Collision-Free WLANs: From Concepts to Working Protocols. A PhD. Proposal

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Abstract. In the upcoming years the number of devices that exchange data wirelessly is though to increase dramatically, even nowadays home environments no longer lack the wireless network congestion only seen before at office/public spaces (like wireless hot-spots). The current Medium Access Control (MAC) protocol is known to be prone to collisions, which increase with the number of stations in the wireless network. Many proposals have been made to amend the current standard, but at the time of this writing the drawbacks related to collisions have not been fixed. One of the reasons why implementing new MAC protocols is a challenging task relates to the prototyping difficulties associated to the really fast processing speed required to execute the protocol in real-time. Prototype implementations would make it possible to test proposed MAC protocols in realistic channel conditions and traffic patterns.

This PhD Thesis Proposal aims at designing and prototyping next-generation MAC protocols for IEEE 802.11-like networks, going from concept proposals to hardware implementation.

1 Introduction

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is the protocol used in Wireless Local Area Networks (WLANs) to coordinate transmissions. Nodes should avoid simultaneous transmissions because the medium is shared, so concurrent transmissions attempts will result in indecipherable messages to the receivers. This event is referred to as a *collision*.

For CSMA/CA, time is slotted. As a result, there are three kind of slots: *empty*, *successful* and *colllision* slots, where successful and collision slots contain successful transmissions or collision events. While the remaining are just tiny empty slots of a fixed time length.

Every time there is a contention for transmission, CSMA/CA forces contenders to count down from a randomly generated number (from now on referred to as backoff counter), decrementing it by one per every passing empty slot. When the backoff expires (reaches zero), contenders will attempt transmission. Nevertheless, because the backoff counter is generated at random, there might be cases where two or more contenders simultaneously attempt transmission and a collision occurs, significantly degrading the throughput of the system.

It is possible to obtain greater levels of throughput than the achieved by CSMA/CA under optimal parameter configuration by picking a deterministic backoff counter after successful transmissions. This approach is called Carrier Sense Multiple Access with Enhanced Collision Avoidance (CSMA/ECA) [1]. Results also show that by making simple modifications on the behavior of the current protocol, CSMA/ECA is able to allocate more contenders in a collision-free fashion while preserving the system fairness by equally distributing the system throughput among all nodes.

Many years of testing have settled CSMA/CA as the default protocol for this type of networks, even-though many other proposals claim to outperform it, e.g. [1–5]. Nevertheless, their proposed adjustments tested by simulation are not included in the current standard.

Recent approaches to design and implement MAC protocols on cheap commodity hardware [6, 7] opened the possibility to prototype some of the protocols proposed by the research community. Although at an early phase and steep learning curve, these alternatives allow researchers of all levels to make substantial contributions.

1.1 Motivation

As mentioned before, many proposals to amend the collision problem in CSMA/CA have been made and none is included in the current standard.

Taking a guess-look at what is to come in a few years time at the Small-Office/Home-Office (SOHO) scenario, WLANs are expected to be as crowded as never before. From tablets, laptops, smart phones, watches, smart health/activity monitoring devices; to traffic prioritization, accommodating these many devices and services will soon out-challenge CSMA/CA.

Even though CSMA/CA in theory is able to coordinate medium access for many contenders, it does so at the price of a reduced throughput induced by collisions. This is completely leveraged by CSMA/ECA, which in fact provides greater throughput than CSMA/CA in almost every testable scenario.

The goal of this PhD Thesis is twofold: 1) develop mechanisms to accommodate a large number of contenders in a collision-free fashion, taking into consideration different channel models, traffic patterns and quality of service, and 2) to generate mechanisms for MAC protocol prototyping in cheap commodity Wireless Network Interface Cards (WNICs) [6].

2 State of the Art

For the following paragraphs an overview of the state of the art is presented. Ranging from the current standard, referencing other proposed protocols, to end at the description of CSMA/ECA and the Wireless MAC Processor architecture [6].

It is worthwhile to note that the words *node*, *contenders* and *stations* may be used interchangeably without any different implication.

2.1 CSMA/CA: the current standard

Each node in a WLANs runs an instance of CSMA/CA protocol. As briefly mentioned in Section 1, in this time-slotted networks nodes draw a random backoff counter $B \in [0, CW(k)]$ everytime they have a packet to transmit; where $CW(k) = 2^k CW_{\min}$ is the contention window at backoff stage $k \in [0, m]$ with m its maximum value, and $CW_{\min}$ being the minimum contention window with typical value of $CW_{\min} = 16$.

Every passing empty slot decrements the backoff counter in one, and freezes when another node's transmission is detected. When the backoff expires ($B = 0$), the contending node attempts transmission.

Because the backoff is computed at random, it is possible that two or more nodes pick the same value. When the corresponding stations attempt transmission, none will receive an *ACKnowledgement* (ACK) from the receiver given that they attempted transmission at the same time. This is considered a collision.

The way CSMA/CA handles collisions is summarized in the following bullets:

– A collision is assumed if no ACK is received by the transmitter.
– CSMA/CA instructs colliding nodes to double their contention window by increasing the backoff stage k in one. This measure doubles the range of possible values drawn when computing the backoff counter, thus reducing the probability of two stations picking the same value.

If a node successfully transmits (receives an ACK from the receiver):

– Resets its backoff stage ($k = 0$).
– If it has another packet to transmit, the node generates a backoff counter and the process is restarted.

CSMA/CA uses a Binary Exponential Backoff (BEB) technique in order to reduce the collision probability (or the event of two stations picking the same backoff counter). Nevertheless, this technique does not eliminate collisions. In fact, stations that have successfully transmitted in the past may collide in the future. Figure 1 provides and example of CSMA/CA's behavior.
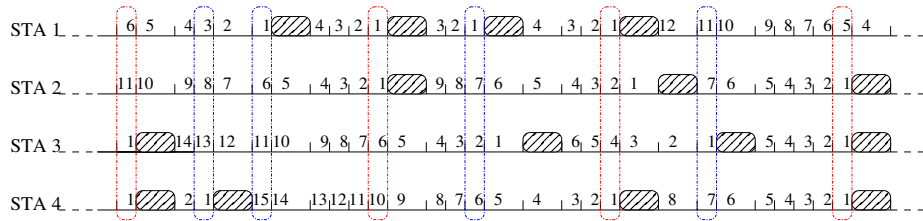

Fig. 1: For stations running CSMA/CA ($CW_{\min} = 16$)

2.2 Going beyond CSMA/CA's throughput

There have been many works proposing modifications to CSMA/CA [1–4, 8–14]. Nevertheless, and as pointed out in [15], there is a group among them that considers backwards compatibility with legacy users and at the same time provides levels of throughput beyond those provided by CSMA/CA. This performance boost is the result of eliminating collisions by choosing a deterministic backoff counter instead of a random one. The approach was first introduced in [12] and then tested under different conditions such as saturated and unsaturated scenarios [1–4].

It is called Carrier Sense Multiple Access with Enhanced Collision Avoidance (CSMA/ECA) and its similarities and differences with CSMA/CA are described in the following.

CSMA/ECA is a collision-free MAC protocol that allows many contenders to coordinate access to the medium in a totally distributed manner. It starts from the simple idea of picking a deterministic backoff counter $B_d = CW(k)/2$ after successful transmissions. By doing so, nodes that successfully transmitted in the past, will do so without colliding with other successful CSMA/ECA nodes in future cycles. Hence the collision-free state.

Nevertheless, when the number of contenders (n) is greater than the deterministic backoff $(n > B_d)$, collisions reappear. CSMA/ECA handles collision much more like CSMA/CA does, but in order to restore the collision-free state with this increased number of contenders, CSMA/ECA instructs nodes **not** to reset their backoff stage (k), resulting in a increased B_d. This is called *Hysteresis*, and ensures that many more contenders can be allocated in a collision-free state.

Hysteresis instructs some nodes to have greater backoff counters than others, unevenly sharing channel access time. This unfairness issue is leveraged 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 measure was first proposed by Fang et al. [3], and further implemented as *Fair Share* [15] for CSMA/ECA. Figure 2 shows a working example of CSMA/ECA.
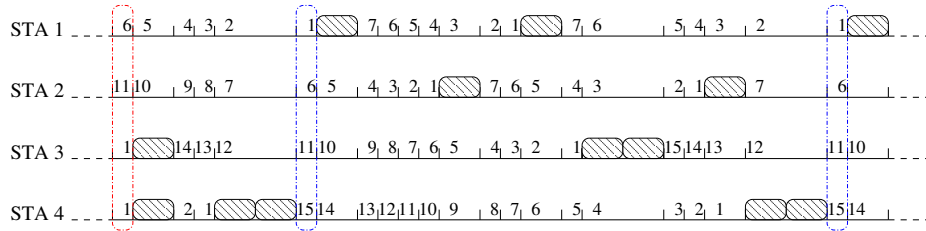

Fig. 2: For stations running CSMA/ECA ($CW_{\min} = 16$)

2.3 Prototyping MAC protocols in real hardware

MAC protocols face new challenges that come alongside upcoming scenarios like: vehicular, mesh and ad-hoc networks; quality of service (QoS) and traffic differentiation; and spectrum reutilization in cognitive networks.

Although plenty of proposals address the shortcomings of CSMA/CA, many are discarded either for deviating too much from the current standard operation or for their unlikeliness of real-world deployment.

The current implementation of MAC protocols in WNICs is done in a closed form, meaning that usually time-critical (or Lower-MAC) tasks are hardware-coded without the possibility of modification by third-parties.

One step towards openness came with the release of OpenFWWF [16], the first open-source firmware of the Distributed Coordination Function (DCF) that rules CSMA/CA operation in WLANs. Its release opened the possibility for modifications to the Lower-MAC, thus augmenting its potential against other slower options like the ones using the Universal Software Radio Peripheral (USRP) [17] and GNURadio [18] combination [19] or the still hardware-limited FPGA alternatives, like [20].

Nevertheless, OpenFWWF is tightly related to the hardware platform it was released for (Broadcom/AirForce54G cards) and extensions require rewriting of large chunks of assembly code, which makes it difficult to implement by non-experts.

Wireless MAC Processors (WMP) [6] aim at lowering the barriers for MAC protocol implementation in commodity hardware. By carefully identifying and translating the MAC operations into different Extended Finite State Machines (XFSM), it became possible to designate Lower-MAC tasks to the general-purpose CPU equipped in most WNICs. Furthermore, the WMP-Editor (shown in Figure 3) allows programmers to combine different XFSM and configure the MAC events and conditions that would trigger their preconfigured tasks.

Although WMP-Editor allows for the modification of certain MAC parameters, at its current version it is not possible to fully customize the contention mechanism. For the successful implementation of contention mechanisms like the one found in CSMA/ECA, certain backoff function parameters need further customization.

3 Research Objectives

As was mentioned in the previous sections, picking a deterministic backoff after successful transmissions provides higher throughput than CSMA/CA in most common scenarios. CSMA/ECA's backoff strategy allows nodes to achieve a collision-free state even for a very large number of CSMA/ECA contenders; while its fairness mechanisms ensure that all stations share the same available system throughput in the long-term.

The following paragraphs detail the general and specific objectives of this research.
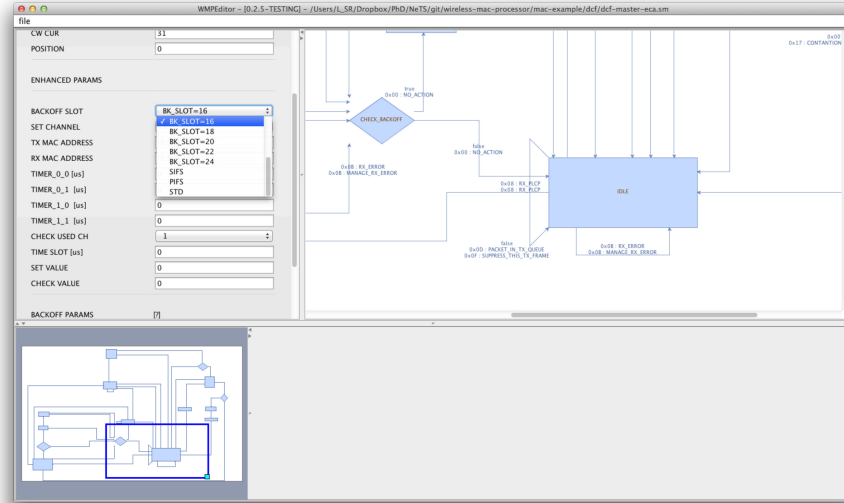
Fig. 3: WMP-Editor Layout

3.1 General Objective

– Investigate and develop methods that would allow the construction of a collision-free MAC protocol capable of coping with upcoming Small-Office/Home-Office (SOHO) scenarios, while facilitating its prototyping on real hardware.

3.2 Specific Objectives

Ranging from research challenges to debugging, the following subsection details what are believed to be the required steps to accomplish this research's general objective. Each specific objective represent a result of it own, while their *phases* dictate the activities required to fulfill it.

1. Investigate and develop mechanisms to allocate a great number of contenders in a collision-free fashion while considering Quality of Service (QoS) requirements of IEEE 802.11e networks

   Phases:
   1.a) Investigate and develop mechanisms that would allow CSMA/ECA to accommodate many contenders in a collision-free fashion.
   1.b) Design and evaluate the operation of CSMA/ECA in conjunction with the Enhanced Distribution Channel Access (EDCA).

1.c) Develop CSMA/ECA in a discrete event-based simulator.

1.d) Identify the performance metrics that will allow an unbiased comparison with CSMA/CA.

1.e) Design simulation tests for metrics gathering under different traffic patterns, QoS settings and considering mixed scenarios (shared network with some nodes running CSMA/CA and others CSMA/ECA).

1.f) Perform the simulation tests designed in the previous phase.

1.g) Document the results for future comparison with the hardware implementation.

Result: Performance evaluation of CSMA/ECA under EDCA.

2. Design methods to develop and test CSMA/CA into the WMP platform.

   Phases:

   2.a) Install the WMP-Editor on a host PC to study its components and configuration.

   2.b) Identify the software and hardware requirements needed to replicate CSMA/CA as a WMP.

   2.c) Design methods to develop CSMA/CA as a WMP.

   2.d) Develop a WMP containing the CSMA/CA functionality (WMP-CSMA/CA), ready to be uploaded to the appropriate WNICs.

   2.e) Design evaluation methods for the WMP-CSMA/CA so its performance can be compared with analytical models.

   2.f) Develop automated metric gathering scripts on the client PCs in order to achieve the goals set at Phase 2e.

   2.g) Upload the WMP-CSMA/CA into the necessary WNICs.

   2.h) Perform the evaluations designed in Phase 2e and analyze the results.

   Result: Method, procedures and performance evaluation of CSMA/CA as a running WMP.

3. Progressively modify WMP-CSMA/CA into WMP-CSMA/ECA.

   Phases:

   3.a) Identify the required modifications in WMP-CSMA/CA needed for it to become WMP-CSMA/ECA.

   3.b) Design methods for translating the missing characteristics into functioning XFSM.

   3.c) Develop CSMA/ECA into a WMP.

   3.d) Design evaluation methods for WMP-CSMA/ECA so its performance can be compared against the results obtained in Phase 1g.

   3.e) Perform the evaluations designed in the previous phase.

4. Extend the functionality of CSMA/ECA to RFID in the attempt to reduce convergence and tag-reading time.

   Phases:
   4.a) Gather metrics about the current performance of the system.
   4.b) Identify the required modifications to CSMA/ECA so it can work in a RFID environment.
   4.c) Design methods for introducing the required modifications to CSMA/ECA.
   4.d) Design simulation scenarios so the modified CSMA/ECA's performance can be analyzed.
   4.e) Perform the simulations designed in the previous phase.
   4.f) Document the results and compare them with the performance of the network before incorporating CSMA/ECA.

4 Research Plan and Methodology

In order to fulfill the objectives described in Section 3, a convenient and dynamic methodology should be implemented.

Given the great deal of software development, reverse engineering and debugging involved in the specific objectives, it is required to build a research plan with a methodology able to:

- Adapt to constant changes in the specific objectives/phases, even at advanced stages.
- Consider collaboration with peers acquainted with other knowledge areas.
- Facilitate frequent working-software deliveries with minimum bugs.

Based on this, it is thought to implement the principles of Agile Software Development [21, 22], which very well correspond with the requirements mentioned above.

4.1 Shot-term Control

Following the recommendations provided by the Agile methodology, a fifteen-minute meeting will be held everyday (if possible) with the thesis supervisor. This short, and preferably standing-up meetings complement the process of development by:

- Keeping everyone up-to-date on the state of the development.
- Increases supervisor-student collaboration.
- Helps keep the high frequency of the technical reports.

These technical reports are to delivered on a monthly basis and must provide sufficient overview of the research efforts, including:

- Current state of the research (looking at the objectives/phases).

- Past, current and future tasks (up until the next report).
- Required knowledge or material to fulfill the current objective/phases.

By implementing the Agile recommendations and following the short-term control measures described above, it is possible to keep track of the efforts towards the general objective.

4.2 Description of the Plan by Years

Agile methods are thought to be adaptive, meaning that the far future (six months from now) will present unknown problems; nevertheless it is more efficient at solving short-term problems, as was described previously at Section 4.1.

To leverage this issue, the objectives presented in Section 3 can be distributed over the remaining years as follows:

- **First year:** at the time of this writing, objectives 1a, 1c, 1d, 1e are either finished or ongoing work. Further details can encountered at Section 5. The remaining phases of the first specific objective are to be finished during the first year.
- **Second year:** will be dedicated to the study of the WMP architecture. This step will provide the knowledge to continue achieving objectives. It is expected to achieve specific objective 2, as well as 3a and 3b.
- **Third year:** is to be dedicated at the completion of specific objective 3 and 4.

A summary of the distribution of the activities throughout the remaining years is shown in Figure 4.

5 Summary of Prior Work

As was mentioned in Section 4.2, most of the first specific objective has been successfully developed. Its results derived in collaboration with experts from international institutions and two publications:

1. Sanabria-Russo, L., Barcelo, J., Bellalta, B: "Fairness in Collision-Free WLANs". INFOCOM 2013 Student Poster Session, Turin - Italy. ArXiv e-prints (February 2013).
2. Sanabria-Russo, L., Faridi, A., Bellalta, B., Barcelo, J., Oliver, M.: "Future Evolution of CSMA Protocols for the IEEE 802.11 Standard". Second IEEE ICC Workshop on Telecommunications Standards: From Research to Standards (June 2013).

Results of publication 1 [5] are summarized in Figure 5. The work includes the introduction of the concept of hysteresis and fair share to CSMA/ECA. It involved a thorough study of CSMA/ECA for then being able to adapt it to a simulation environment.

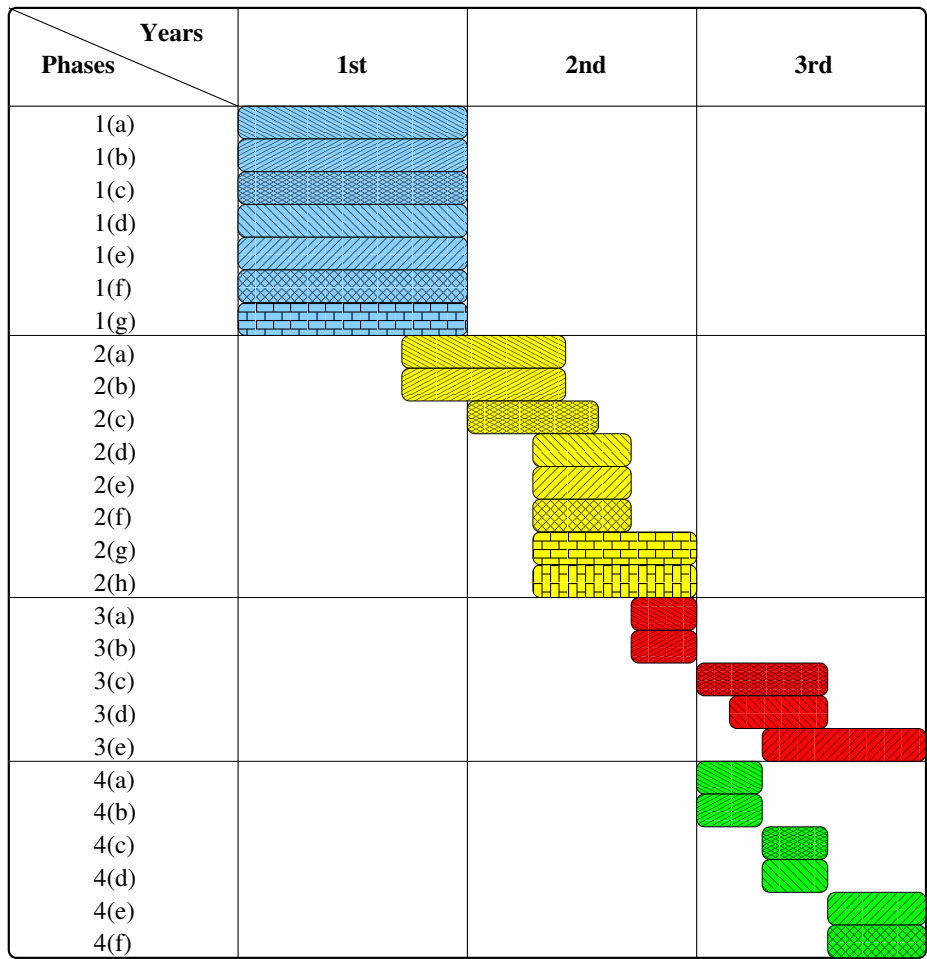| Years Phases	1st	2nd	3rd
1(a)			
1(b)			
1(c)			
1(d)			
1(e)			
1(f)			
1(g)			
2(a)			
2(b)			
2(c)			
2(d)			
2(e)			
2(f)			
2(g)			
2(h)			
3(a)			
3(b)			
3(c)			
3(d)			
3(e)			
4(a)			
4(b)			
4(c)			
4(d)			
4(e)			
4(f)			

Fig. 4: Gantt diagram

For delivering the results, a modified version of the COST simulator [23] was used. This tool separates the different components of the wireless networking communication (hosts, channel, queue and other components), permitting to modify their behavior independently.

Results from publication 2 [15] are contained in Figure 6. Apart from showing the throughput enhancements over CSMA/CA, it is also shown how the proportion of collision slots reduces to zero in time when using CSMA/ECA. Furthermore, code snippets are presented to highlight the slight variations between CSMA/ECA and CSMA/CA.
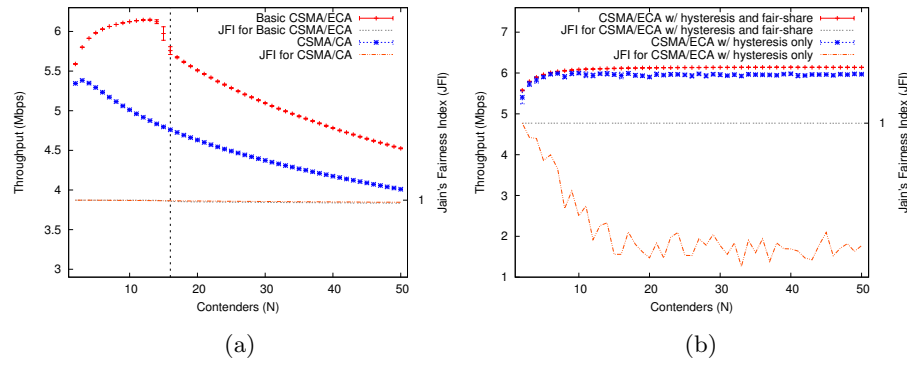

Fig. 5: 5a) Throughput of CSMA/CA vs. CSMA/ECA without hysteresis and fair share (referred to as Basic CSMA/ECA). 5b) Throughput and fairness when incorporating hysteresis and fair share to CSMA/ECA.
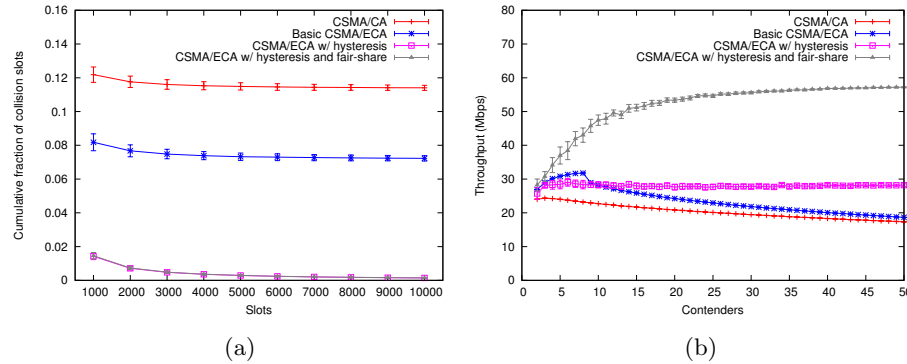

Fig. 6: 6a) Cumulative fraction of slots spent in collisions for $N = 12$ nodes. 6b) Throughput.

Up until the date of this writing, only [5] has been presented. It took place at the 32nd IEEE INFOCOM, April 14-19 at Turin, Italy. The conference provided the opportunity to meet with people involved in the FLAVIA and Wireless MAC Processors projects [7, 6], which have been providing helpful assistance ever since.

Between Jun 9-13 2013, the second work derived from this ongoing research [15] is to be presented at IEEE ICC in Budapest - Hungary. This presentation will show the convenience and enhancements provided by CSMA/ECA, which hopefully will increase it relevance in front of the responsible for amendments to the standard.

Apart from representing the fulfillment of various phases (see Section 3), these two publications provided some necessary connections with people acquainted with vital research fields needed for the fulfillment of this work's general objective.

6 Significance

It is not hard to encounter the crowded WLANs scenario exemplified in Section 1.1. Even nowadays it is not rare to have multiple WiFi devices at home attempting to access the channel at the same time: watching an on-line video stream, surfing the Web, receiving VoIP calls and uploading data from your personal health monitoring device.

CSMA/CA has been the de facto standard for coordinating transmissions in WLANs; nevertheless, its performance degrades when imposing heavy traffic on crowded scenarios like the one proposed above, where tens of devices must coordinate their transmission attempts in a totally distributed manner. This degradation in the system performance can be appreciated in the form of video lags while streaming or in below-average download speeds.

By removing the randomness from CSMA/CA's contention mechanism, the proposed CSMA/ECA achieves a better performance while allowing many nodes to coexist in a collision-free environment. Nevertheless, CSMA/ECA lacks of mechanisms to face different scenarios regarding: Quality of Service (QoS), hidden/exposed node mechanisms, performance against different traffic patterns and contention parameters optimization; which on the other hand have been the focus of study in CSMA/CA for many years.

Although it has proven to best CSMA/CA's throughput in controlled simulation environments, CSMA/ECA is far away from being considered as an amend to the standard and/or be hard-coded in real WNICs.

This work aims at bringing the benefits of CSMA/ECA to home WLANs by means of its implementation on real hardware. Its successful completion will provide a better alternative to CSMA/CA, capable of coping with the strict requirements of future networks and services. Furthermore, it will lay the groundwork for MAC protocol prototyping in cheap commodity hardware following the WMP principle, so anyone in the research community will be able to fol-

low the procedures contained in this work, replicate and further develop MAC technologies.

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