

# A High Efficiency MAC Protocol for WLANs: Providing Fairness in Dense Scenarios

Luis Sanabria-Russo, Jaume Barcelo, Boris Bellalta

**Abstract**—Collisions are a main cause of throughput degradation in WLANs. The current contention mechanism used in IEEE 802.11 networks is called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). It uses a Binary Exponential Backoff (BEB) technique to randomise each contender attempt of transmitting, effectively reducing the collision probability. Nevertheless, CSMA/CA relies on a random backoff that while effective and fully distributed, in principle is unable to completely eliminate collisions, therefore degrading the network throughput as more contenders attempt to share the channel. Carrier Sense Multiple Access with Enhanced Collision Avoidance (CSMA/ECA) is able to create a collision-free schedule in a fully distributed manner using a deterministic backoff after successful transmissions. Hysteresis and Fair Share are two extensions of CSMA/ECA to support a large number of contenders in a collision-free schedule. CSMA/ECA offers better throughput than CSMA/CA and short-term throughput fairness.

This work describes CSMA/ECA and its extensions. Additionally, it provides the first evaluation results of CSMA/ECA in non-saturated traffic conditions as well as its performance when coexisting with CSMA/CA nodes. Furthermore, the effects of imperfect clocks over CSMA/ECA's deterministic backoff mechanism and its consequences when attempting to implement the protocol in real hardware are also analysed.

**Index Terms**—CSMA/ECA, WLAN, MAC, Collision-free, Clock Drift.

## I. INTRODUCTION

Wireless Local Area Networks (WLANs or WiFi networks [1]) are a popular solution for wireless connectivity, whether in public places, work environments or at home. This technology works over an unlicensed spectrum in the Industrial, Scientific and Medical (ISM) radio bands (at around 2.4 or 5 GHz), offering a good tradeoff between performance and costs, which is a main reason for its popularity.

The Medium Access Control (MAC) scheme used in WLANs is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. It has been widely adopted by manufacturers and consumers, making it inexpensive to implement and an ubiquitous technology. Nevertheless, the ever-growing throughput demands from upper layers are faced with a bottleneck at the WLANs' MAC [2], which by its nature is prone to collisions that degrade the overall performance as more nodes join the network.

The research community has pushed forward many alternatives to the current MAC in WLANs [3]–[13], but when a

proposal deviates too much from CSMA/CA, or some time-critical operations are modified, its hardware implementation as part of WLANs' MAC often becomes unlikely [14], with the standardisation process taking many years without certainty of approval [2].

A CSMA/CA replacement should be able to provide advantages in terms of throughput, spectrum efficiency and number of supported contenders. All of the aforementioned without sacrificing short-term throughput fairness. Furthermore, it must also serve existing users, which means it has to be backwards compatible.

A suitable candidate, and the one to be evaluated in this work, is called Carrier Sense Multiple Access with Enhanced Collision Avoidance (CSMA/ECA) [7]. It is capable of attaining higher throughput than CSMA/CA by making a simple modification to the contention mechanism. In CSMA/ECA, nodes use a deterministic backoff after successful transmissions, constructing a collision-free schedule among successful contenders in a fully decentralised way. This backoff mechanism ensures that more channel time is spent on successful transmissions rather than recovering from collisions, thus increasing the throughput of the network. Further enhancements (or extensions), like *Hysteresis* and *Fair Share* [15] allow CSMA/ECA to support many more contenders in a collision-free schedule. Moreover, CSMA/ECA and its extensions are designed for allowing nodes to transmit as frequently as possible while keeping an even distribution of the available bandwidth among users.

The 802.11 High Efficiency WLAN (HEW) Study Group (SG) envisions very crowded scenarios as one of the future challenges for WLAN protocols [16], specifically those usually encountered at stadiums or conference rooms. Further, if the need for serving many users is combined with the increased throughput demands from the upper layers, a performance improvement at the MAC becomes paramount. Although many studies have been made analysing the performance of CSMA/ECA [7], [8], [15], [17], there are still several open aspects that require further attention and additional insight to consider CSMA/ECA as a potential CSMA/CA replacement. Namely, neither assesses the protocol's backwards compatibility property or its behavior under non-saturated traffic conditions while serving many users. Furthermore, the impact of imperfect clocks over the deterministic backoff mechanism is also lacking.

**In this part we should also assess the channel error scenario and the real implementation with OpenFWWF.**

This paper fills those gaps by extending [15], and consolidates the push for CSMA/ECA as a potential replacement of CSMA/CA for next generation WLANs. In detail, this paper

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L. Sanabria-Russo (luis.sanabria@upf.edu), J. Barcelo (jaume.barcelo@upf.edu) and B. Bellalta (boris.bellalta@upf.edu) are with the Department of Information and Communication Technologies, Universitat Pompeu Fabra, Barcelona, Spain.

provides the following contributions:

- First results on the achievable throughput and delay of CSMA/ECA with Hysteresis and Fair Share under non-saturated traffic conditions for very large number of nodes.
- The impact of imperfect clocks on CSMA/ECA with Hysteresis and Fair Share's deterministic backoff and its consequences on the achieved performance.
- **The effect of channel errors over collision-free schedules and how to solve the issue of converging rapidly to the biggest cycle length with the Schedule Reset mechanism.**
- Formulation of the throughput bounds for CSMA/ECA with Hysteresis and Fair Share.
- Coexistence and backwards compatibility with CSMA/CA nodes under different traffic conditions.
- Implementation of CSMA/ECA in real hardware.

Results, derived from a modified version of the COST [18] simulator, show that CSMA/ECA with Hysteresis and Fair Share is capable of accommodating many users in collision-free schedules. Further, as tests in a mixed network with different proportions of CSMA/CA and CSMA/ECA nodes show, the aggregated throughput is higher than the observed in CSMA/CA-only networks without significant sacrifice from legacy stations.

Beyond simulations results, the implementation of CSMA/ECA prototypes [19]–[22] show that the construction of collision-free schedules using a deterministic backoff after successful transmissions is possible and results in a throughput increase by reducing the number of corrupted frames. **We then present the first real hardware implementation of CSMA/ECA with Hysteresis. Results show that indeed it is able of providing higher throughput and lower collisions than CSMA/CA for the same number of contenders.**

An overview of similar distributed and collision-free MAC protocols for WLANs is provided in Section II. CSMA/ECA, as well as its extensions for allocating many contenders in a collision-free schedule are explained in Section III. Section IV details the simulation environment for testing CSMA/ECA, while Section V explains the results. An overview of CSMA/ECA real-hardware implementations is compiled in Section VI, followed by a summary of the still missing CSMA/ECA features needed to become the next CSMA/CA replacement in Section VII. Conclusions are drawn in Section VIII.

## II. RELATED WORK

Time in WLANs is divided into tiny empty slots of fixed length  $\sigma_e$ , collisions, and successful slots of length  $\sigma_c$  and  $\sigma_s$ , respectively. Collision and successful slots contain collisions or successful transmissions, making them several orders of magnitude larger than empty slots ( $\sigma_e \ll \min(\sigma_s, \sigma_c)$ ). One of the effects of collisions is the degradation of the network performance by wasting channel time on collisions slots.

Recent advances in the WLANs PHY [2], [23] push the research community towards the development of MAC protocols able to take advantage of a much faster PHY. By reducing the time spent in collisions nodes are able to transmit

more often, which in turn translates to an increase in the network throughput. Further, the upcoming MAC protocols for WLANs should work without message exchange between contenders, that is, work in a fully distributed fashion in order to avoid injecting extra control traffic that may reduce the data throughput.

The following are MAC protocols for WLANs, distributed and capable of attaining greater throughput than CSMA/CA by constructing a collision-free schedule.

### A. Zero Collision MAC

Zero Collision MAC (ZC-MAC) [24] achieves a zero collision schedule for WLANs in a fully distributed way. It does so by allowing contenders to reserve one empty slot from a predefined virtual schedule of  $N$ -slots in length. Backlogged stations pick a slot in the virtual cycle to attempt transmission. If two or more stations picked the same slot in the cycle, their transmissions will eventually collide. This forces the involved contenders to randomly and uniformly select other empty slot from those detected empty in the previous cycle plus the slot where they collided. When all  $M$  stations reserve a different slot, a collision-free schedule is achieved.

ZC-MAC is able to outperform CSMA/CA under different scenarios. Nevertheless, given that the length of ZC MAC's virtual cycle has to be predefined without actual knowledge of the real number of contenders in the deployment, the protocol is unable to provide a collision-free schedule when  $M > N$ . Furthermore, if  $N$  is overestimated ( $N \gg M$ ), the fixed-width empty slots between each contender's successful transmission are no longer negligible and contribute to the degradation of the network performance<sup>1</sup>. Additionally, Z-MAC nodes require common knowledge of where the virtual schedule starts/ends. This is not considered in CSMA/CA and constitutes an obstacle towards standardisation.

### B. Learning-MAC

Learning-MAC [25] is another MAC protocol able to build a collision-free schedule for many contenders. It does so defining a *learning strength* parameter,  $\beta \in (0, 1)$ . Each contender starts by picking a slot for transmission  $s$  of the schedule  $n$  of length  $C$  at random with uniform probability. After a contender picks slot  $s(n)$ , its selection in the next schedule,  $s(n+1)$ , will be conditioned by the result of the current attempt. (1) and (2) extracted from [25] show the probability of selecting the same slot  $s(n)$  in cycle  $n+1$ .

$$\left. \begin{aligned} p_{s(n)}(n+1) &= 1, \\ p_j(n+1) &= 0, \end{aligned} \right\} \quad \text{Success} \quad (1)$$

$$\left. \begin{aligned} p_{s(n)}(n+1) &= \beta p_{s(n)}(n), \\ p_j(n+1) &= \beta p_j(n) + \frac{1-\beta}{C-1}, \end{aligned} \right\} \quad \text{Collision} \quad (2)$$

<sup>1</sup>With a very large  $N$  and  $M \leq N$ , the overall aggregated throughput will start to decrease as  $M \rightarrow N$ . This is due to the very big period of time between successful transmissions. For the opposite case, that is  $M > N$ , the same effect is produced albeit with an increased number of collisions.

for all  $j \neq s(n)$ ,  $j \in \{1, \dots, C\}$ . That is, if a station successfully transmitted in  $s(n)$ , it will pick the same slot on the next schedule with probability one. Otherwise, it follows (2).

The selection of  $\beta$  implies a compromise between fairness and convergence speed, which the authors determined  $\beta = 0.95$  to provide satisfactory results.

L-MAC is able to achieve higher throughput than the current MAC with a very fast convergence speed. Nevertheless, the choice of  $\beta$  suppose a previous knowledge of the number of empty slots ( $C - N$ , where  $N$  is the number of contenders), which is not easily available to the current MAC or may require a centralised entity [13].

Further extensions to L-MAC introduced an *Adaptive* schedule length in order to increase the number of supported contenders in a collision-free schedule. This adaptive schedule length is doubled or halved depending on the presence of collisions or many empty slots per schedule, respectively. The effects of reducing the schedule length may provoke a re-convergence phase which can result in short-term fairness issues. Moreover, L-MAC nodes also require common knowledge of the start/end of the schedule.

**NOTE:** We should show the performance of L-ZC and L-MAC alongside Basic CSMA/ECA. It is very important to define L-ZC given that the paper only talks about ZC. Also, we should clarify that the virtual schedule size is the same for all contenders, but they are not need to have an universal view of it.

### III. CARRIER SENSE MULTIPLE ACCESS WITH ENHANCED COLLISION AVOIDANCE (CSMA/ECA)

CSMA/ECA [7] is a fully distributed and collision-free MAC for WLANs. It differs from CSMA/CA in that it uses a deterministic backoff,  $B_d = CW_{\min}/2$  after successful transmissions, where  $CW_{\min}$  is the minimum contention window of typical value  $CW_{\min} = 16$ . By doing so, contenders that successfully transmitted on schedule  $n$ , will transmit without colliding with other successful nodes in future cycles.

Collisions are handled as in CSMA/CA, which is described in Algorithm 1. In Algorithm 1, the node starts by setting the retransmissions counter and backoff stage to zero ( $r \in [0, R]$  and  $k \in [0, m]$  respectively,  $m$  is the maximum backoff stage of typical value  $m = 5$ , and  $R$  is the retransmissions limit with typical value  $R = m + 1$ ), then generates a random backoff,  $B$ . When the Acknowledgement (*ack*) for a sent packet is not received by the sender a collision is assumed. Upon collision, the involved nodes will double their contention window by incrementing their backoff stage in one and using a random backoff,  $B \in [0, 2^k CW_{\min}]$ . This procedure is described between Line 10 and 13 of Algorithm 1.

Algorithm 2 provides an explanation of CSMA/ECA deterministic backoff mechanism, which main difference with CSMA/CA (and therefore with Algorithm 1) relies on the selection of a deterministic backoff after a successful transmission (compare Line 18 in Algorithm 1 with Line 18 in Algorithm 2). Figure 1 shows an example of CSMA/ECA dynamics with four contenders.

```

1 while the device is on do
2    $r \leftarrow 0$ ;  $k \leftarrow 0$ ;
3    $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
4   while there is a packet to transmit do
5     repeat
6       while  $B > 0$  do
7         wait 1 slot;
8          $B \leftarrow B - 1$ ;
9       Attempt transmission of 1 packet;
10      if collision then
11         $r \leftarrow r + 1$ ;
12         $k \leftarrow \min(k + 1, m)$ ;
13         $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
14      until ( $r = R$ ) or (success);
15       $r \leftarrow 0$ ;
16       $k \leftarrow 0$ ;
17      if success then
18         $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
19      else
20        Discard packet;
21         $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
22    Wait until there is a packet to transmit;

```

**Algorithm 1:** CSMA/CA.  $r$  indicates the number of retransmission attempts, while  $R$  is the maximum retransmission attempts limit. When it is reached, the packet waiting for transmission is dropped.

In Figure 1, the *STA-#* labels represent stations willing to transmit. The horizontal lines represent a time axis with each number indicating the amount of empty slots left for the backoff to expire. Stations willing to transmit begin the contention for the channel by waiting a random backoff,  $B$ . The first outline highlights the fact that stations STA-3 and STA-4 will eventually collide because they have selected the same  $B$ . After recomputing the random backoff, STA-4's attempt results in a successful transmission, which instructs the node to use a deterministic backoff,  $B_d = 7$  in this case. By doing so, all successful STAs will not collide among each other in future cycles.

Collision slots being orders of magnitude larger than empty slots degrade the network performance. When CSMA/ECA builds the collision-free schedule all contenders are able to successfully transmit more often, increasing the aggregated throughput beyond CSMA/CA's. Figure 2 (redrawn from [15]), shows the achieved throughput of CSMA/ECA and CSMA/CA, alongside the Jain's Fairness Index (JFI) [26].

Referring to Figure 2, CSMA/ECA is able to achieve an aggregated throughput that goes beyond CSMA/CA up until the number of contenders ( $N$ ) is greater than  $B_d$  ( $B_d = 7$  in the case of the figure). Beyond this point, the network will have a mixed behavior relating to backoff mechanisms: some nodes will successfully transmit and use a deterministic backoff while others will collide due to the lack of empty slots and return to a random backoff. As more contenders join

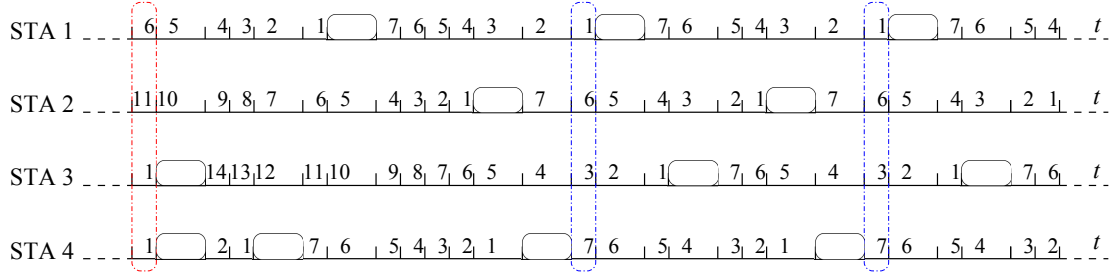


Fig. 1. An example of the temporal evolution of CSMA/ECA in saturation

```

1 while the device is on do
2    $r \leftarrow 0$ ;  $k \leftarrow 0$ ;
3    $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
4   while there is a packet to transmit do
5     repeat
6       while  $B > 0$  do
7         wait 1 slot;
8          $B \leftarrow B - 1$ ;
9       Attempt transmission of 1 packet;
10      if collision then
11         $r \leftarrow r + 1$ ;
12         $k \leftarrow \min(k + 1, m)$ ;
13         $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
14      until ( $r = R$ ) or (success);
15       $r \leftarrow 0$ ;
16       $k \leftarrow 0$ ;
17      if success then
18         $B_d \leftarrow (2^k CW_{\min})/2 - 1$ ;
19         $B \leftarrow B_d$ ;
20      else
21        Discard packet;
22         $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
23    Wait until there is a packet to transmit;

```

**Algorithm 2:** CSMA/ECA.

the network, CSMA/ECA performance will approximate to CSMA/CA's.

The *JFI for CSMA/ECA* and *JFI for CSMA/CA* curves in Figure 2 show the Jain's Fairness index for both protocols. Both protocols have a JFI equal to one, which suggests that the available throughput is shared evenly among all stations.

#### A. Supporting many more contenders

As was mentioned before, CSMA/ECA is only able to build a collision-free schedule if the number of contenders  $N$ , is less or equal than  $B_d$ . When  $N > B_d$ , collisions reappear.

To be able to attain a collision-free schedule even when the number of contenders exceeds  $B_d$ , we introduce *Hysteresis*. Hysteresis is a property of the protocol that instructs nodes not to reset their backoff stage ( $k$ ) after successful transmissions, but to use a deterministic backoff  $B_d = CW(k)/2$ , where  $CW(k) = 2^k CW_{\min}$ . This measure allows the adaptation

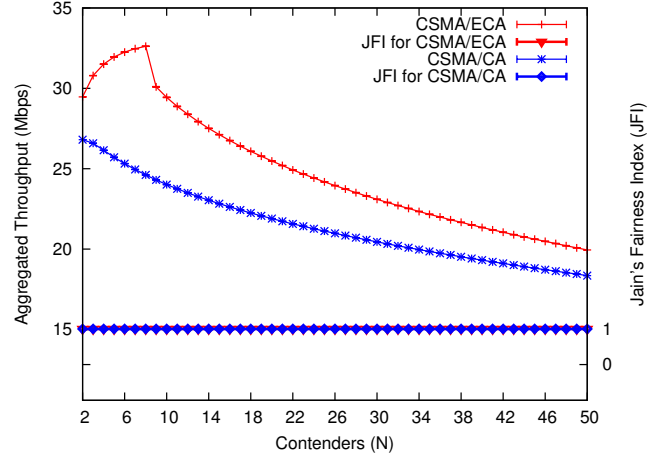


Fig. 2. CSMA/ECA example in saturation: throughput (simulation parameters can be found in Section IV)

of the schedule length, admitting many more contenders in a collision-free schedule. This idea of a schedule is significantly different from the virtual schedule required by the protocols described in Section II, that is, CSMA/ECA with Hysteresis does not require a previous knowledge of the number of contenders, the result of previous transmissions or the start/end of the schedule, easing its implementation in real hardware.

Hysteresis enables CSMA/ECA nodes to have different schedules ( $B_d$ ), carrying the undesired effect of unevenly dividing the channel time among contenders (i.e., some nodes will have to wait more in order to attempt transmissions).

This unfairness issue is solved by instructing nodes at backoff stage  $k$  to transmit  $2^k$  packets on each attempt, thus proportionally compensating those nodes at higher backoff stages. This additional extension to CSMA/ECA is called *Fair Share*. CSMA/ECA with Hysteresis and Fair Share will be referred to as CSMA/ECA<sub>Hys+FS</sub> in order to distinguish it from what was described until this point.

The idea of allowing the transmission of more packets to stations that transmit less often was initially proposed by Fang et al. in [25]. It was later adapted to CSMA/ECA<sub>Hys</sub> and named Fair Share in [15]. Figure 3 shows the JFI for CSMA/CA as well as for CSMA/ECA<sub>Hys+FS</sub>.

In Figure 3, the only curve deviating from JFI = 1 is *CSMA/ECA with Hysteresis*, suggesting an uneven partition of the channel access time among contenders (which is fixed with Fair Share).



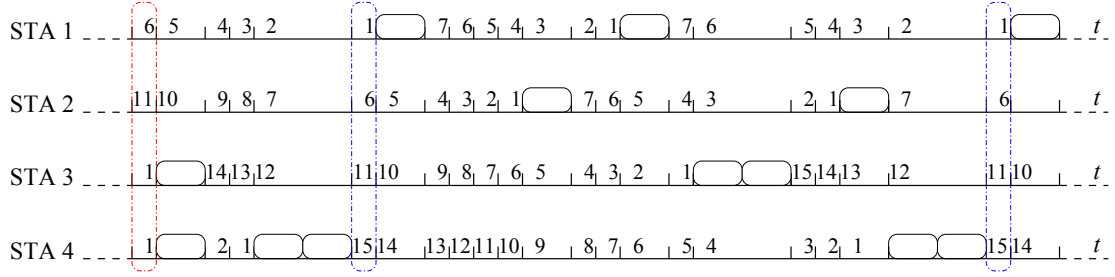


Fig. 4. An example of the temporal evolution of CSMA/ECA<sub>Hys+FS</sub> in saturation ( $CW_{\min} = 16$ )

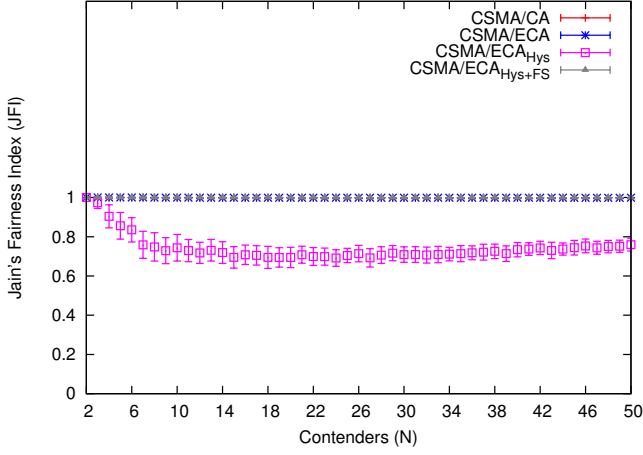


Fig. 3. Fairness comparison with nodes under saturation (simulation parameters can be found in Section IV)

Algorithm 3 shows an implementation of CSMA/ECA<sub>Hys+FS</sub>, while an example of CSMA/ECA<sub>Hys+FS</sub> with four contenders is shown in Figure 4. In the figure the first outline indicates a collision between STA-3 and STA-4, which will provoke an increment on both station's backoff stage ( $k \leftarrow k + 1$ ). Once STA-4's random backoff expires, CSMA/ECA<sub>Hys+FS</sub> instructs the station to transmit  $2^k$  packets, and then use a deterministic backoff,  $B_d = CW(k)/2$ . The same behavior is followed by STA 3.

With Hysteresis and Fair Share, CSMA/ECA<sub>Hys+FS</sub> is able to achieve greater throughput than CSMA/CA and for many more contenders, as shown in Figure 5 extracted from [15]. In the figure, the CSMA/ECA<sub>Hys+FS</sub> curve shows a greater throughput because collisions are eliminated and Fair Share allows nodes to send  $2^k$  packets upon each transmission. This throughput increase is the result of aggregation via Fair Share, which also carries the effect of raising the average time between successful transmissions (see Section V-A3), which may affect delay-sensitive traffic, like gaming or live video/voice/tv streaming.

**We should also incorporate CSMA/CA<sub>FS</sub>??.**

### B. The effects of Aggregation

Fair Share is an **A-MPDU** aggregation mechanism that coupled with the collision-free schedule built by CSMA/ECA<sub>Hys</sub> is able to provide short-term fairness. However, it also improves the throughput since the aggregation process makes

```

1 while the device is on do
2    $r \leftarrow 0$  ;  $k \leftarrow 0$ ;
3    $b \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
4   while there is a packet to transmit do
5     repeat
6       while  $B > 0$  do
7         wait 1 slot;
8          $B \leftarrow B - 1$ ;
9       Attempt transmission of  $2^k$  packets;
10      if collision then
11         $r \leftarrow r + 1$ ;
12         $k \leftarrow \min(k + 1, m)$ ;
13         $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
14      until ( $r = R$ ) or (success);
15       $r \leftarrow 0$ ;
16      if success then
17         $B_d \leftarrow (2^k CW_{\min})/2 - 1$ ;
18         $B \leftarrow B_d$ ;
19      else
20        Discard packet;
21         $k \leftarrow 0$ ;
22         $B \leftarrow \mathcal{U}[0, 2^k CW_{\min} - 1]$ ;
23    Wait until there is a packet to transmit;

```

Algorithm 3: CSMA/ECA<sub>Hys+FS</sub>

the packet transmission more efficient by reducing overheads. The downside of Fair Share is that it may increase the time between two consecutive transmissions from the same node, which may affect negatively delay-sensitive applications such as gaming or high definition real-time video. **An example of the duration of a transmission is provided by (5) in the following Section III-C.**

In scenarios where short-term fairness and the time between consecutive transmissions are not relevant, Fair Share can be replaced by *Maximum Aggregation* (MaxAg), which will significantly improve the system throughput. In Maximum Aggregation all nodes aggregate as many packets as possible at every transmission, i.e., they send  $2^m$  packets in each attempt.

Figure 6 shows the aggregated throughput for CSMA/ECA<sub>Hys+FS</sub>, CSMA/CA<sub>MaxAg</sub> and CSMA/ECA<sub>Hys+MaxAg</sub>. Although CSMA/CA<sub>MaxAg</sub> performs maximum aggregation, collisions degrade the aggregated

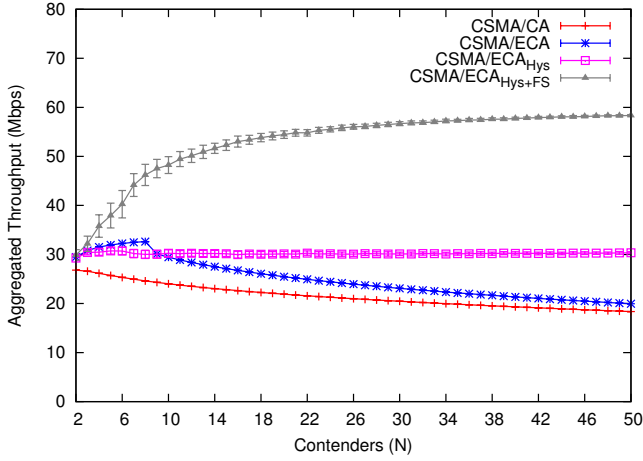


Fig. 5. Throughput comparison [15] (simulation parameters can be found in Section IV)

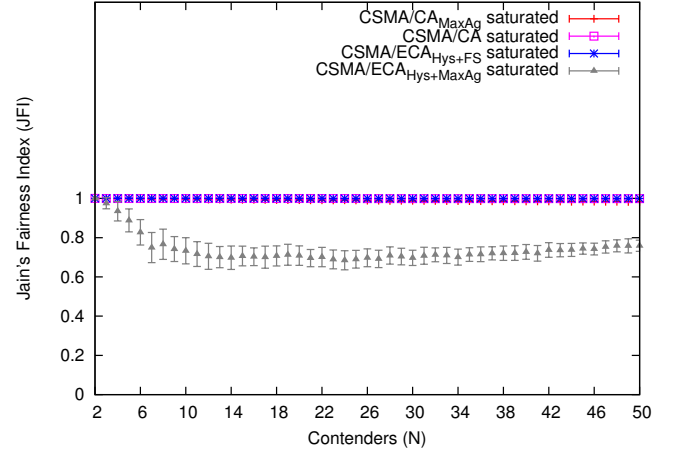


Fig. 7. Fairness comparison when using maximum aggregation

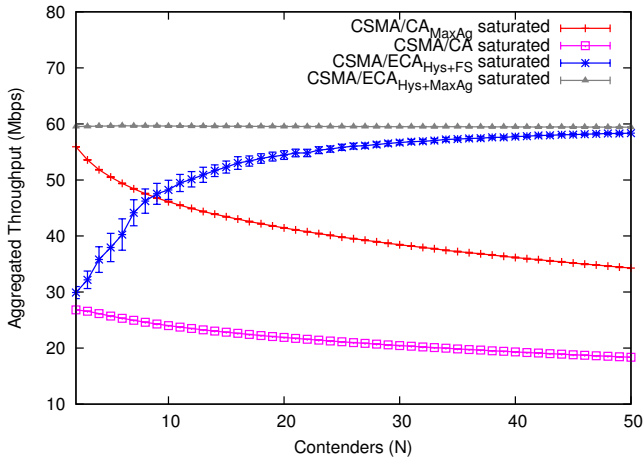


Fig. 6. Throughput comparison with CSMA/CA<sub>MaxAg</sub>: even though at low number of contenders CSMA/CA<sub>MaxAg</sub> achieves greater throughput than CSMA/ECA<sub>Hys+FS</sub>, collisions eventually degrade the throughput below CSMA/ECA<sub>Hys+FS</sub>'s when the number of contenders increases past  $N = 10$

throughput as more contenders attempt transmission. On the other hand, CSMA/ECA<sub>Hys+FS</sub> is able to build a collision-free schedule and takes advantage of the aggregation provided by Fair Share, which opposed to just using CSMA/ECA<sub>Hys+MaxAg</sub>, it is fair (see Figure 7).

To summarise the effects of using aggregation:

- It increases the aggregated throughput: because nodes are able to send multiple packet in each attempt, the system throughput is increased. Moreover, Fair Share compensates those nodes at higher backoff stages to ensure throughput fairness.
- Maximum aggregation supposes the deactivation of the Fair Share mechanism: performing maximum aggregation upon each transmission attempt is equivalent to having different schedule lengths and not compensating nodes at higher backoff stages. Although the aggregated throughput increases, this results in an uneven distribution of the channel time among contenders, which renders it unfair.
- Longer periods between transmission attempts: given that each transmission takes longer, the time between

transmission attempts also increases. This may specially affect delay-sensitive applications.

Since we consider that fairness and a short inter-transmission time are even more important than raw throughput for the next generation of WLANs, we keep CSMA/ECA<sub>Hys+FS</sub> as the reference protocol. **Is this still true?**

### C. Throughput bounds of CSMA/ECA<sub>Hys+FS</sub>

They correspond to the maximum and minimum achievable throughput without the possibility of collisions using Hysteresis and Fair Share. The ideal CSMA/ECA<sub>Hys+FS</sub> network uses the minimum schedule length that guarantees a collision-free operation. That is, with a schedule length of  $C = 2^k B_d$ , where  $k = \lceil \log_2(N/B_d) \rceil$ . Using this minimum schedule length,  $N$  nodes will be at the same backoff stage if  $N \leq B_d$ . Otherwise,  $h = N - (C - N)$  nodes would occupy the  $k$ -th backoff stage and the other  $N - h$  nodes the  $(k - 1)$ -th one. The system throughput is computed as follows:

$$S = \begin{cases} h s_k(l_k) + (N - h) s_{k-1}(l_{k-1}), & \text{if } N > B_d \\ N s_k(l_k), & \text{otherwise} \end{cases} \quad (3)$$

where  $s_k(l_k)$  and  $s_{k-1}(l_{k-1})$  are the throughput achieved by the nodes at the  $k$ -th and  $(k - 1)$ -th backoff stages sending  $l_k$  and  $l_{k-1}$  packets respectively. These are given by:

$$s_k(l_k) = \frac{l_k L}{h T(l_k) + 2(N - h) T(l_{k-1}) + \sigma_e(C - N)} \quad (4a)$$

$$s_{k-1}(l_{k-1}) = \frac{l_{k-1} L}{(N - h) T(l_{k-1}) + k \frac{T(l_k)}{2}} \quad (4b)$$

where  $L$  is the data payload,  $T(l_k)$  and  $T(l_{k-1})$  are the duration of the transmission of  $l_k$  and  $l_{k-1}$  packets, respectively;  $\sigma_e$  is the duration of an empty slot. Additionally,  $T(l_k)$  derives from (5):

$$T(l_k) = \left( T_{\text{PHY}} + \left\lceil \frac{\text{SF} + l_k(\text{MD} + \text{MH} + L) + \text{TB}}{L_{\text{DBPS}}} \right\rceil T_{\text{sym}} \right) + \text{SIFS} + \left( T_{\text{PHY}} + \left\lceil \frac{\text{SF} + L_{\text{BA}} + \text{TB}}{L_{\text{DBPS}}} \right\rceil T_{\text{sym}} \right) + \text{DIFS} + \sigma_e \quad (5)$$

where  $T_{\text{PHY}} = 32 \mu\text{s}$  is the duration of the PHY-layer preamble and headers,  $T_{\text{sym}} = 4 \mu\text{s}$  is the duration of an OFDM (Orthogonal Frequency Division Multiplexing) symbol. SF is the *service field* (16 bits), MD is the *MPDU Delimiter* (32 bits), MH is the *MAC header* (288 bits), TB is the number of *tail bits* (6 bits),  $L_{\text{BA}}$  is the *Block-ACK* length (256 bits) and  $L_{\text{DBPS}} = 256$  is the number of bits in each OFDM symbol. SIFS, DIFS and  $\sigma_e$  values can be found in Table I.

The *Lower-bound* is derived from considering the operation of an ideal CSMA/ECA<sub>Hys+FS</sub> network. Nodes use the minimum backoff stage possible and aggregate proportionally, thus yielding the minimum throughput achievable by a CSMA/ECA<sub>Hys+FS</sub> network. It is computed following (3) with  $l_k = 2^k$  and  $l_{k-1} = 2^{k-1}$ .

The *Upper-bound* is obtained from considering the operation of a network using CSMA/ECA<sub>Hys+FS</sub>, but forcing nodes to use the maximum backoff stage for determining the cycle length and the level of aggregation. It is also computed using (3) but considering that all nodes are in the maximum backoff stage ( $k = m$ ) and therefore  $l_k = 2^m$ .

The maximum throughput achievable is the result of deactivating the Fair Share rules by forcing nodes to use maximum aggregation regardless of their backoff stage. This is called *Maximum Aggregation (Hys+MaxAg)* in Figure 8. It can be derived from (3) considering  $l_k = 2^m$  and  $l_{k-1} = 2^m$ .

It is interesting to see in Figure 8 how collisions force colliding CSMA/ECA<sub>Hys+FS</sub> contenders to increase their backoff stage and aggregate more with Fair Share. This explains why the CSMA/ECA<sub>Hys+FS</sub> curve separates itself from the *Lower-bound* at a very low number of contenders.

Although using maximum aggregation (see *Maximum Aggregation (Hys+MaxAg)* curve in Figure 8) increases the throughput it carries the effect of unevenly distributing the available bandwidth among contenders, as mentioned in Section III-B.

The tools for deriving these two curves are available as MATLAB functions in [27].

#### D. Clock drift issue in decentralized collision-free MAC protocols

CSMA/ECA relies on stations being able to correctly count empty slots and consequently attempt transmissions in the appropriate slot according to the backoff timer. Failure to do so may be caused by clock imperfections inside the Wireless Network Interface Cards (WNIC), which is commonly referred to as *clock drift*. As pointed out in [28], clock drift is a common issue that degrades the throughput in distributed collision-free MAC protocols like the ones reviewed in Sect. II.

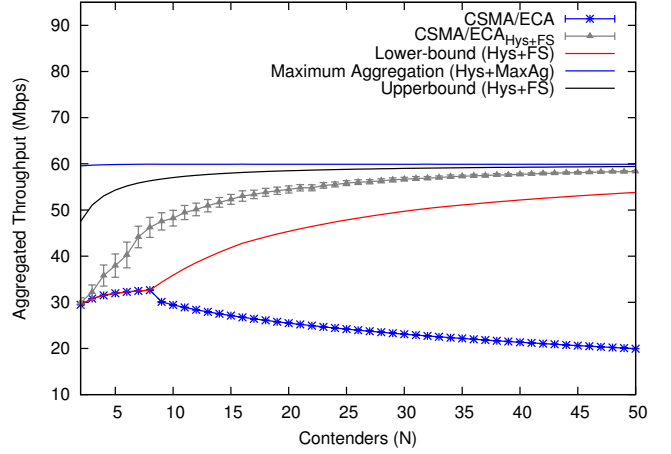


Fig. 8. Upper and Lower throughput bounds for CSMA/ECA<sub>Hys+FS</sub>

While miscounting empty slots have no significant effect on CSMA/CA's throughput [28], it has a direct impact on CSMA/ECA. In a collision-free schedule with saturated CSMA/ECA contenders, a station miscounting empty slots will *drift* to a possibly busy slot, collide and force a re-convergence (if possible) to a collision-free schedule (see Sect. V-A2).

#### E. Real hardware implementation

Replacing the firmware of commercial WLAN cards with the Open Firmware for WiFi Networks, OpenFWWF [29], allows the modification of time-sensitive operations in the MAC, like the backoff procedure. In Section VI we provide details regarding the testbed, the firmware used and present results of real experiments using CSMA/ECA.

#### F. Backwards compatibility and coexistence

CSMA/ECA<sub>Hys+FS</sub> springs from a modification to CSMA/CA's backoff mechanism. It keeps the range of values CSMA/CA nodes use to draw a random backoff (i.e., use the same  $CW_{\min}$  and  $CW_{\max}$ ), allowing CSMA/ECA<sub>Hys+FS</sub> contenders to coexist with CSMA/CA nodes in the same network. Further, the selection of CSMA/ECA<sub>Hys+FS</sub>'s deterministic backoff,  $B_d$ , is the expected value for the current backoff stage  $k$  ( $B_d := \lceil E[0, CW(k)] \rceil$ ) [15], which ensures fairness among contenders. An overview of the attained throughput for different proportions of CSMA/ECA<sub>Hys+FS</sub> and CSMA/CA nodes is presented in Section V-C.

### IV. SIMULATION SCENARIO

This section provides the simulation parameters for testing CSMA/ECA<sub>Hys+FS</sub> under two different traffic conditions, namely saturated and non-saturated. Further, the simulation of the clock drift effect, and the coexistence with CSMA/CA are also subjects to be addressed in this section.

TABLE I  
PHY AND MAC PARAMETERS FOR THE SIMULATIONS **REVIEW**

PHY	
Parameter	Value
PHY rate	65 Mbps
Empty slot	9 $\mu$ s
DIFS	28 $\mu$ s
SIFS	10 $\mu$ s
MAC	
Parameter	Value
Maximum backoff stage ( $m$ )	5
Minium Contention Window ( $CW_{\min}$ )	16
Maximum retransmission attempts	6
Packet size (Bytes)	1024
MAC queue size (Packets)	1000

#### A. Scenario details

Results are obtained by running multiple simulations over a modified version of the COST simulator [18], available at [30]. PHY and MAC parameters are detailed in Table I. Some assumptions were made in order to test the performance at the MAC layer:

- Unspecified parameters follow the IEEE 802.11n (2.4 GHz) standard.
- All nodes are in communication range.
- No Request-to-Send (RTS) or Clear-to-Send (CTS) messages are used.
- There are no external interference or channel errors. **Remove.**
- Collisions take as much channel time as successful transmissions.

The aforementioned assumptions ensure that the simulation results are just effects of the MAC behavior, thus isolating it from external factors, i.e.: **channel imperfections**. Further, in a collision-free CSMA/ECA<sub>Hys+FS</sub> operation there is no need for RTS/CTS mechanisms, given that successful nodes already know their respective transmission slot. **Maybe here is where the conversation about hidden nodes should take place?**

If not mentioned otherwise, results are derived from 100 simulations of 100 seconds in length. Figures also show the standard deviation.

#### B. Saturated and Non-saturated stations

A saturated station always has packets in its MAC queue. This is modelled by setting the packet arrival rate to the MAC queue ( $\Delta_{\text{PAR}}$ ) to a value greater than the achievable throughput. To ensure saturation, stations are set to fill their MAC queue at  $\Delta_{\text{PAR}} = 65$  Mbps, which is purposefully greater than the effective capacity of the channel.

To evaluate the performance under non-saturated conditions, stations need to be able to empty their MAC queues. To do so, the packet arrival rate to the MAC queue is set to  $\Delta_{\text{PAR}} = 1$  Mbps. These values of  $\Delta_{\text{PAR}}$  have proven to produce the desired effects.

#### C. Channel errors

Here we explain how we implement our channel errors model.

#### D. Performance under clock drift

Clock drift is simulated by setting a drift probability,  $p_{cd}$ . Each station has a probability of  $p_{cd}/2$  of miscounting one slot more, and  $p_{cd}/2$  of miscounting one slot less. This approach follows the one proposed by Gong et. al in [28].

#### E. Coexistence with CSMA/CA

To test the performance of CSMA/CA and CSMA/ECA<sub>Hys+FS</sub> stations in the same network, simulations are set with a CSMA/CA node density of 1/4, 1/2 and 3/4 of the total.

### V. RESULTS

#### A. Saturated nodes

In CSMA/CA, a large number of saturated nodes will normally be related to a high collision probability. This effect is in part the result of resetting the backoff stage after a successful transmission and the generation of a new random backoff. However, this scenario provides an advantageous condition to CSMA/ECA<sub>Hys+FS</sub> nodes. In saturation, CSMA/ECA<sub>Hys+FS</sub> nodes build a collision-free schedule and stick to their deterministic backoff as long as they transmit successfully, effectively eliminating collisions.

This section aims at overiewing the throughput of CSMA/CA and CSMA/ECA<sub>Hys+FS</sub> in saturation, as well as the collision probability, the average time between successful transmissions and the effect of clock drift over the throughput.

1) *Throughput*: CSMA/ECA<sub>Hys+FS</sub> nodes are able to build a collision-free schedule, use the channel more efficiently and experience a throughput increase, as seen in Figure 9. As mentioned in Section III-A, Hysteresis allows the allocation of more contenders in a collision-free schedule, while Fair Share ensures an even distribution of the available throughput. In contrast, CSMA/CA throughput keeps decreasing due to an augmented number of collisions as the number of nodes increases (see Figure 10). Further, Figure 11 shows the fraction of collision slots for CSMA/ECA<sub>Hys+FS</sub> and CSMA/CA as simulation time passes. In the figure, is appreciated how the fraction of collision slots keeps decreasing once CSMA/ECA<sub>Hys+FS</sub> reaches the collision-free schedule.

2) *Effect of clock drift over the achieved throughput in saturation*: Figure 12 shows the network aggregated throughput with 16 saturated stations and an increasing clock drift probability.

In Figure 12, a station has a clock drift probability equal to  $p_{cd}$ . Each station has a probability of  $p_{cd}/2$  of miscounting one slot more, and  $p_{cd}/2$  of miscounting one slot less. Because CSMA/CA is based on a random backoff, miscounting slots has no significant effect on the throughput. For the CSMA/ECA curve, it is possible to appreciate a slight decrease of the throughput as  $p_{cd}$  increases, caused by collisions due to the drift.

The CSMA/ECA<sub>Hys+FS</sub> curve in Figure 12 shows instead an increase of the aggregated throughput as  $p_{cd}$  grows. Collisions make CSMA/ECA<sub>Hys+FS</sub> contenders to increment their backoff



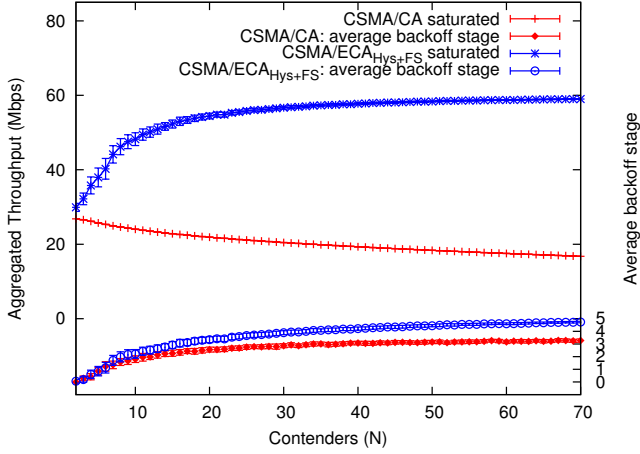


Fig. 9. Throughput under saturated conditions

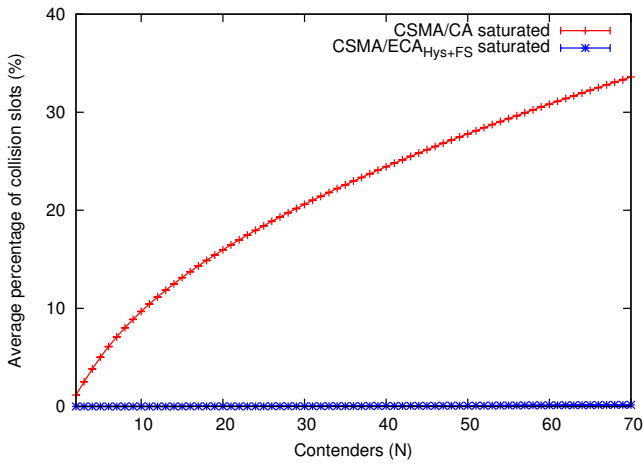


Fig. 10. Average percentage of collision slots: the fraction of time slots containing collisions.

stage and aggregate packets for transmissions according to Fair Share, effectively increasing the throughput.

As it also can be appreciated in the figure, the average backoff stage for CSMA/ECA<sub>Hys+FS</sub> contenders increases rapidly to its maximum value ( $m = 5$ ), reducing the effect of clock drift over CSMA/ECA<sub>Hys+FS</sub> nodes given that their transmissions would now be separated by more slots.

3) *Time between successful transmissions*: It is related to the elapsed time between the contention for transmission and the reception of an ACK.

In Figure 13 all tests with maximum aggregation, namely CSMA/CA<sub>MaxAg</sub> and CSMA/ECA<sub>Hys+MaxAg</sub>, have an increased average time between successful transmissions. This is due to the multiple packets that are sent in each attempt. CSMA/CA<sub>MaxAg</sub>, though, has an increased value due to collisions also taking longer channel time.

Although CSMA/ECA<sub>Hys+FS</sub> has an increased average time between successful transmissions due to Fair Share, it has a lower metric when compared with the maximum aggregation curves in Figure 13.

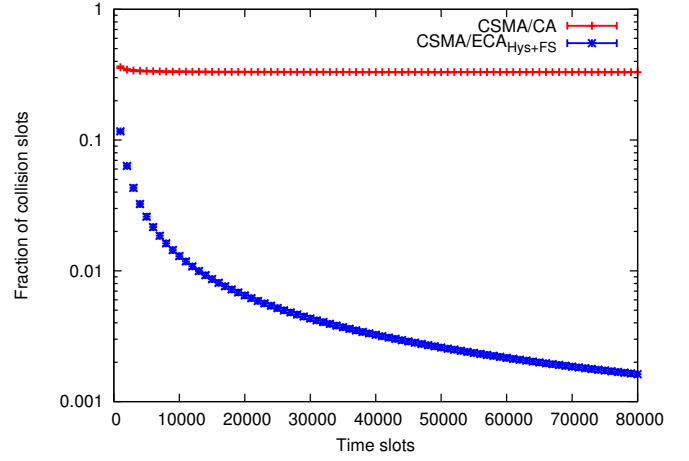


Fig. 11. Evolution of the fraction of collision slots in a scenario with 70 saturated stations.

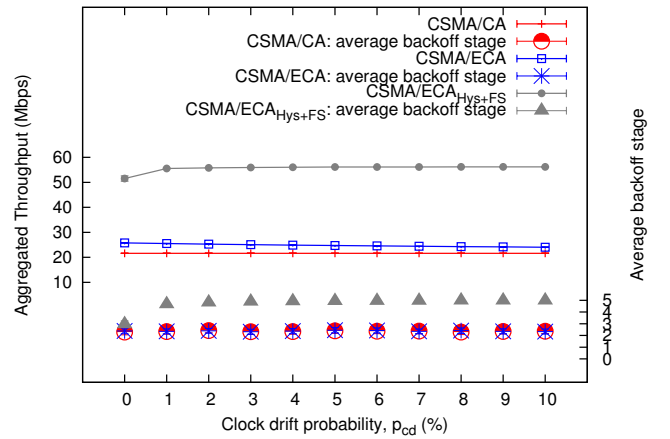


Fig. 12. Throughput when increasing the clock drift probability

### B. Non-saturated nodes

Emptying the MAC queue in CSMA/ECA<sub>Hys+FS</sub> means that nodes will reset their backoff stage and use a random backoff when a new packet arrives at the queue, breaking the collision-free schedule (if any) for CSMA/ECA<sub>Hys+FS</sub> contenders. The following show the impact over throughput, delay and time between successful transmissions when using CSMA/CA and CSMA/ECA<sub>Hys+FS</sub> in non-saturated conditions.

1) *Throughput*: In Figure 14, the aggregated throughput increases linearly for the CSMA/CA *non-saturated* curve until saturation is reached at around 22 nodes, where the throughput begins to degrade. The CSMA/ECA<sub>Hys+FS</sub> *non-saturated* curve has a similar behavior, entering saturation at around 60 nodes. Further, at around 30 nodes we see an increase in the average backoff stage for CSMA/ECA<sub>Hys+FS</sub> contenders which suggests an increment in collisions. This effect is shown in Figure 15 and Figure 16, where at around 35 nodes CSMA/ECA<sub>Hys+FS</sub> contenders start colliding and dropping packets.

After 40 contenders, the MAC queue of CSMA/ECA<sub>Hys+FS</sub> nodes starts to fill, as appreciated in Figure 17, gradually

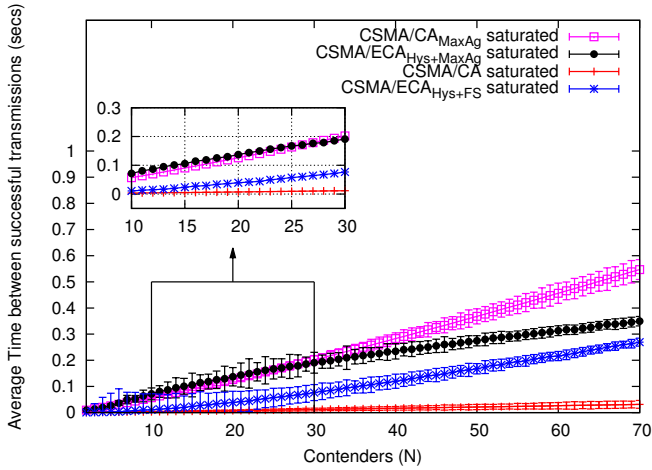


Fig. 13. Average time between successful transmissions: averaging over all stations

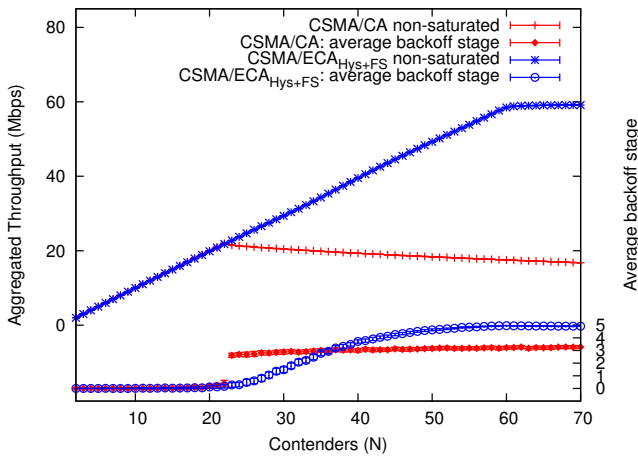


Fig. 14. Throughput in non-saturation conditions

building a collision-free schedule due to CSMA/ECA<sub>Hys+FS</sub>'s deterministic backoff after successful transmissions. This allows CSMA/ECA<sub>Hys+FS</sub> to outperform CSMA/CA.

2) *Delay*: This metric refers to the elapsed time between the injection of a packet into the station's MAC queue and the reception of an ACK for such packet.

In Figure 18, a rapid increase in the delay for CSMA/CA nodes is appreciated at the saturation point (around 20 contenders), whereas CSMA/ECA<sub>Hys+FS</sub>'s delay is still low.

Further, with CSMA/ECA<sub>Hys+FS</sub> the percentage of blocked packets from the MAC queue is lower than CSMA/CA or CSMA/CA<sub>MaxAg</sub> (see Figure 19). This is due to the construction of a collision-free schedule which ensures that nodes transmit frequently (Hysteresis) and Fair Share which reduces the average delay given that more packets are transmitted and acknowledged with a single ACK.

As CSMA/ECA<sub>Hys+FS</sub> nodes get saturated, the delay increases due to longer queueing and contention time (see the number of packets in the MAC queue for CSMA/ECA<sub>Hys+FS</sub> nodes in Figure 17 and how it is related to the increase in delay shown in Figure 18).

Figure 20 shows the average time between successful trans-

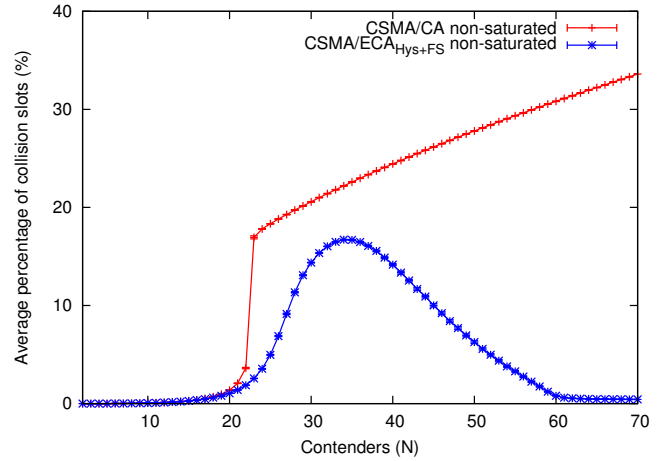


Fig. 15. Average percentage of collision slots: the fraction of time slots containing collisions in non-saturated conditions

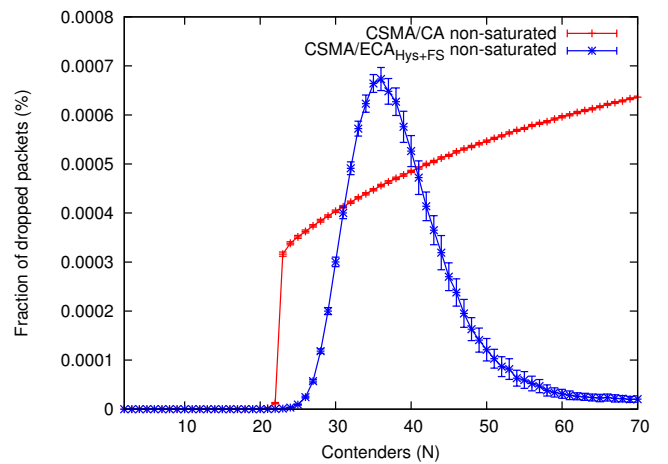


Fig. 16. Percentage of dropped packets due to reaching the retransmission threshold

missions. It is possible to see from the figure that when the saturation point is approached the average time between successful transmissions increases, resembling Figure 13. Moreover, this effect is related to an increase in collisions: colliding nodes should begin a new contention for a retransmission, which may result in a successful transmission or another collision, the latter further increasing the average time between successful transmissions.

### C. Coexistence with CSMA/CA

CSMA/ECA is thought to be an evolution of CSMA/CA given its similarities and the ability to coexists with the latter. This section provides simulations results for a setup of different proportions of CSMA/CA nodes in a network where there are also CSMA/ECA<sub>Hys+FS</sub> contenders, that is: 1/4, 1/2 and 3/4 of the total nodes run CSMA/CA, while the rest uses CSMA/ECA<sub>Hys+FS</sub>. This network configuration will be referred to as *mixed network setup* from here on.

1) *Throughput*: Figure 21 shows the network throughput for different proportions of CSMA/CA nodes in a mixed network setup.

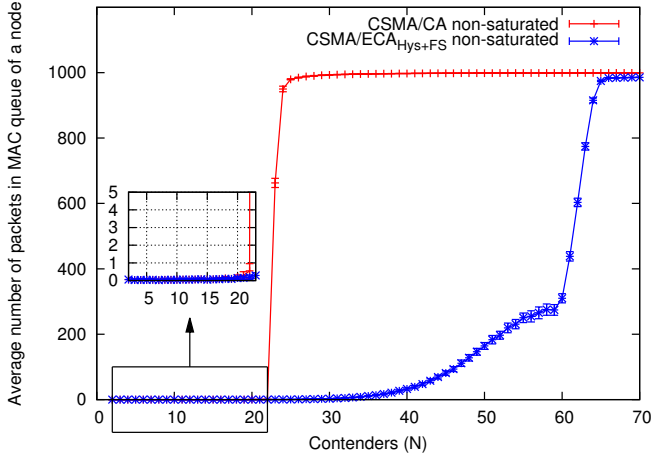


Fig. 17. Average number of packets in the MAC queue of a node

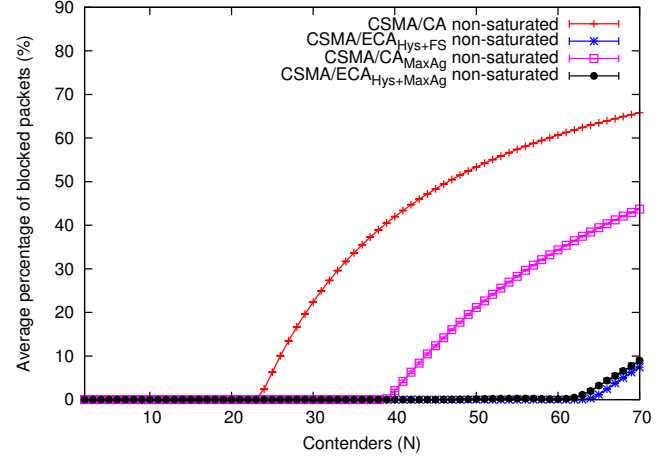


Fig. 19. Average fraction of blocked packets. When the MAC queue is full, packets coming from the upper layers must be discarded or blocked

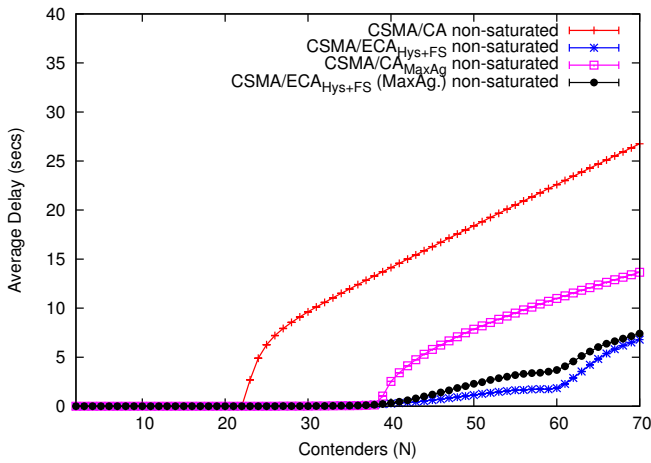


Fig. 18. Average system delay: averaging over all stations

In the figure it is appreciated how the mixed network setups curves lay between the CSMA/CA and CSMA/ECA<sub>Hys+FS</sub> curves. As the proportion of CSMA/CA nodes decreases, the throughput increases as the result of a lower probability of collision, as can be seen in Figure 22. A similar behavior is observed when testing the same proportion of nodes under non-saturated conditions. Figure 23 and Figure 24 show the average aggregated throughput and fraction of collisions slots in a non-saturated mixed network setup.

As shown in Figure 21 and Figure 23, at a lower proportion of CSMA/CA nodes (1/4) the average aggregated throughput is the greatest among the tested mixed network setups. This is because collisions trigger Hysteresis and Fair Share in CSMA/ECA<sub>Hys+FS</sub> nodes, lowering the number of times these nodes enter in a contention and reducing the overall collision probability when compared to an only CSMA/CA network (see Figure 22 and Figure 24). As the proportion of CSMA/CA nodes increases, the network throughput approximates to CSMA/CA.

## VI. REAL HARDWARE IMPLEMENTATION

The implementation of CSMA/ECA<sub>Hys+FS</sub> should be carried out at a firmware level due to the tight timing constraints

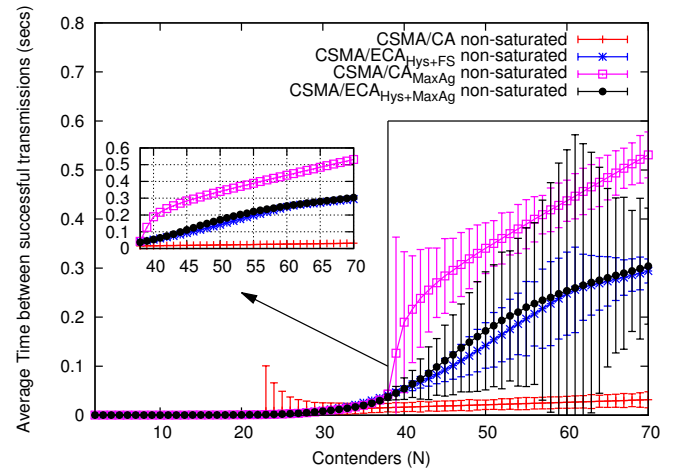


Fig. 20. Average time between successful transmissions in non-saturated conditions: averaging over all stations

related to the backoff procedure. There are several alternatives to modify the backoff operation in WNICs, either using open firmware like OpenFWWF [29] or through Field Programmable Gate Arrays (FPGA).

Although the FPGA option would in theory provide the strict timing requirements, the associated costs and difficulty are greater than the OpenFWWF alternative. OpenFWWF provides an open CSMA/CA firmware for a specific model of Broadcom WNICs' chipset, so the resulting firmware can be uploaded and tested in real commercial hardware.

By making the modifications represented in Algorithm 2, a proof-of-concept prototype of CSMA/ECA was built using commercial hardware [19]–[21]. The prototype was able to create a collision-free schedule among a reduced number of contenders using big deterministic backoffs (such as 128 or 256 slots). Nevertheless, clock drift, imprecise timing [31] and other prototyping non-idealities prevented the construction of a collision-free schedule when using a small deterministic back-off or dynamic rate adaptation algorithms, like Minstrel [32].

Although the timing inaccuracy issues were identified and leveraged to prototype a similar protocol in real hardware [22], further development on the prototype is being carried out in

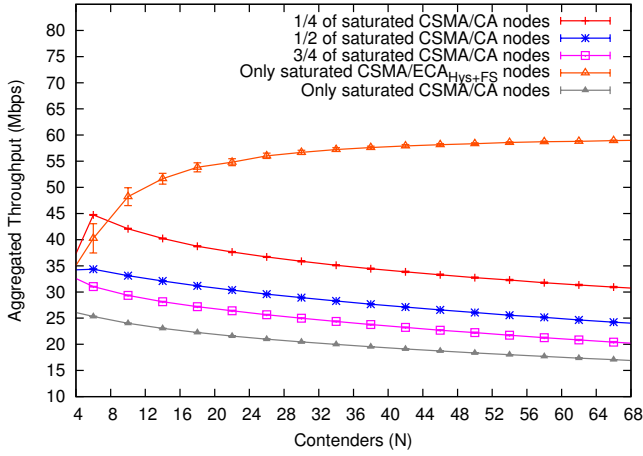


Fig. 21. Network throughput when composed by various proportions of CSMA/CA and CSMA/ECA<sub>Hys+FS</sub> nodes

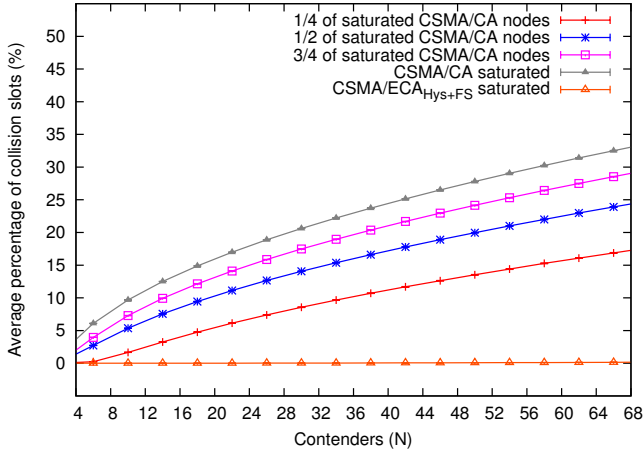


Fig. 22. Average percentage of collision slots for the tested mixed network setups proportions

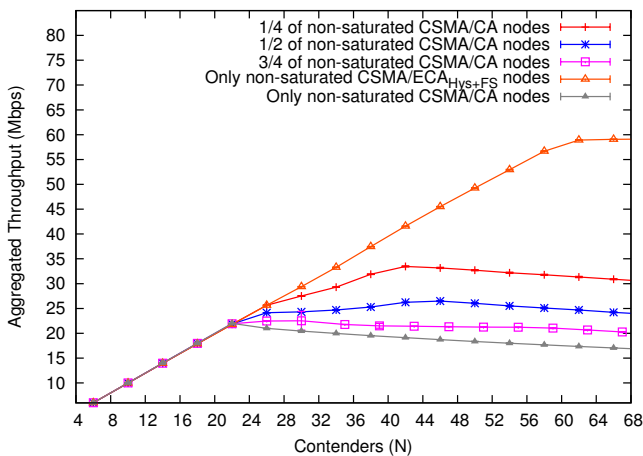


Fig. 23. Network throughput when composed by various proportions of non-saturated CSMA/CA and CSMA/ECA<sub>Hys+FS</sub> nodes

order to incorporate Hysteresis and Fair Share.

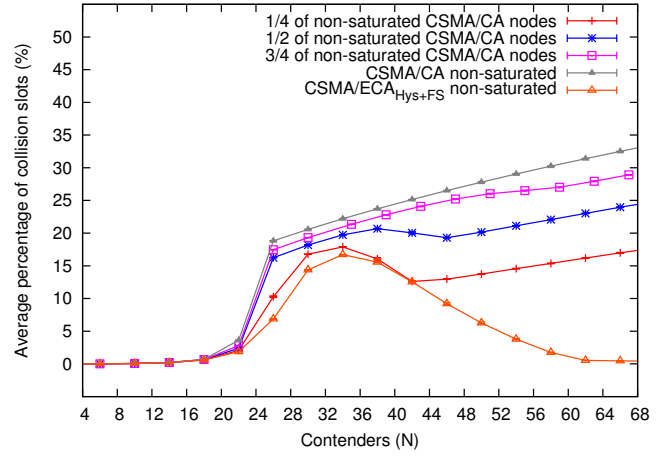


Fig. 24. Average percentage of collision slots for the tested mixed network setups proportions in non-saturated conditions

## VII. TRANSITIONING TOWARDS CSMA/ECA<sub>Hys+FS</sub>

The current PHY enhancements considered by the HEW study group include higher modulation and coding schemes as well as full duplex radios, capable of receiving and transmitting at the same time, thus augmenting the achievable throughput. Furthermore, already existing technologies like Channel bonding and Multiple-User Multiple-Input Multiple-Output (MU-MIMO) also seek to increase the throughput. The latter by allowing the transmission of different packets to multiple destinations at the same time, while the former bonds multiple WiFi channels together in order to increase the available bandwidth. Using CSMA/ECA<sub>Hys+FS</sub> alongside these features would provide enhanced performance by constructing collision-free schedules, thus substantially decreasing the time spent recovering from collisions.

Additionally, there are several features and scenarios still to be analysed for CSMA/ECA<sub>Hys+FS</sub> networks. Part of what is left for future work is summarised in the following:

- The performance of a CSMA/ECA<sub>Hys+FS</sub> network in presence of other neighbouring wireless networks and hidden nodes: transmissions from other network may negatively affect the maintenance of the collision-free schedule when not all devices in the CSMA/ECA<sub>Hys+FS</sub> WLAN are able to listen to them. As a consequence, not all stations will pause the backoff accordingly, resulting in large slot drifts that in consequence will disrupt the collision-free schedule, approximating CSMA/ECA<sub>Hys+FS</sub> performance to CSMA/CA's. A similar effect is expected when in the presence of hidden nodes.
- Traffic differentiation: although priorities using different contention windows in CSMA/ECA<sub>Hys+FS</sub> proved to outperform CSMA/CA, other Enhanced Distributed Channel Access (EDCA) mechanisms like the Arbitration Inter-Frame Spacing (AIFS) would not work [33], whereas the following EDCA mechanisms would:
  - Transmission Opportunity (TXOP): stations with an increased TXOP are able to transmit more packets. APs in CSMA/ECA<sub>Hys+FS</sub> can use a big TXOP in order to transmit more than users.



- Multiple Queues: [33] provides performance metrics for two traffic categories. In order to transition to CSMA/ECA<sub>Hys+FS</sub> a total of four access categories (AC) should be implemented, as in EDCA. Priorities to the multiple queues can be granted through different minimum and maximum contention windows.

CSMA/ECA<sub>Hys+FS</sub> with multiple access categories is expected to provide better traffic differentiation in WLANs, mainly due to the elimination of collisions by using a deterministic backoff after each access category's successful transmission.

- Coexistence with EDCA stations in the same WLAN.

## VIII. CONCLUSIONS

CSMA/ECA<sub>Hys+FS</sub> is able to construct a collision-free schedule with many contenders. Taking advantage of this condition, the cumulative throughput experienced by CSMA/ECA<sub>Hys+FS</sub> nodes goes beyond the achievable by CSMA/CA for any number of nodes. All of these while preserving throughput fairness. Further, as non-saturated CSMA/ECA<sub>Hys+FS</sub> networks get crowded the cumulative throughput keeps increasing up to the saturation point, contrary to the throughput degradation seen in CSMA/CA networks.

As CSMA/ECA<sub>Hys+FS</sub> is thought to be the next MAC for WLANs, coexistence with CSMA/CA nodes is paramount. Results show that coexistence is not an issue for any proportion of CSMA/ECA<sub>Hys+FS</sub>/CSMA/CA users. Moreover, when the network is composed with a majority of CSMA/ECA<sub>Hys+FS</sub> nodes, the cumulative throughput increases from CSMA/CA's.

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