}$ value which is a known constant. Since the following equation holds for P_t

$$1 - P_t = (1 - P_t)(1 - P_{edca})(1 - \tau_{dcf})^{N_{dcf}} + P_t(1 - P_{edca}) \quad (101)$$

we have that, the larger P_{edca} , the smaller τ_{dcf} . Since τ_{dcf} is a decreasing function of c_{dcf} , this means that c_{dcf} is larger.

From the above, we have that H_1^{min} is an increasing function of P_{edca} and therefore takes its minimum value with the smallest P_{edca} possible, i.e., $P_{edca} = 0$. The proof follows. \square

Lemma 4: H_2^{max} is maximized for $P_{edca} = 0$.

Proof: From Eq. (92) we have

$$H_2 = K \cdot H_2^a \cdot H_2^b \quad (102)$$

where K is a positive constant and

$$H_2^a = \frac{\tau_{dcf}}{(1 - \tau_{dcf})^2} \quad (103)$$

$$H_2^b = 1 - P_{edca} \quad (104)$$

H_2^a is clearly an increasing function of τ_{dcf} . As we have seen that τ_{dcf} decreases with P_{edca} , this implies that H_2^a will take its maximum value with the smallest P_{edca} possible, i.e., $P_{edca} = 0$.

H_2^b is a decreasing function of P_{edca} that also takes its maximum value with $P_{edca} = 0$. The proof follows. \square

With the above, we have an upper bound for K_p which is independent of P_{edca} but still dependent on N_{dcf} . In the following, we set P_{edca} to the values given by the above two lemmas and find the values of N_{dcf} that minimize H_1^{min} and maximize H_2^{max} , respectively.

Lemma 5: H_1^{min} is minimized for $N_{dcf} = 1$.

Proof: H_1^{min} can be rewritten as

$$H_1^{min} = 1 - H_1^{min,a} - H_1^{min,b} \cdot H_1^{min,c} \quad (105)$$

where

$$H_1^{min,a} = (1 - P_t)P_{ack} \frac{\tau_{dcf,0}\tau_{dcf}}{3\tau_{dcf,0} - \tau_{dcf}} \quad (106)$$

$$H_1^{min,b} = \frac{\tau_{dcf,0}^2}{3\tau_{dcf,0} - \tau_{dcf}} \quad (107)$$

$$H_1^{min,c} = N_{dcf} \frac{\tau_{dcf}}{1 - \tau_{dcf}} \quad (108)$$

Since τ_{dcf} and P_{ack} decrease with N_{dcf} , it can be seen that $H_1^{min,a}$ is a decreasing function of N_{dcf} . Similarly, it can be

seen that $H_1^{min,b}$ is also a decreasing function of N_{dcf} . In the following, we proof that $H_1^{min,c}$ also decreases with N_{dcf} .

The proof goes by induction. Let us denote by $\tau_{dcf,N}$ the τ_{dcf} value that corresponds to a given $N_{dcf} = N$ and proof that

$$N \frac{\tau_{dcf,N}}{1 - \tau_{dcf,N}} \geq (N + 1) \frac{\tau_{dcf,N+1}}{1 - \tau_{dcf,N+1}} \quad (109)$$

Note that, given that P_t is constant, the following equality holds

$$(1 - \tau_{dcf,N})^N = (1 - \tau_{dcf,N+1})^{N+1} \quad (110)$$

from where

$$\tau_{dcf,N} = 1 - (1 - \tau_{dcf,N+1})^{(N+1)/N} \quad (111)$$

From the above we have

$$\begin{aligned} \tau_{dcf,N} \frac{1 - \tau_{dcf,N+1}}{1 - \tau_{dcf,N}} &= (1 - (1 - \tau_{dcf,N+1})^{(N+1)/N}) \\ &\cdot \frac{1 - \tau_{dcf,N+1}}{(1 - \tau_{dcf,N+1})^{(N+1)/N}} \\ &= (1 - (1 - \tau_{dcf,N+1})^{(N+1)/N}) \\ &\cdot \frac{1}{(1 - \tau_{dcf,N+1})^{1/N}} \end{aligned} \quad (112)$$

from where

$$\tau_{dcf,N} \frac{1 - \tau_{dcf,N+1}}{1 - \tau_{dcf,N}} = \frac{1}{(1 - \tau_{dcf,N+1})^{1/N}} - (1 - \tau_{dcf,N+1}) \quad (113)$$

Note that

$$\frac{1}{(1 - a)^k} \geq 1 + ka \quad (114)$$

holds for $a > 0$. This is proved similarly to the Bernoulli inequality [32]; consider the function

$$f(a) = (1 - a)^{-k} - 1 - ka \quad (115)$$

Its derivative is equal to

$$f'(a) = \frac{k}{(1 - a)^{k+1}} - k \quad (116)$$

which satisfies

$$f'(a) > 0, a > 0 \quad (117)$$

$$f'(a) < 0, a < 0 \quad (118)$$

meaning that we have a global minimum for $a = 0$. Since $f(0) = 0$ this implies $f(a) > 0$ for $a > 0$ which proves Eq. (114).

Applying Eq. (114) to Eq. (113) yields

$$\tau_{dcf,N} \frac{1 - \tau_{dcf,N+1}}{1 - \tau_{dcf,N}} \geq 1 + \frac{1}{N} \tau_{dcf,N+1} - (1 - \tau_{dcf,N+1}) \quad (119)$$

from where

$$\tau_{dcf,N} \frac{1 - \tau_{dcf,N+1}}{1 - \tau_{dcf,N}} \geq \frac{N + 1}{N} \tau_{dcf,N+1} \quad (120)$$

Recombining the above terms we have Eq. (109), which proves that $H_1^{min,c}$ is decreasing.

With all the above we have that H_1^{min} is an increasing function of N_{dcf} and therefore takes its minimum value when N_{dcf} is minimum, i.e. $N_{dcf} = 1$. The proof follows. \square

Lemma 6: H_2^{max} is maximized for $N_{dcf} = 1$.

Proof: H_2^{max} can be rewritten as

$$H_2^{max} = K \cdot H_2^{max,a} \cdot H_2^{max,b} \quad (121)$$

where K is a constant and

$$H_2^{max,a} = \frac{1}{1 - \tau_{dcf}} \quad (122)$$

$$H_2^{min,b} = N_{dcf} \frac{\tau_{dcf}}{1 - \tau_{dcf}} \quad (123)$$

Since $H_2^{max,a}$ and $H_2^{max,b}$ are decreasing functions of N_{dcf} , H_2^{max} takes its maximum value when N_{dcf} is minimum. The proof follows. \square

The combination of all the above lemmas leads to our final result included in the following theorem.

Theorem 1: The system is guaranteed to be stable as long as K_p is configured smaller than the following expression

$$K_p^{max} = \left(\frac{2 - \alpha}{\alpha} \right) \frac{1 + H_1^{min}}{H_2^{max}} \quad (124)$$

where H_1^{min} and H_2^{max} correspond to the expressions given by Lemmas 1 and 2 evaluated at $N_{dcf} = 1$.

Proof: Lemmas 1 and 2 give conservative bounds for H_1 and H_2 , which are H_1^{min} and H_2^{max} , respectively. Lemmas 3 and 4 give further conservative bounds to these expressions by evaluating them at $P_{edca} = 0$. Finally, Lemmas 5 and 6 show that the most conservative values for the resulting expressions are obtained when they are evaluated at $N_{dcf} = 1$. The result is the expression K_p^{max} given by Eq. (124). The proof follows. \square



Albert Banchs received his Telecommunications Engineering degree from the Polytechnical University of Catalonia in 1997, and the PhD degree from the same university in 2002. His Ph.D. received the national award for best thesis on broadband networks. He was a visitor researcher at ICSI, Berkeley, in 1997, worked for Telefonica I+D, in 1998, and for NEC Europe Ltd., Germany, from 1998 to 2003. Since 2003, he is with the University Carlos III of Madrid.

A. Banchs authors over 50 publications in peer-reviewed journals and conferences and four patents (two of them granted). He is associated editor for IEEE Communications Letters and has been guest editor for IEEE Wireless Communications and Computer Networks. He has served on the TPC of a number of conferences and workshops including IEEE Infocom, IEEE ICC and IEEE Globecom, and is TPC chair for European Wireless 2010.



Pablo Serrano got his Telecommunication Engineering degree and his PhD from the Universidad Carlos III de Madrid (UC3M) in 2002 and 2006, respectively. He has been with the Telematics Department of UC3M since 2002, where he currently holds the position of Assistant Professor. In 2007 he was a Visiting Researcher at the Computer Network Research Group at Univ. of Massachusetts Amherst partially supported by the Spanish Ministry of Education under a José Castillejo grant. His current work focuses on

performance evaluation of wireless networks. He has over 20 scientific papers in peer-reviewed international journal and conferences. He also serves as TPC member of several international conferences, including IEEE Globecom and IEEE Infocom.



Luca Vollero is an Assistant Professor at the Laboratory on Elaboration Systems and Bioinformatics of the University Campus Bio-Medico of Rome. Luca Vollero received the M.S. degree in Telecommunications Engineering (2001) and the PhD degree in Computer Science (2005) from the University of Naples "Federico II". His research interests include networks modeling and simulations, design and evaluation of systems for mobility in heterogeneous networks, multimedia data elaboration, image processing.

Luca Vollero is a member of IEEE, IEEE Computer Society, IEEE Communications Society and ACM.