Rate, Power and Carrier-Sense Threshold Coordinated Management for High-Density IEEE 802.11 Networks

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***Abstract*—Nowadays, trying to obtain better coverage and performance, and allowed by the low-hardware prices, it is common to deploy a large number of IEEE 802.11 devices in offices, meeting rooms or auditoriums configuring the so called high-density networks. In such a scenario, the shared nature of the transmission medium causes interference problems. Some physical-layer- and link-layer-adaptation mechanisms to palliate those problems have been developed, however, most of them have not been independently implemented and assessed. In this paper, we implement in a simulator some of the existent solutions, compare them in a simulation environment and show that, in some situations, the existing solutions can lead to a starvation problem. Finally, we propose a new mechanism that manages data-rate, transmit power and carrier-sense threshold to ameliorate this problem.**

I. Introduction

IEEE 802.11 networks (WiFi) are now common in offices, campuses, airports and almost all urban area buildings. Generally, these networks are not planned nor carefully managed. Plenty of these deployments try to offer full zone coverage with a short distance from Access Points to terminals without considering metrics such as throughput or quality of service. This strategy, usually, leads to networks with strong performance and reliability issues due, mostly, to RF interference [1]. Given the ubiquity of the IEEE 802.11 standard there is a need for a solution to the problem that does not modify that protocol. Currently, there is a wide variety of ongoing research trying to improve the performance of high-density networks, in this paper we focus on the novel research area that manages the configuration of the IEEE 802.11 MAC and PHY layer for infrastructure networks.

This paper extends and improves the initial work presented in [2]. This time, we deeply review a variety of mechanisms that control parameters such as transmit power, data rate or carrier-sense threshold in Section II. Later, in Section III, we describe in detail our novel mechanism which addresses the problems suffered by networks with a heterogeneous wireless configuration, in particular the starvation problem generated by disparate transmit powers and carrier-sense thresholds, and finally we evaluate the solution both, in some representative scenarios that isolate problematic situations and in some more realistic scenarios.

A. Background

In the IEEE 802.11 standard [3] there are defined four coordination functions or methods for accessing the medium: the *Distributed Coordination Function* (DCF), the *Point Coordination Function* (PCF), the *Hybrid Coordination Function* (HCF) (which uses two mechanisms EDCA and HCCA) and the *Mesh Coordination Function* (MCF). IEEE 802.11 networks can work in three modes, infrastructure, ad-hoc and mesh. In the infrastructure mode each client associates with an Access Point (AP) and use the AP to send and receive traffic. In the ad-hoc and mesh mode the network is a collection of devices which are associated in such a way that they can send traffic directly between them. Most devices, when working in infrastructure mode, use DCF as the default configuration, therefore we will that one in this work.

DCF uses *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) to regulate the access to the medium. In this protocol a device must sense the medium to determine if another device is transmitting (physical carrier sense) before to start transmitting itself. If the medium is busy, the device waits until the end of the detected transmission. Then, before attempting to transmit again, the device waits for a random backoff time while the medium is idle and, then, it transmits its frames (see Figure 1). An ACK frame signals a successful transmission, should it not be received by the sender, it retransmits the presumed-lost frame.

In detail, the physical carrier sense in IEEE 802.11 standard is performed by the *Clear Channel Assessment* (CCA) function. CCA is defined in [3] as the logical function in the physical layer (PHY) that determines the current state of use of the wireless medium, i.e. if the medium is IDLE or BUSY. This function uses two mechanisms: Carrier Sense (CS) and Energy Detection (ED). In this case, CS refers to a particular case of carrier sensing and not to the general carrier sense mechanism mentioned earlier. CS is the capability of a node to not only detect but also decode the preamble of a signal (it is also known as Signal Detection). When this mechanism detects a preamble the CCA must be set to BUSY for the time necessary to finish the transmission. This time is indicated in the header of the frame either as the time in microseconds or the length and the data rate. On the other hand, Energy Detection can be defined as the ability of a node to sense the energy on the channel, where this energy could be from noise floor, non-WiFi devices causing interference or WiFi devices whose transmissions are too low or corrupted. As can be seen, this function needs a value to define if the energy detected is enough to set the medium as busy. This value is defined in [3] as the ED threshold – could also be referred as CCA sensitivity– and depends on the modulation scheme used. In the literature is common to find

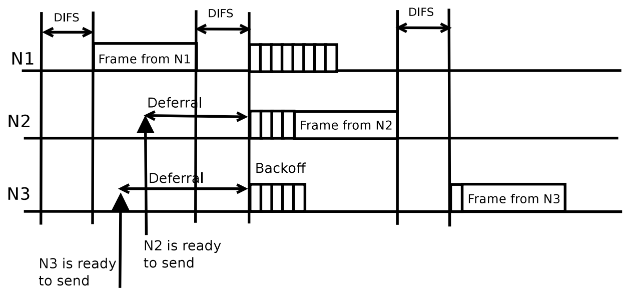

Fig. 1. DCF Backoff

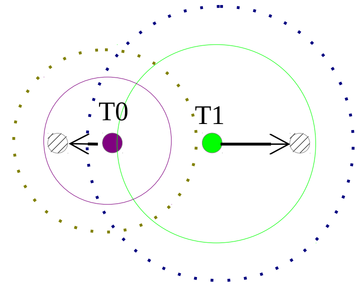

Fig. 2. The Starvation Problem

the term *carrier-sense threshold* to refer to the ED threshold. For convenience we will also use this terminology although we know it is not the best election.

Definitions

Let us define some concepts used through this document.

- Transmit Power (P_{TX}) is the signal strength generated by the transmitter (TX).
- Received Signal Strength (RSS) is the power of the transmission signal received by a receptor (RX).
- Noise Floor (N) is the signal strength from all kind of noise sources or unwanted signal (thermal noise, interference from other equipment).
- Signal to Noise Ratio (SNR) is the relation between the signal strength and the noise floor. For example the SNR at a receiver would be $SNR = RSS - N$. If we are working in Watts instead of dB the SNR is expressed as $SNR = \frac{RSS}{N}$. In this work we will measure signal strength in dBm.
- Signal to Interference plus Noise Ratio ($SINR$) is similar to the SNR but it explicitly take into account the signal strength generated by other users in the medium. It is important in interference-limited environments.
- Path Loss (L) is the attenuation due to propagation effects.
- Transmission Opportunity ($TXOP$) is the fraction of time that the medium is available for transmission on a particular node.

B. The Problem

In an interference dominated network the data rate at which nodes can communicate depends on the $SINR$ at the receiver, the higher the $SINR$ the higher the supportable data rate. As we mentioned before, the $SINR$ is affected by the path loss, therefore, the distance between two nodes has a major influence on the data transmission rate. Adding APs to palliate this problem reduces the distance between APs but increases the interference between co-channel APs. Interference impacts in different ways: (i) on the sender, the interference makes the carrier-sense mechanism to activate and defer the transmissions, how much interference is allowed depends on the CCA sensitivity; (ii) on the receiver, the increased interference causes a decrease of the $SINR$, jeopardizing the benefits of a distance reduction.

In this work we assume an appropriate channel assignment has already been made but, as we are working with high-density wireless networks, the non-overlapping WiFi channels are not enough to completely isolate the devices and then interference do exist. So, we concentrate on the problem left after a channel allocation has been made, in which some nodes are inevitably in the same channel

The Starvation Problem: To avoid the interference problem, it is natural to try to manipulate the transmission power at each AP. However, this may conduct the network to another troublesome situation: the starvation problem. For an explanation of the problem we will use the Circle Model [1] to define two distinct ranges (based on the definitions from [4]):

- Transmission Range. A receiver inside the transmission range of a transmitter will receive a packet successfully (if there is no interference).
- Carrier Sense Range. A node inside the carrier sense range of a transmitter will sense the medium busy when transmissions occur. Among other things, it depends on the transmit power of the transmitter and the carrier-sense threshold of the receiver.

In Figure 2 the small colour-filled circles are the transmitters and the white circles the receivers, an arrow between the transmitter and the receiver indicates a transmission flow. The big continuous circles represent the transmission range of the transmitter and the dotted circles represent the carrier sense range of the receiver (centered on the transmitter). What we show in that figure is an asymmetric exposed-terminal problem: T0 can sense T1 and though defer transmission but T1 does not sense T0 and transmits continuously, causing an unfair access to the medium.

II. Related Work

The adaptation of MAC and PHY sub-layer parameters has been a topic of research for at least the past fifteen years. In particular, there is major work in the areas of data rate control, transmit power control, carrier-sense threshold (CST) control and the combination of them. In the area of WiFi networks, plenty of research has been done for ad-hoc networks, however, the application of these solutions to infrastructure networks (our case of study) is difficult because of the implicit assumption for ad-hoc networks that the communication can be done from any node to any node of the network.

In this work we are interested in the mechanisms that try to reduce interference between APs; for achieving this, all existing proposals perform transmit power control. Moreover, existing solutions combine transmit power and data rate control or transmit power and CST control. However, only a few of these works consider the starvation problem.

There exists two widely used approaches to perform parameter control. To use the frame loss (link-layer information) or the received signal strength (physical-layer information) so as to estimate the channel conditions.

As said in Section I-A in the IEEE 802.11 standard receivers use acknowledge frames (ACKs) to inform the transmitter of a correctly received data frame. So, a non received ACK may indicate that the sent frame was not received because the signal at the receiver was too low or because it collided with another transmission.

Another approach is to use the $SINR$ at the receiver given that a low $SINR$ can be due to low power at the transmitter or to high interference from other nodes. In this case the information is at the receiver and not at the transmitter so different techniques are implemented to send this information to the transmitter. Several works [1], [5], [6] claim that this method is difficult to implement because of the complexity of understanding signal propagation and differences in measurements from different hardware. Even more, although exists an standardized metric (RSSI), different hardware report very different values for the same situation as shown in a recent study [7]. Hence, in what follows we will focus on link-layer approach solutions.

A. Parameter Adaptation Based on Frame Loss

Power-controlled Auto Rate Fallback (PARF) is a self-managing technique presented in [1] that is based on transmit power and data rate control. It tries to minimize interference among neighboring APs based on *Auto Rate Fallback* (ARF), a mechanism that only tunes the data rate. ARF is based on probing 802.11 ACKs messages: an ACK loss implies a reduction in data rate and a successful reception an increase. Then, PARF adds transmit power control to ARF by reducing the transmit power if at the higher data rate there is no loss, and keeps reducing it until a minimum threshold is reached or until transmissions start to fail. If fails keep occurring, then transmit power is increased until a maximum value where, should the fails persist, a data rate fallback starts.

Very similar ideas are presented in [8], we call it *Adapting PARF* (APARF). The most interesting difference from [1] is that the threshold used to decide a change in data rate or transmit power is dynamically adapted. The purpose behind this idea is to estimate the channel conditions; for example, a channel changing fast would need a small threshold so as to rapidly adapt.

ConTPC [9] (*Conservative Transmit Power Control*) is another mechanism similar to PARF but it only controls transmit power. In ConTPC nodes learn the relation between the delivery rate and the transmit power of all their links. This is possible because each node broadcasts frames at all available power levels with information of the transmit power used.

Ramachandran et. al. in [5] present *Symphony*, a data-rate- and transmit-power-control mechanism which is implicitly based on frame loss. The idea is to make data rate and transmit power control so as to keep the performance of each link at least as good as the performance obtained at the maximum transmit power. Symphony runs in all network nodes, APs and clients, and has two phases that must be synchronized between all nodes. This seems to be the most important drawback of the algorithm because for AP synchronization a central controller is needed and, to synchronize clients, APs need to send synchronization frames.

Minstrel-Piano (MP) [6] follows the same idea of transmit power control presented in others works, that is: to transmit at the data rate given by the data rate control with the minimum power possible. Moreover, to control transmit power, this proposal also uses information of the received ACKs to estimate interference. The idea is to enhance the already existent Minstrel algorithm with per-frame power control. The Minstrel algorithm [10] is a data-rate-control algorithm based on throughput to choose the best data rate, this means that successfulness is measured in terms of throughput and not directly on success of the transmissions. The algorithm record the success of all transmissions (if an ACK was received for each frame sent) for each link and data rate used and also adds an exploration part (probing) where transmissions are made in other data rates.

To add transmit power control to Minstrel, Piano send frames at different powers and try to statistically learn the impact of transmit power on throughput. This work is, to our knowledge, the only one that addresses the technical problems of implementing the mechanism in hardware. The article explains how the multi-rate-retry chain is used in Atheros cards to add per-frame power control. However, the code is not yet available for public use (as of September 2014).

As can be seen, various of these mechanisms (PARF, APARF and ConTPC) are based on rate adaptation mechanisms that are relatively old and known to have issues. For example in [11] is mentioned the problem that rate should only be decreased when losses are caused by bad channel conditions and not when losses are because of collisions (generated by hidden nodes). To solve these issues several works propose to differentiate type of losses so as to estimate channel conditions better.

B. Solutions to the Starvation Problem

The starvation problem due to asymmetric links has been mentioned and studied in different works from literature: [12], [1], [13], [14], [15] but only some of them propose a solution to the problem.

Mhatre et. al. [13] use a cross-layer approach for power control to attack the interference among APs in HD wireless networks. They address the problem of throughput starvation because of asymmetric links. The authors demonstrate that it is possible to maintain the symmetry of a network, with all nodes sensing all other nodes, if power control goes along with control of the CST. The main conclusion of this work is that if the transmit power of a node is high, then its CST should be low. In the framework that implements their ideas each AP to send information to its neighbours on beacon frames.

A similar idea is presented by *Liu et. al.* [14] based on a *iterative greedy algorithm* to optimize power and carrier-sense threshold. For avoiding starvation the authors propose to adapt carrier-sense threshold after the power is selected. The authors claim that collecting and using global information the mechanism can choose a value for the threshold so as to hear

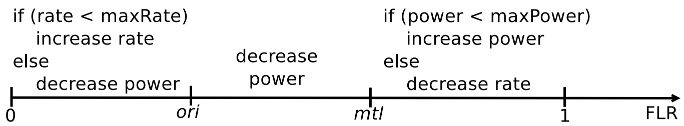

Fig. 3. PRCS Decisions for Power and Rate Adaptation

all transmissions that interfere with the current transmission or will be interfered by the current transmission.

As we will see later there are two important aspects that differentiate these works from ours: All of them use some kind of signal measurement to estimate interference at the receiver and all of them control the power and CST globally and not per-link.

III. Power, Rate and Carrier-Sense Control

In this Section we present PRCS, a new mechanism that jointly adapts transmit power, data rate and carrier-sense threshold based on statistical measurements of frame loss and transmission opportunity. The mechanism is based on an existing rate adaptation algorithm called *Robust Rate Adaptation Algorithm* (RRAA) [11] and on a modification of it done in [5] called RRAA+, both are solutions that, unless those surveyed above, just try to control transmit rate disregarding transmit power. The goal of PRCS is to mitigate interference (increasing performance) by tuning transmit power and data rate, but, differently from previous works, it also focuses on avoiding starvation.

A. Transmit Power and Data Rate Control

The goal of PRCS is to use the lowest possible power without degrading the performance of links. Thus, PRCS firstly try to find the best rate at maximum power for the current channel conditions and then, if losses are stable starts to reduce transmission power.

PRCS calculates the frame loss rate (FLR) on a window of frames and adapt data rate and transmit power to maintain FLR on certain values. The algorithm defines two thresholds, *Maximum Tolerable Loss* threshold (T_{MTL}) and *Opportunistic Rate Increase* threshold (T_{ORI}), the first to decide when to have a rate reduction and the second to decide for a rate increase. For selecting the values of T_{MTL} the *critical* FLR of a rate R_i is defined as the FLR that would make R_i to get the same throughput as the next lower rate (R_{i-1}) if it has no loss.

$$Throughput(R_i) * (1 - FLR_{crit}(R_i)) = Throughput(R_{i-1})$$

then

$$FLR_{crit}(R_i) = 1 - \frac{Throughput(R_{i-1})}{Throughput(R_i)} = 1 - \frac{TX_{time}(R_i)}{TX_{time}(R_{i-1})}$$

This means that, $FLR_{crit}(R_i)$ is the maximal loss allowable at rate R_i if at rate R_{i-1} there are no losses. As might be improbable that losses disappear at rate R_{i-1} the threshold is chosen as $T_{MTL}(R_i) = \alpha * FLR_{crit}(R_i)$ with $\alpha \geq 1$. For each rate, FLR_{crit} is computed using the transmission time, which, knowing the frame size, can be calculated straightforward.

For selecting the values of T_{ORI} the algorithm uses a heuristic based on this formula: $T_{ORI}(R_i) = \frac{T_{MTL}(R_{i+1})}{\beta}$ where R_{i+1} is the next higher rate. The idea is that for increasing the rate the FLR must be smaller than T_{MTL} at the next higher rate so

1: **if** $loss > tmtl(rate)$ **and** $power < maxPower$ **then**
2: $pdTable[rate][power]\ /=\ \gamma$
3: $power++$
4: **else if** $loss > tmtl(rate)$ **and** $power == maxPower$ **then**
5: $pdTable[rate][power]\ /=\ \gamma$
6: $rate--$
7: **end if**
8: **if** $loss < tori(rate)$ **then**
9: **for all** $r < rate$ **do**
10: $pdTable[r][power]\ *=\ \delta$
11: **end for**
12: **if** $rate < maxRate$ **and** $power == maxPower$ **and** $rand() < pdTable[rate+1][power]$ **then**
13: $rate++$
14: **else**
15: **for all** $p > power$ **do**
16: $pdTable[rate][p]\ *=\ \delta$
17: **end for**
18: **if** $rand() < pdTable[rate][power+1]$ **then**
19: $power--$
20: **end if**
21: **end if**
22: **else if** $loss >= tori(rate)$ **and** $loss < tmtl(rate)$ **and** $power > 0$ **then**
23: **for all** $p > power$ **do**
24: $pdTable[rate][p]\ *=\ \delta$
25: **end for**
26: **if** $rand() < pdTable[rate][power+1]$ **then**
27: $power--$
28: **end if**
29: **end if**

Algorithm 1: PRCS Power and Rate Adaptation Algorithm

that when increasing the rate the algorithm keeps at that rate and do not decrease instantly.

For power control the algorithm considers three different cases (see Fig. 3). When the FLR is between the values accepted for a given rate the mechanism decrease the power while the FLR do not exceed the T_{MTL} threshold. When the FLR surpasses the T_{MTL} threshold the mechanism first increases power until the maximum power and then if FLR do not improve decrease rate. Finally, the rate is increased when the FLR is below the T_{ORI} threshold until maximum rate and then if the FLR is still good decrease power. So, when initialized at maximum rate and power, the mechanism first reduced the data rate if the FLR is high so as to reach an accepted FLR and just then start reducing power. It is important to notice that in the border cases of $maxRate$ and $minRate$ the T_{ORI} threshold takes the value of 0 and the T_{MTL} threshold the value of 1.

To improve convergence the algorithm uses a *Probabilistic Decision* (PD) mechanism. The rationale behind this mechanism is to smooth the changes of rate and power based on previous decisions of the algorithm. The mechanism maintains a probability for each rate and power combination, which is used to decide for a rate or power change. When the power is increased or the rate decreased (losses are increasing) the probability for the current rate and power combination is decreased by a γ factor (see lines 2 and 5 of Algorithm 1). On the other side, when the conditions for a rate increase or power decreased are satisfied, the probability of all the lower rates or the higher powers are increased using a δ value (see lines 10 and 16 of Algorithm 1). Then, when the FLR is low enough for a rate increase or a power decrease the algorithm will decide to change them based on the PD probability. This means that the change of rate or power is made on a probabilistic manner. It is important to note that this algorithm is executed on a per-link basis, so

Rate (Mbits/s)	Critical FLR (%)	T_{MTL}	T_{ORI}	$ewnd$
54	0.0761	0.0951	0.0000	40
48	0.2000	0.2500	0.0476	40
35	0.2628	0.3285	0.1250	40
24	0.2081	0.2602	0.1643	40
18	0.3014	0.3768	0.1301	20
12	0.1669	0.2086	0.1884	20
11	0.0751	0.0939	0.1043	20
9	0.3159	0.3949	0.0470	10
6	0.1283	0.1604	0.1974	6
5.5	0.6142	0.7678	0.0802	6
2	0.4853	0.6066	0.3839	6
1	0.0000	1.0000	0.3033	6

TABLE I. THRESHOLDS FOR PRCS

current power, rate and the pdTable are maintained for each existent link.

For the thresholds parameters we use the same values as in [11] ($\alpha = 1.25$ and $\beta = 2$) and we calculate the FLR_{crit} for a frame size of 1500 bytes, the results are shown in Table I. In this Table is also shown the values for the Estimated Window Size (*ewnd*) which is the number of frames needed to calculate a new FLR. As higher rates would transmit more frames in the same period as lower rates, the *ewnd* is higher at higher rates.

B. Starvation and Transmission Opportunity

As said above, the transmission opportunity of a link is the fraction of time that the medium is available for transmission on that particular link. So, we can define *Starvation* as the lack of transmission opportunity. Bellow we formalize this definition.

In 802.11 a node can be in four possible states:

- TX — When the node is transmitting.
- RX — When it is receiving.
- BUSY — When it sense the medium busy.
- IDLE — When it sense the medium idle and it is not transmitting.

Lets define T_{TX},T_{RX},T_{BUSY} and T_{IDLE} as the periods of time (during an interval of time T) the node was on state TX, RX, BUSY and IDLE respectively. Notice that $T = T_{TX} + T_{RX} + T_{BUSY} + T_{IDLE}$. So, the transmission opportunity on interval T can be defined as:

$$TXOP = \frac{T_{TX} + T_{IDLE}}{T} = 1 - \frac{T_{RX} + T_{BUSY}}{T}$$

and the busy probability as:

$$P_{BUSY} = \frac{T_{RX} + T_{BUSY}}{T} = 1 - TXOP$$

Hence, starvation is an effect of high values of $T_{RX} + T_{BUSY}$ meaning that much of the time the node is receiving or in BUSY state.

Though, measuring the transmission opportunity of a link is a possible way of detecting starvation because of asymmetric sensing, however, the optimum value for TXOP depends on the scenario. For example, the TXOP of a link sharing the channel with another ten links is expected to be lower than that of a link with only one interferer link. So, in PRCS, we follow the ideas introduced by Hua and Zheng in [15] to calculate the expected transmission opportunity ($TXOP_{exp}$) the links should have based on some local measurements. In particular, these authors present a mechanism to calculate the expected busy probability (P^{exp}_{BUSY}) only by measuring the FLR.

```
if sentFrames >= ewnd then
    P_BUSY = busyTime/ett
    if P_BUSY > P^exp_BUSY then
        cst+ = η
    end if
end if
if loss > tmtl(rate) and power < maxPower then
    pdTable[rate][power] / = γ
    power + +
else if loss > tmtl(rate) and power == maxPower then
    if cst > minCst then
        cst− = η
    else
        pdTable[rate][power] / = γ
        rate − −
    end if
end if
```

Algorithm 2: PRCS Carrier-Sense-Threshold Adaptation Algorithm

```
function TxInit(MAC destMac)
    ett[destMac]+ = currTime − prevTime
    busyTime[destMac]+ = countBusy
    countBusy = 0
    prevTime = currTime
end function
```

Algorithm 3: T_{BUSY} Measurement Algorithm

C. Carrier-Sense-Threshold Control

As mentioned before, PRCS adds carrier-sense-threshold control to the power and rate adaptation algorithm to deal with asymmetric links. This approach is motivated by the works of Fuemmeler et. al. [16] and Mhatre et. al. [13] which propose to maintain the product $P_{TX} * CST$ constant to reduce the asymmetries and starvation provoked by them. However, these approaches suffer of a problem: the correct value of this constant is difficult to find and depends on the channel and scenario characteristics. So, what we propose is to control the CST on statistical bases, in the same way we do with power and rate.

The idea is to measure the TXOP to detect starvation and, to increase the CST if starvation is detected just after lowering transmit power. The system, then, becomes less vociferous and less sensitive at the same time.

In our implementation we only consider the busy period (T_{BUSY}) of the TXOP, the parameter which is more related to the CST. Remember that a node enters the BUSY state when the interference signal received is higher than the CST. We measure P_{BUSY} every $ewnd$ frames and if the value is higher than a threshold (calculated as we described before) we increase the CST by η. On the other hand, when losses increase more than T_{MTL} and we are using a non-minimal CST, we decrease CST. This is done because losses can be caused by collisions which are produced by terminals hidden by an increased CST. In Algorithm 2 we depict a pseudocode of the carrier-sense-threshold control part of the PRCS mechanism.

To control the per-link CST we need to measure P_{BUSY} for each link. To achieve this there is a counter that accumulates the periods of time that a node is in BUSY state, this is: trying to transmit and sensing the medium busy. Assuming that the protocol did not give up for any frame, the value of that counter corresponds with the time that the medium has been busy for the current frame (see Algorithm 3).

IV. EVALUATION

We have experimentally compared the performance of PRCS with the following rate and power control mechanisms: PARF [1], Adapting PARF (APARF) [8], MP [6] and RRPAA (PRCS without CST control). We disregard ConTPC because its similarity with PARF and let Symphony aside because its requirement of synchronization between APs, a difficult and uncommon task in current networks. It is important to notice that, to the best of our knowledge, non of the existing works that deal with the starvation problem are based only on frame loss.

For the comparison, we consider the following metrics:

- *Per-link throughput*, as the throughput obtained by one AP-client link.
- *Global network throughput*, as the sum of all the per-link throughputs on a given network.
- *Per-link transmission opportunity*, which is defined as the fraction of time that the medium is available for transmission on a particular node.
- *Power efficiency*, as the ratio between the link throughput and the average transmit power that link uses. The average transmit power measures the power per second used by a node to transmit.

The evaluation was conducted on the NS3 Network Simulator [17] with the necessary modifications to provide transmit power control. We implemented each of the tested mechanisms in the simulator based on the descriptions taken from the corresponding articles. The code of the modified simulator, the implemented mechanisms, and the experiments made can be found at [18].

All the experiments use the IEEE 802.11a standard which provides nine different data rates: 6, 9, 11, 12, 18, 24, 36, 48, 54 Mbps. The transmit-power-control mechanisms use 18 power levels from 0 to 17 dBm and the fixed power techniques use 17 dBm. The medium is modelled such that the propagation speed is equal to a constant, the speed of light, and the propagation loss follows a log distance model with a reference loss of 46.6777 dB at a reference distance of 1.0 m.

For the evaluation, we consider two different scenarios: i) a simple scenario with two interfering AP to STA links (two different APs and two different STAs) that tries to isolate some of the studied problems; and ii) a more realistic high-density scenario with 25 AP-STA pairs.

A. Two-Links Scenario

This scenario consists of two links, Link-0 and Link-1, each one established between one AP generating traffic and one STA receiving it. The links are deployed so that Link-0 is a link with short AP-Client distance and Link-1 with longer distance. We generate an UDP constant-bit-rate flow at 54 Mbps with a duration of 100 seconds from the AP to the STA to be sure that the AP always has data to send. The data flow is made of frames of 1500 bytes. The experiments are executed 50 times each, varying the seed for the simulator's random number generator so as to obtain independent runs. For all cases we show the median and the 0%- and 100%-quantiles which define a prediction-interval of a 96% probability.

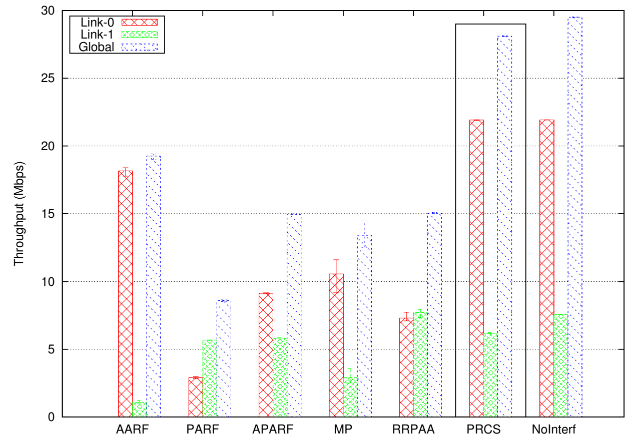

Fig. 4. Throughput in the Two-Links Scenario.

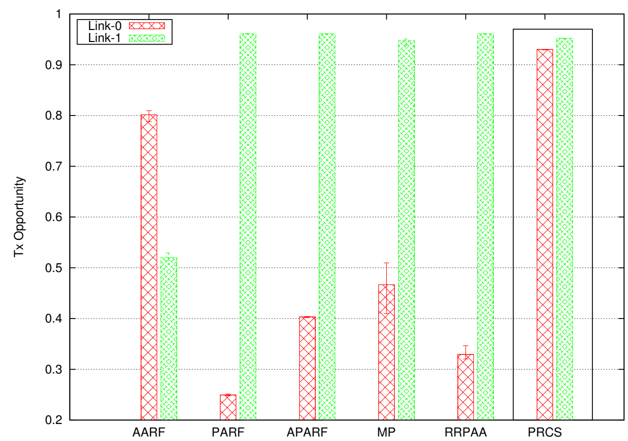

Fig. 5. TX Opportunity in the Two-Links Scenario.

We evaluate the performance of PRCS, the transmit-power-and data-rate-control mechanisms PARF, APARF, MP and RRPAA and the data-rate-only adaptation mechanism AARF. Additionally, we also depict the no-interference case (NoInterf) as a throughput upper bound.

In Figure 4 the throughput obtained by each mechanism is depicted. The first thing we can notice is how all the power-control mechanisms reduce the global network throughput. In particular, while the throughput of Link-1 is increased, the throughput of Link-0 is reduced by more than a half in the best case. This degradation is produced by the adaptation mechanism itself when it lowers the power of Link-0 causing the generation of a starvation problem. This can be better seen in Figure 5 where we show the average transmission opportunity of the transmitters. In this graph we can clearly see how all of the power and rate control mechanisms reduce the average transmission opportunity for Link-0.

In the figures is boxed the performance of our mechanism PRCS. It can be seen that PRCS achieves a significant performance improvement (83% over the best mechanism in total network throughput) getting the same throughput as the *NoInterf* solution. Moreover, in Figure 5 it is shown how the transmission opportunity of both links are increased over 0.9 getting a fair access to the medium.

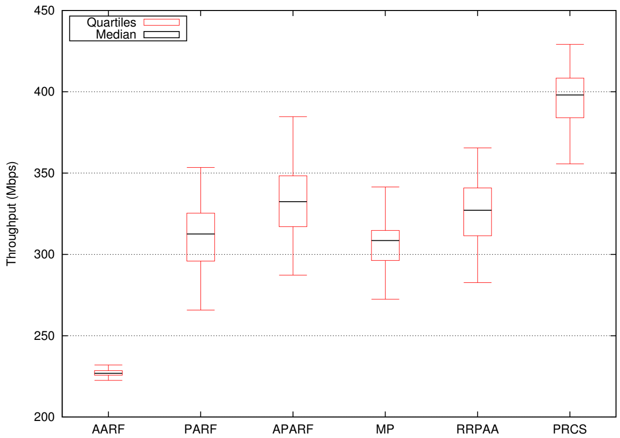

Fig. 6. Global Network Throughput in the High-Density Scenario.

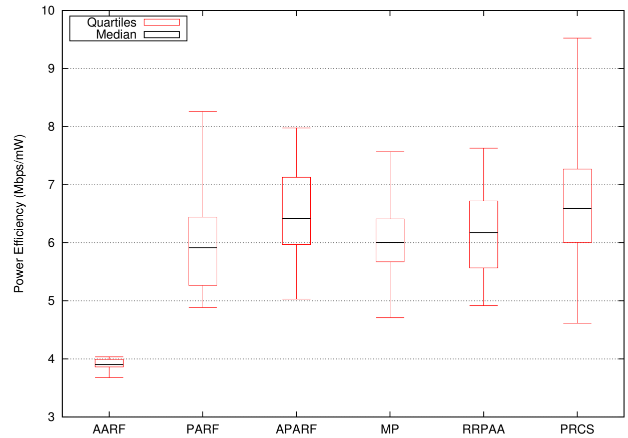

Fig. 7. Power Efficiency in the High-Density Scenario.

These results show that PRCS is able to completely isolate the links without jeopardizing the performance. This can be achieved by a power reduction jointly with the carrier-sense threshold increment in Link-0 which makes the sender less sensitive. The higher CST in Link-0 sender does not impact on Link-1 because the power used is low enough so as to not generate interference.

With this simple evaluation we can confirm the importance of adding CST control to power-control mechanisms. Our solution not only avoids starvation of Link-0 but also improves overall performance significantly.

B. High-Density Scenario

For this scenario the simulation consists of 25 APs deployed on a squared grid and separated by a distance of 50 meters. Each AP generates down-link traffic to one STA which is deployed randomly around the AP. The traffic consist of an UDP constant-bit-rate flow of 20 Mbps with data frames of 1500 bytes. We run 40 different simulations varying the positions of the STAs around the APs, generating then 40 different network configurations. We calculate the global throughput obtained by the network, the global power efficiency of the network and the per-link transmission opportunity.

We test the same mechanisms as in the previous scenario: AARF, PARF, APARF, MP, RRPAA and PRCS. In Figure 6 we show the median of the global network throughput, the 25% and 75% quantiles and the minimal and maximal global network throughput. As expected, there is a high variability in the results, because the position of clients in the network has an important impact on performance. However, we can clearly see that PRCS outperforms the rest of the algorithms, obtaining a median improvement of about 20% in comparison with RRPAA. Studying the results in detail, the improvement of PRCS over RRPAA varies between 5% and 38% depending on the positions of the STAs.

In Figure 7 we show the median of the global power efficiency and the 0%, 25%, 75% and 100% quantiles. From the figure we can notice that PRCS efficiency is similar to the efficiency of the other evaluated mechanisms. Then, we can conclude that PRCS obtains higher throughput and fairness at the cost of using higher power levels.

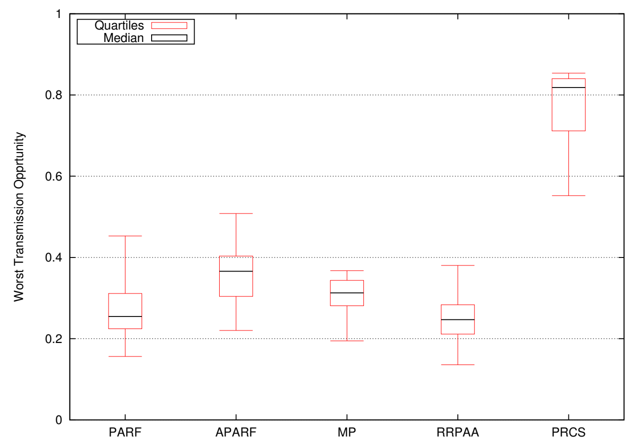

Fig. 8. Worst Transmission Opportunity in the High-Density Scenario.

Finally, in Figure 8 we compare the transmission opportunities obtained by each link. For this comparison we took the link with worst transmission opportunity of the 25 links of the network for each network configuration evaluated and show the median and quartiles over the 40 executions. It can be seen that PRCS obtains an important improvement of the transmission opportunity making the worst transmission opportunity much higher. This shows that starvation is considerably reduced in all links.

This experiment, closer to real deployments, show us the importance of the joint management of transmit-power and CST in high-density scenarios.

V. Conclusions and Future Work

In this work we describe some of the interference-related problems of IEEE 802.11 networks, in particular the starvation problem, a problem that the related work generally neglects in situations that are not exceptional, but common situations in the context of high-density wireless networks.

To address the starvation problem we have developed PRCS, a novel mechanism which autonomicaly adapts data rate, transmit power and carrier-sense threshold. In line with existent power control mechanisms, our solution reduces transmit power to reduce interference but it also reduces carrier sense sensitivity when reducing power. This technique avoids asymmetrical links and facilitates more spatial reuse.

The main difference between our mechanism and the surveyed work is the usage of two different thresholds for rate and power changes. This characteristic permits us to reduce power (and therefore, interference) in cases where most other algorithms would not be capable. An existing mechanism that can do it is Minstrel-Piano, however, PRCS has two important differences from Minstrel-Piano. MP uses long-term smoothed estimation (EWMA) for the FLR , which adds complexity and consumes resources, while PRCS uses only the last computed FLR. Additionally, experiments in [11] show that a long-term estimation does not provide any gain in this particular case. Another difference with MP is that this solution sends probe frames at different rates and powers periodically. This can cause two undesired effects: to add overhead by sending frames at rates or powers that will probably fail; and to produce poor estimations of the optimal rate and power given the low statistical significance of a probe frame sent every 10 frames (the default value in MP).

Comparing PRCS with PARF, APARF and MP on the NS3 simulator we show that PRCS outperforms all of them in the exposed terminal scenario and, so far, our mechanism shows all the benefits of previous works while it does not suffer from the starvation problem caused by asymmetric links. All the code necessary to reproduce these experiments is available at [18].

In most cases, the related current solutions are not independently implemented and their existent implementations are not publicly available. Therefore, our contribution is twofold: (i) we have implemented several recently proposed algorithms and we made them available through public git repositories; (ii) we propose a novel mechanism that mitigates the problem of starvation caused by power control.

The presented experiments do not include some important factors such as different types of traffic, different packet sizes or node mobility, therefore, future work has to consider them. Moreover, an implementation in hardware of the proposed mechanisms is necessary to test them in real conditions.

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