# Building The Next MAC for WLANs

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***Abstract*—Collisions are a main cause of throughput degradation in WLANs. The current contention mechanism used in this type of network called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) uses a Binary Exponential Backoff (BEB) technique to delay each contender attempt of transmitting, effectively reducing the collision probability. Nevertheless, CSMA/CA relies on a random backoff that while effective and totally distributed, in principle is unable to eliminate collisions; degrading the network throughput as more contenders attempt to share the channel. Carrier Sense Multiple Access with Enhanced Collision Avoindance (CSMA/ECA) is able to create a collision-free schedule in a totally distributed manner by means of picking a deterministic backoff after successful transmissions. CSMA/ECA is able to support many contenders in a collision-free schedule, surpassing the achieved throughput of CSMA/CA and providing short-term throughput fairness among contenders.**

**This work describes CSMA/ECA and its mechanisms to achieve a collision-free schedule with many contenders by providing insightful simulation under different network traffic conditions and hardware anomalies such as an imperfect clock.**

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

## I. INTRODUCTION

Wireless Local Area Networks (WLANs or IEEE 802.11 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), which is a main reason for its popularity.

The Medium Access Control (MAC) scheme used in WLANs is called Distributed Coordination Function (DCF) and is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. It has been widely adopted by manufacturers and consumers, making it very cheap to implement and an ubiquitous technology (DCF and CSMA/CA will be used interchangeably throughout this work). Nevertheless, the ever-growing throughput demands from upper layers have proven to be limited by 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 time-critical operations are modified, its hardware implementation as part of WLANs' MAC often becomes unlikely [14]; the standardization process taking many years without certainty of approval [2].

A CSMA/CA replacement should be able to provide advantages in terms of throughput and handle many contenders without sacrificing short-term throughput fairness. Furthermore, to support the existing user base and ease its implementation on real hardware, the new MAC protocol should be built on top of the current standard, ensuring backwards compatibility and avoiding a drastic deviation from CSMA/CA.

A suitable candidate, and the one to be tested 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 pick a deterministic backoff after successful transmissions; constructing a collision-free schedule among successful contenders. Further enhancements, like *Hysteresis* and *Fair Share* [15] allowed CSMA/ECA to support many more contenders in a collision-free schedule without compromising short-term fairness.

Although many studies have been made analysing the performance of CSMA/ECA [7], [8], [15], [16], neither assesses the protocol's backwards compatibility property under different traffic conditions. Furthermore, the impact of imperfect clocks over the deterministic backoff mechanism is also lacking.

This work provides the first performance analysis of CSMA/ECA [15] under unsaturated conditions, as well as its resilience to imperfect clocks.

The rest of this work is divided as follows: an overview of similar distributed and collision-free MAC protocols for WLANs is provided in Section II. CSMA/ECA, as well as its properties for allocating many contenders in a collision-free schedule are explained in Section III. Section IV details the simulation procedure for testing CSMA/ECA, while Section V explains the results. Conclusions are drawn in Section VI.

## 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 an order of magnitude larger than empty slots ($\sigma_e \ll \min(\sigma_s, \sigma_c)$). One of the effects of collisions is the degradation the network performance by wasting channel time on collisions slots.

Big advances in the WLANs PHY [2], [17] push the 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. The followings 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) [**?**] achieves a zero collision schedule for WLANs in a totally distributed way. It does so by allowing contenders to reserve one empty slot ($s_e$) 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 pick the same slot in the cycle, their transmissions will eventually collide; forcing the involved contenders to randomly and uniformly select other empty slot from those detected 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 successful transmission are no longer negligible and contribute to the degradation of the network performance.

### B. Learning-MAC

Learning-MAC [18] is another MAC protocol is 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. Equation 1 and Eq. 2 extracted from [18] show the probability of selecting the same slot $s(n)$ in cycle $n + 1$.

$$\left.\begin{aligned} p_{s(n)}(n+1) = 1, \\ p_j(n+1) = 0, \end{aligned}\right\} \qquad \textit{Success} \tag{1}$$

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

, for all $j \neq s(n)$, $j \in \{1, \ldots, C\}$. 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 Eq. 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 better levels of 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 *Adaptative* schedule length in order to increase the number of supported contenders in a collision-free schedule. This adaptive schedule length ($C_i$) 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. Furthermore, L-MAC is unable to achieve a collision-free schedule unless $N \leq C$.

## III. Carrier Sense Multiple Access with Enhanced Collision Avoidance (CSMA/ECA)

CSMA/ECA [7] is a totally distributed and collision-free MAC for WLANs. It differs from DCF in that it picks 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 do so without colliding with other successful nodes in future cycles.

Collisions are handled as in DCF. Upon collision, the involved nodes will double their contention window by incrementing their *backoff stage* $k \in [0, m]$ in one and picking a random backoff, $B \in [0, 2^k CW_{\min}]$; where $k$ is reset ($k = 0$) after each successful transmission and $m$ is the maximum backoff stage of typical value $m = 5$. Figure 2 shows an example of CSMA/ECA dynamics.

In Figure 2, the *STA-#* labels represent stations willing to transmit. The horizontal lines are a time abstraction 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 picking 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 pick 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 DCF's. Figure **??** shows the achieved throughput of CSMA/ECA and CSMA/CA, alongside the Jain's Fairness Index (JFI) [19].

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 $B_d = 7$. Beyond this point, the network will have a mixed behavior relating to backoff mechanisms: some nodes will successfully transmit and pick a deterministic backoff while others will collide due to the lack of empty slots and return to a random backoff. As more contenders join 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. A value equal to one throughout the range of contenders suggests that the available throughput is shared evenly among all stations.

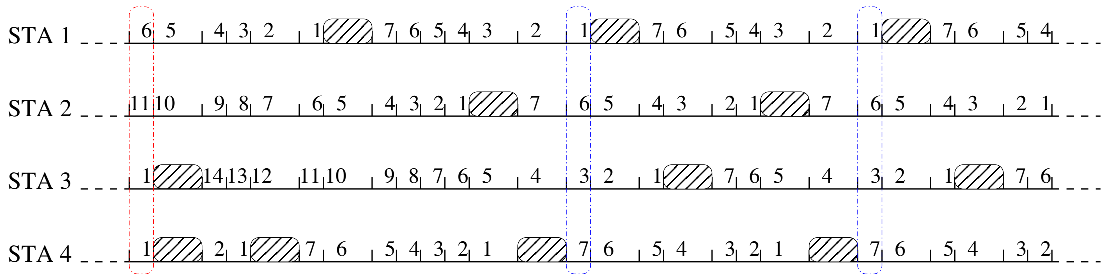


Fig. 1. CSMA/ECA example in saturation

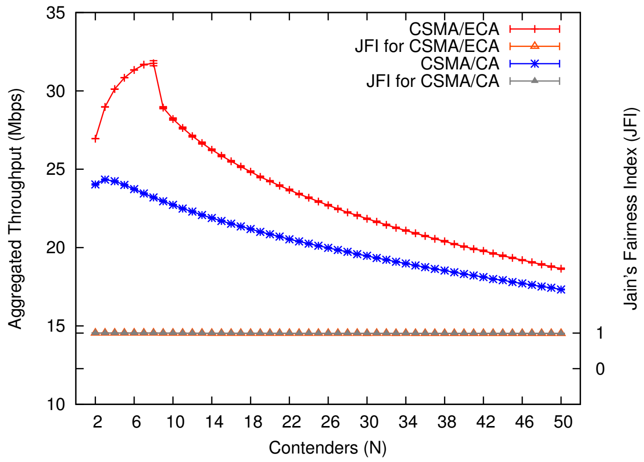


Fig. 2. CSMA/ECA example in saturation

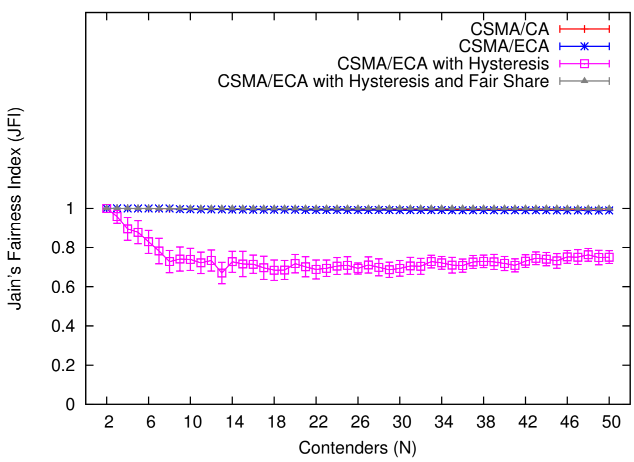


Fig. 3. Fairness comparison with nodes under saturation

### *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 recover the collision-free schedule CSMA/ECA instructs nodes **not** to reset their backoff stage ($k$) after successful transmissions, but to pick a deterministic backoff $B_d = CW(k)/2$; where $CW(k) = 2^k CW_{\min}$. This measure allows the adaptation of the schedule length, admitting many more contenders in a collision-free schedule. This extension to CSMA/ECA is called *Hysteresis*.

Hysteresis enables CSMA/ECA nodes to have different schedules ($B_d$), carrying the undesired effect of unevenly divide the channel time among contenders (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$_{\text{Hys+FS}}$ in order to distinguish it from what was described until this point.

Fair Share was first proposed by Fang. et al. in [18], and later implemented for CSMA/ECA [15]. Figure 3 shows the JFI for CSMA/CA as well as for CSMA/ECA$_{\text{Hys+FS}}$.

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

As with Figure 2, Figure 4 shows four stations attempting to transmit. The first outline indicates a collision between STA-3 and STA-4, which will provoke an increment on both station's backoff stage ($k = k + 1$). Once STA-4's random backoff expires, CSMA/ECA$_{\text{Hys+FS}}$ instructs the station to transmit $2^k$ packets, and then pick a deterministic backoff, $B_d = CW(k)/2$. The same behavior is followed by STA 3.

With Hysteresis and Fair Share, CSMA/ECA$_{\text{Hys+FS}}$ 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 with Hysteresis and Fair Share* curve shows a greater throughput because collisions are eliminated and Fair Share allows nodes to send $2^k$ packets upon each transmission.

### *B. Clock drift issue in descentralized 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 [20], clock drift is a common issue that degrades the throughput in distributed collision-free MAC protocols like the ones reviewed in Sect. II.

Miscounting empty slots has a direct impact on CSMA/ECA. In a collision-free schedule with saturated

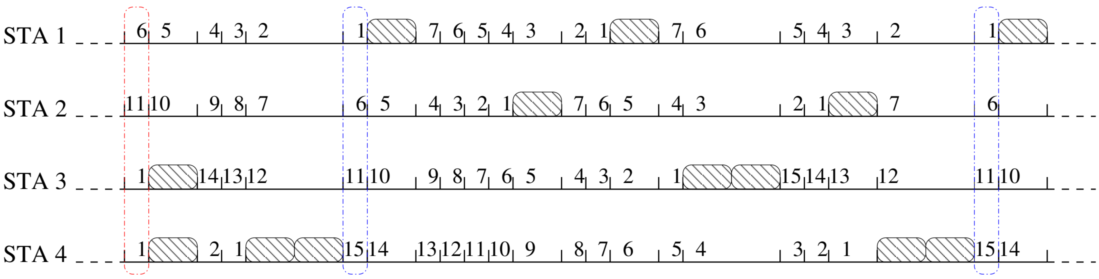


Fig. 4. CSMA/ECA$_{\text{Hys+FS}}$ example in saturation ($CW_{\min} = 16$)

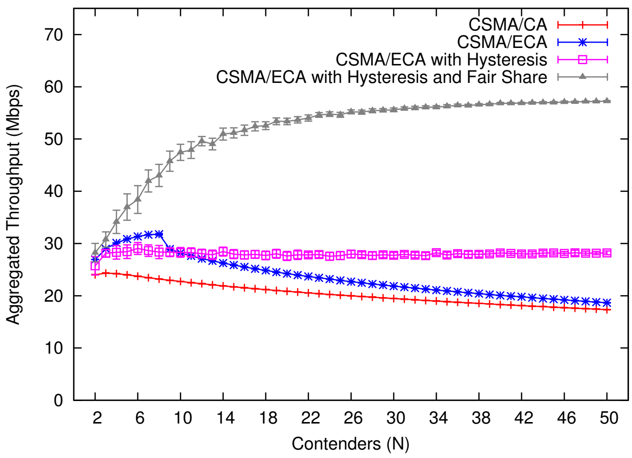


Fig. 5. Throughput comparison [15]

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.

## IV. Simulation

This section provides the simulation parameters for testing CSMA/ECA$_{\text{Hys+FS}}$ under two different traffic conditions, namely saturated and unsaturated. Further, the simulation of the clock drift effect, and the coexistence with CSMA/CA are also subjects to be addressed in this section.

### A. Technical details

Results are obtained by making iterative simulations over a modified version of the COST [21] simulator, available at [22]. PHY and MAC parameters are detailed in Table I. The following assumptions were made:

- Unspecified parameters follow the IEEE 802.11n standard.
- All nodes are within reach of each other.
- There are no external interferences or channel errors.
- Collisions take as much channel time as successful transmissions ($\sigma_s = \sigma_c$).

If not mentioned otherwise, results are derived from 100 simulations of 100 seconds in length. Figures show 95% confidence intervals.

TABLE I
PHY and MAC parameters for the simulations

| PHY | |
|---|---|
| **Parameter** | **Value** |
| PHY rate | 11 Mbps |
| Empty slot | 16 $\mu s$ |
| DIFS | 34 $\mu s$ |
| SIFS | 9 $\mu s$ |
| **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 |

### B. Saturated and Non-saturated stations

A saturated station always has packets in its MAC queue, that is, its packet arrival rate to the MAC queue ($\Delta_{\text{PAR}}$) has to be 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 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 ΔPAR have proven to produce the desired effects.

### C. 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 [20].

### D. Coexistance with CSMA/CA

To test the performance of CSMA/CA and CSMA/ECA$_{\text{Hys+FS}}$ stations in the same network, simulations are done with a CSMA/CA node density of 1/3, 1/2 and 2/3 of the total.

## V. Results

### A. Saturated scenario

In CSMA/CA, a saturated scenario coupled with a big number of contenders will normally be related to an increase in the collision probability. This effect is in part the result of resetting the backoff stage after a successful transmission and the generation of a random backoff. On the other hand, a saturated scenario provides an advantageous condition to CSMA/ECA$_{\text{Hys+FS}}$ nodes in terms of the reduction in the number of collisions, given that a collision-free schedule would be possible (without considering unideal external conditions).

This section aims at overviewing the throughput of CSMA/CA and CSMA/ECA$_{\text{Hys+FS}}$ in saturation, as well as the collision probability, the average service time and the effect of clock drift over the throughput.

*1) Throughput:* CSMA/ECA$_{\text{Hys+FS}}$ nodes are able to build a collision-free schedule, thus the increase in the throughput, as seen in Figure 6. 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. Whereas CSMA/CA throughput is degraded by collisions as the number of contenders increases (see Figure 7).

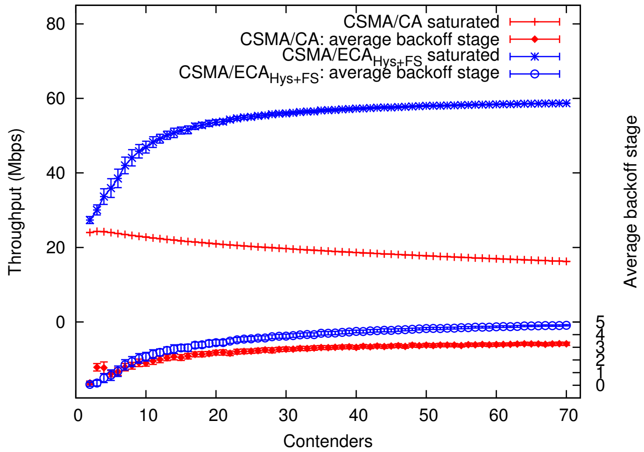


Fig. 6. Throughput under saturated conditions

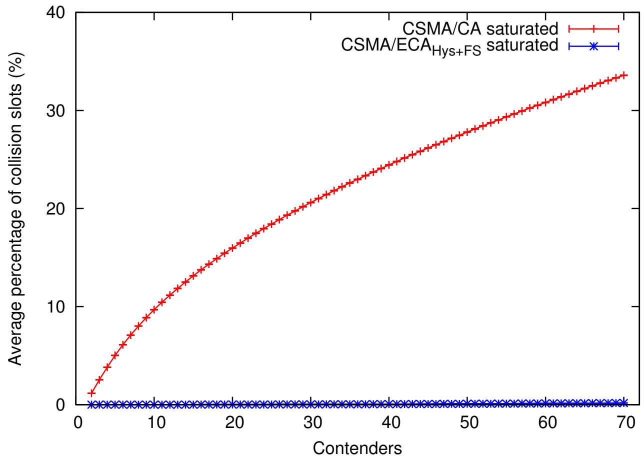


Fig. 7. Average percentage of collision slots: the fraction of time slots containing collisions.

*2) Effect of clock drift over the achieved throughput in saturation:* Figure 8 shows the network aggregated throughput with 16 saturated stations and an increasing clock drift probability.

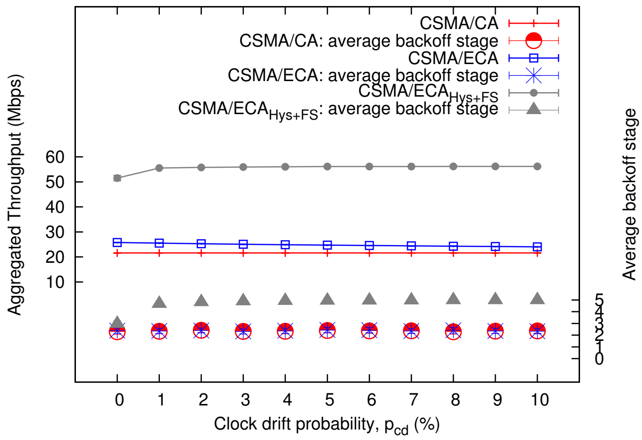


Fig. 8. Throughput when increasing the clock drift probability

In Figure 8, 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 an increased number of collisions due to the drift.

The CSMA/ECA$_{\text{Hys+FS}}$ curve in Figure 8 shows instead an increase of the aggregated throughput as $p_{cd}$ grows. The increase in collisions make CSMA/ECA$_{\text{Hys+FS}}$ contenders to increment their backoff stage ($k = k+1$) and aggregate packets for transmissions according to Fair Share (sending $2^k$ packets in each attempt). As it also can be appreciated in the figure, the average backoff stage for CSMA/ECA$_{\text{Hys+FS}}$ contenders increases rapidly to its maximum value ($m = 5$), provoking the aggregation of packets that causes the throughput increase.

*3) Service Time:* It is related to the elapsed time between the arrival of a packet to the MAC queue up util an acknowledgment is received for such packet(s).

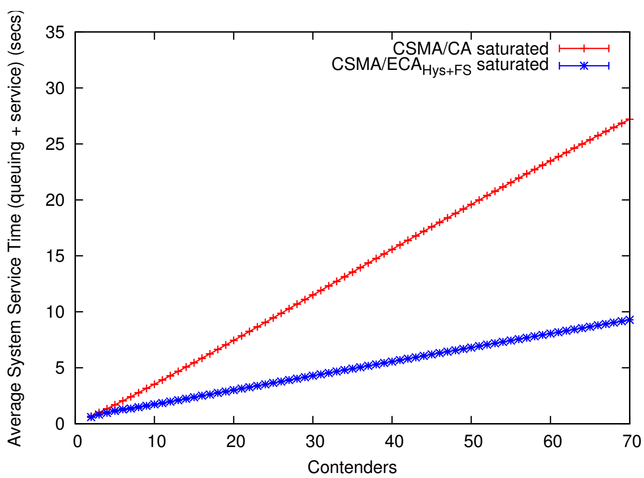


Fig. 9. Average system service time: aggregating the average service of all stations

In Figure 9, CSMA/ECA$_{\text{Hys+FS}}$ shows a lower service time due to the aggregation performed via Hysteresis and Fair Share, mainly because these aggregated transmissions are acknowledged by a single ACK. It is important to highlight that because nodes are in saturation, the arrival time to the MAC queue is considered the same for aggregated packets.

### *B. Unsaturated scenario*

Emptying the MAC queue in CSMA/ECA means that nodes will reset their backoff stage and pick a random backoff when a new packet arrives at the queue; breaking the collision-free schedule (if any) for CSMA/ECA$_{\text{Hys+FS}}$ contenders. The followings show the impact over throughput and service time when using CSMA/CA and CSMA/ECA$_{\text{Hys+FS}}$.

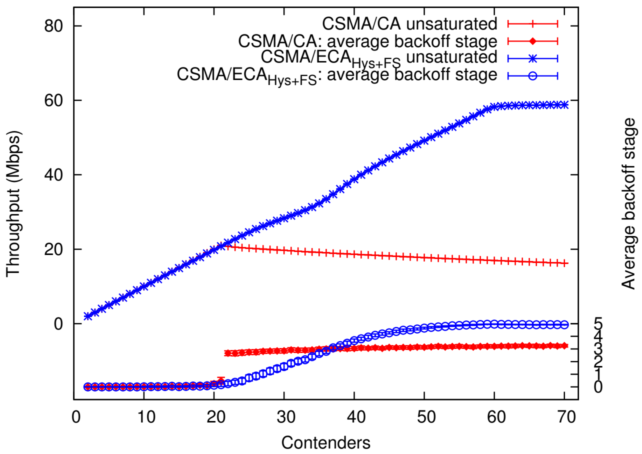


Fig. 10. Throughput in unsaturated conditions

*1) Throughput:* In Figure 10, the aggregated throughput increases linearly for the *CSMA/CA unsaturated* curve until saturation is reached at around 22 nodes, where the throughput begins to degrade. The *CSMA/ECA$_{Hys+FS}$ unsaturated* curve has a similar behavior, entering saturation at around 60 nodes. Nevertheless, it seems to stop the linear increase at around 30 nodes. This throughput degradation coupled with the steep increase in the average backoff stage of CSMA/ECA$_{\text{Hys+FS}}$ contenders suggests an increment in dropped packets due to retransmission attempts. This effect is shown in Figure 11, where at around 30 nodes CSMA/ECA$_{\text{Hys+FS}}$ contenders start colliding and dropping packets.

After 40 contenders, the MAC queue of CSMA/ECA$_{\text{Hys+FS}}$ nodes starts to fill, as appreciated in Figure 12; gradually building a collision-free schedule due to CSMA/ECA$_{\text{Hys+FS}}$'s deterministic backoff after successful transmissions.

*2) Service Time:* In Figure 13, a rapid increase in the service time for CSMA/CA nodes is appreciated at the saturation point (around 20 contenders). For the CSMA/ECA$_{\text{Hys+FS}}$ nodes the service time is still low at CSMA/CA saturation point even-though we see an increase in the number of dropped packets (see Figure 11). This is due to Hysteresis and Fair Share, which reduces the average service time given that more packets are transmitted and acknowledged with a single ACK. As CSMA/ECA$_{\text{Hys+FS}}$ nodes get saturated, the service time increases because of the

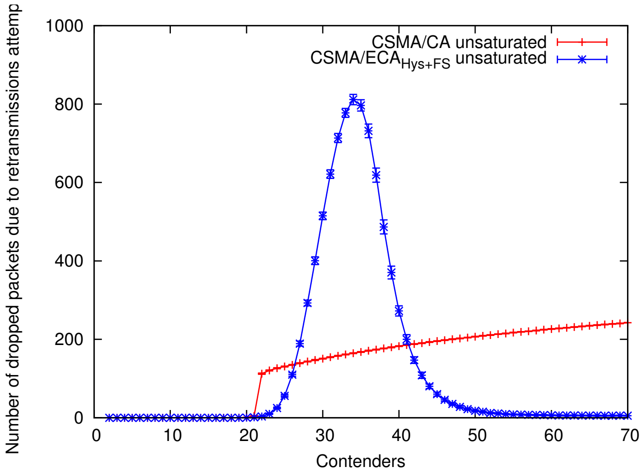


Fig. 11. Number of droppped packets due to retransmissions attempts

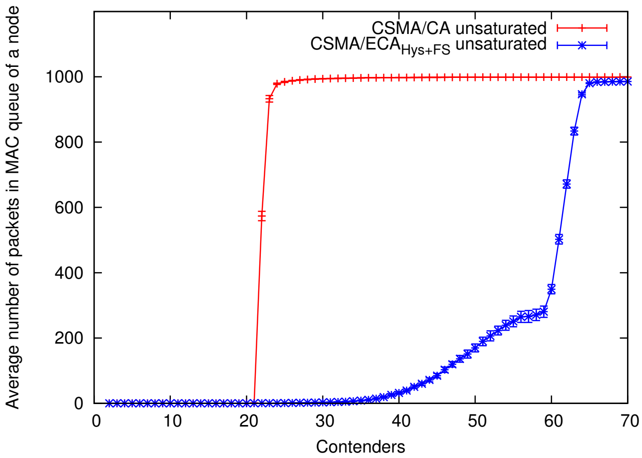


Fig. 12. Number of packets in the MAC queue of a node

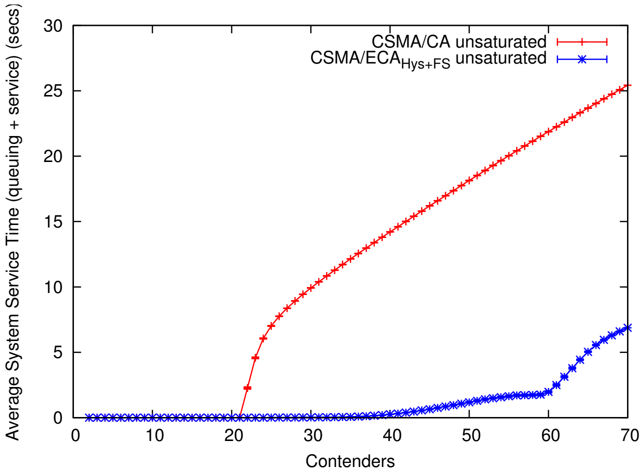


Fig. 13. Average system service time: aggregating the average service of all stations

contention mechanism (see the number of packets in the MAC queue for CSMA/ECA$_{Hys+FS}$ nodes in Figure 12 and how it is related to the increase in service time shown in Figure 13).

### 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/ECA$_{Hys+FS}$ nodes in a CSMA/CA network, namely: 1/4, 1/2 and 3/4 of the total nodes run CSMA/ECA$_{Hys+FS}$, while the rest uses CSMA/CA.

*1) Throughput:* Figure 14 shows the network throughput for different proportions of CSMA/ECA$_{Hys+FS}$ nodes.

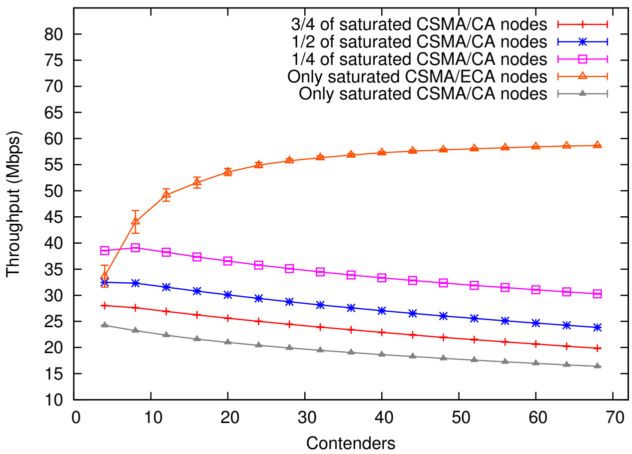


Fig. 14. Network throughput when composed by various proportions of CSMA/ECA$_{Hys+FS}$ nodes

In the figure it is appreciated how the mixed network setups curves lay between the only CSMA/CA and CSMA/ECA$_{Hys+FS}$ curves. As the proportion of CSMA/CA nodes decreases, the throughput increases as the result of a lower probability of collision among CSMA/ECA$_{Hys+FS}$ contenders. Further, although there is still a probability of collisions due to the presence of CSMA/CA contenders, these collisions trigger the Hysteresis and Fair Share extension of CSMA/ECA$_{Hys+FS}$ nodes, producing the throughput increase when compared to a CSMA/CA network. Figure 15 provides an overview of the average throughput of CSMA/CA and CSMA/ECA$_{Hys+FS}$ stations respectively.

## VI. Conclusions

## VII. Acknowledgements

## References


[1] "IEEE Standard for Information Technology - Telecommunications and Information exchange between systems. Local and Metropolitan Area Networks - Specific requirements," *IEEE Std 802.11TM-2012*, p. 1646, 2012.

[2] Perahia, E, "IEEE 802.11n Development: History, Process, and Technology," *Communications Magazine, IEEE*, vol. 46, no. 7, pp. 48–55, 2008.

[3] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: a media access protocol for wireless LAN's," in *ACM SIGCOMM Computer Communication Review*, vol. 24, no. 4. ACM, 1994, pp. 212–225.


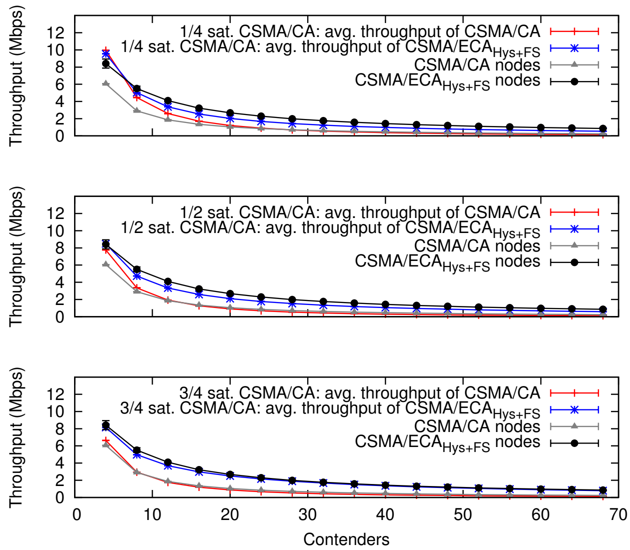


Fig. 15. Average throughput of CSMA/CA stations in a network also composed by various proportions of CSMA/ECA$_{Hys+FS}$ nodes


[4] C. Wang, B. Li, and L. Li, "A new collision resolution mechanism to enhance the performance of IEEE 802.11 DCF," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 4, pp. 1235–1246, 2004.

[5] F. Cali, M. Conti, E. Gregori, and P. Aleph, "Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit," vol. 8, no. 6, pp. 785–799, 2000.

[6] A. Lopez-Toledo, T. Vercauteren, and X. Wang, "Adaptive Optimization of IEEE 802.11 DCF Based on Bayesian Estimation of the Number of Competing Terminals," vol. 5, no. 9, p. 1283, 2006.

[7] J. Barcelo, B. Bellalta, C. Cano, and M. Oliver, "Learning-BEB: Avoiding Collisions in WLAN," in *Eunice*, 2008.

[8] J. Barcelo, B. Bellalta, A. Sfairopoulou, C. Cano, and M. Oliver, "CSMA with Enhanced Collision Avoidance: a Performance Assessment," in *IEEE VTC Spring*, 2009.

[9] Y. He, R. Yuan, J. Sun, and W. Gong, "Semi-Random Backoff: Towards resource reservation for channel access in wireless LANs," in *17th IEEE International Conference on Network Protocols*. IEEE, 2009, pp. 21–30.

[10] J. Barcelo, A. Toledo, C. Cano, and M. Oliver, "Fairness and Convergence of CSMA with Enhanced Collision Avoidance (ECA)," in *2010 IEEE International Conference on Communications (ICC)*, may 2010, pp. 1 –6.

[11] M. Fang, D. Malone, K. Duffy, and D. Leith, "Decentralised learning MACs for collision-free access in WLANs," *Wireless Networks*, vol. 19, pp. 83–98, 2013. [Online]. Available: http://dx.doi.org/10.1007/s11276-012-0452-1

[12] K. Hui, T. Li, D. Guo, and R. Berry, "Exploiting peer-to-peer state exchange for distributed medium access control," in *Information Theory Proceedings (ISIT), 2011 IEEE International Symposium on*. IEEE, 2011, pp. 2368–2372.

[13] J. Barcelo, B. Bellalta, C. Cano, A. Sfairopoulou, and M. Oliver, "Towards a Collision-Free WLAN: Dynamic Parameter Adjustment in CSMA/E2CA," in *EURASIP Journal on Wireless Communications and Networking*, 2011.

[14] I. Tinnirello, G. Bianchi, P. Gallo, D. Garlisi, F. Giuliano, and F. Gringoli, "Wireless MAC processors: Programming MAC protocols on commodity Hardware," in *INFOCOM, 2012 Proceedings IEEE*, march 2012, pp. 1269 –1277.

[15] L. Sanabria-Russo, A. Faridi, B. Bellalta, J. Barceló, and M. Oliver, "Future Evolution of CSMA Protocols for the IEEE 802.11 Standard," in *2nd IEEE Workshop on Telecommunications Standards: From Research to Standards. Budapest, Hungary*, 2013.

[16] G. Martorell, F. Riera-Palou, G. Femenias, J. Barcelo, and B. Bellalta, "On the performance evaluation of CSMA/E2CA protocol with open loop ARF-based adaptive modulation and coding," *European Wireless. 18th European Wireless Conference*, pp. 1 –8, april 2012.

[17] L. Hanzo, H. Haas, S. Imre, D. O'Brien, M. Rupp, and L. Gyongyosi, "Wireless Myths, Realities, and Futures: From 3G/4G to Optical and Quantum Wireless," *Proceedings of the IEEE*, vol. 100, no. Special Centennial Issue, pp. 1853–1888, 2012.

[18] M. Fang, D. Malone, K. Duffy, and D. Leith, "Decentralised learning MACs for collision-free access in WLANs," *Wireless Networks*, pp. 1–16, 2010.

[19] R. Jain, D. Chiu, and W. Hawe, *A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer System*. Eastern Research Laboratory, Digital Equipment Corporation, 1984.

[20] W. Gong and D. Malone, "Addressing Slot Drift in Decentralized Collision Free Access Schemes for WLANs," in *Multiple Access Communications*, ser. Lecture Notes in Computer Science, B. Bellalta, A. Vinel, M. Jonsson, J. Barcelo, R. Maslennikov, P. Chatzimisios, and D. Malone, Eds. Springer Berlin Heidelberg, 2012, vol. 7642, pp. 146–157. [Online]. Available: http://dx.doi.org/10.1007/978-3-642-34976-8_16

[21] E. Yücesan, C. Chen, J. Snowdon, and J. Charnes, "COST: A component-oriented discrete event simulator," in *Winter Simulation Conference*, 2002.

[22] L. Sanabria-Russo, J. Barcelo, and B. Bellalta. (2012) Implementing CSMA/ECA in COST. [Online]. Available: https://github.com/SanabriaRusso/CSMA-E2CA