Self Management of Rate, Power and Carrier-Sense Threshold for Interference Mitigation in IEEE 802.11 Networks

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***Abstract*—Nowadays, it is common to find IEEE 802.11 networks that are deployed in an unplanned and unmanaged manner. Moreover, because of the low hardware cost and, trying to obtain better coverage and performance, a large number of devices are usually installed in reduced spaces causing high-density deployments. This kind of networks experiment several problems related with the shared nature of the transmission medium. In recent years, different transmit power control mechanisms have been proposed to palliate those problems, however, in some situations, the existing solutions can lead to an starvation problem. In this paper, we present a novel mechanism that manages data rate, transmit power and carrier-sense threshold to reduce this problem.**

I. Introduction

Plenty of the omnipresent IEEE 802.11 (WiFi) 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 high-density (HD) networks with performance and reliability issues caused mostly by RF interference [1]. The ubiquity of the IEEE 802.11 standard needs a solution to the problem that does not modify the 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. We review a variety of mechanisms that control WiFi parameters such as transmit power, data rate or carrier-sense threshold noticing that most of these works do not consider all the implications of performing dynamic parameter adaptation. Then, we propose a novel mechanism that addresses the problems suffered by networks with an heterogeneous wireless configuration, in particular the starvation problem generated by disparate transmit powers and carrier-sense thresholds.

II. The Problem

The control of the transmit power is one of the most studied techniques not only for infrastructure-based WiFi but also for ad-hoc-based WiFi and is also widely used in cellular networks. It is an important technique for reducing interference but the trade-offs are obvious: although reducing the transmit power on a node can improve the global transmission performance by reducing interference with the other nodes, it can also increase the own frame losses and, then, trigger a reduction of the data rate (and therefore of the throughput). However, from a detailed study of the state of the art we do found that the mechanisms that show best results in high-density networks are those that manage transmit power and data rate.

In the IEEE 802.11 standard [2] there are defined several coordination functions or methods for accessing the medium. Most devices, when working in infrastructure mode (our case of study), use DCF as the default configuration. DCF uses *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) to regulate the access to the medium. This protocol imposes that for a device to transmit, it must sense the medium to determine if another device is transmitting (physical carrier sense). If the medium is not busy, the device is able to transmit. If the medium is determined to be busy, the device needs to wait for the current transmission to end. Then, before attempting to transmit again, the device waits for a random backoff period of time while the medium is idle.

The starvation problem is a common problem related to the Carrier Sense mechanism that can be produced by heterogeneous levels of transmit power among nodes. For an explanation of the problem we will use the Circle Model to define two distinct ranges:

- 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 Fig. 1 the small colour-filled circles are the transmitters and the dashed 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 (centred on the transmitter). What we show in that figure is an asymmetric exposed-terminal problem, in this case T0 has reduced its transmit power and so T1 will not sense its transmissions. This is represented by also reducing the carrier sense range of T0. So, T0 can sense T1 and though defer transmission but T1 does not sense T0 and transmits continuously, causing an unfair access to the medium.

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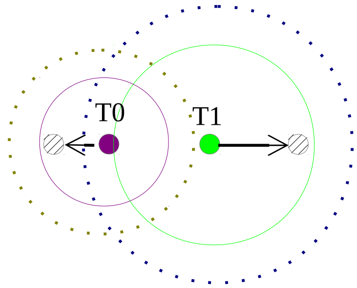

Fig. 1. The Starvation Problem

III. Existing Solutions

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. However, only a few of these works consider the starvation problem. Among those works, there are two widely-used approaches to estimate channel conditions: (i) frame loss monitoring (link-layer information) or (ii) received signal strength monitoring (physical-layer information). In this work we focus on the solutions that use link-layer information applied to infrastructure networks.

Power-controlled Auto Rate Fallback (PARF) [1] and *Conservative Transmit Power Control* (ConTPC) [3] are self-managing techniques which control transmit power and/or data rate control based on probing 802.11 ACKs messages. Very similar ideas are presented in [4], we call this approach *Adapting PARF* (APARF). In this case the threshold used to decide a change in data rate or transmit power is dynamically adapted. Ramachandran et. al. in [5] present *Symphony*, a data-rate- and transmit-power-control mechanism which is implicitly based on frame loss. Minstrel-Piano (MP) [6] follows a more statistical approach. The algorithm record the success of all transmissions (if an ACK was received for each frame sent) for each link data rate and power used and also adds an exploration part (probing) where transmissions are made in other data rates and powers. Then, periodically, a statistics table is updated with the success probability ($p = \frac{successes}{attempts}$) of each data rate and power for each link. In *Mhatre et. al.* [7] the problem of throughput starvation caused by asymmetric links is addressed and sufficient conditions are given to obtain power control without starvation. This mechanism requires beacon-based communication between neighbouring APs. A similar idea is presented by *Liu et. al.* [8] based on a *iterative greedy algorithm* to optimize power and carrier-sense threshold.

As we will see later there are two important aspects that differentiate these starvation avoidance 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.

IV. Power, Rate and Carrier-Sense Control

In this section we present PRCS a new mechanism that jointly adapt 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) [9] and on a modification of it done in [5] called RRAA+. The goal of PRCS is to mitigate interference (and hence increase performance) by tuning the transmit power and data rate, but differently from most previous works it also focuses on avoiding starvation.

A. Transmit Power and Data Rate Control

For PRCS we took the ideas from RRAA+ and implement a power and rate control mechanism based on frame loss rate. The goal of the mechanism is, as many other mechanisms we described, to use the lowest possible power without degrading the performance of links. So PRCS first try to find the best rate at maximum power for the current channel conditions and then, if losses are stable start to reduce 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 (P_{MTL}) and *Opportunistic Rate Increase* threshold (P_{ORI}), the first to decide for a rate decrease and the second for a rate increase. For selecting the values of P_{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 $P_{MTL}(R_i) = \alpha * FLR_{crit}(R_i)$ with $\alpha \geq 1$. For each rate, FLR_{crit} is computed using the transmission time, which, assuming a fixed frame size, it is very easy to calculate.

For selecting the values of P_{ORI} the algorithm uses a heuristic based on this formula: $P_{ORI}(R_i) = \frac{P_{MTL}(R_{i+1})}{\beta}$ where R_{i+1} is the next higher rate. The idea is that for increasing the rate the FLR must be smaller than P_{MTL} at the higher rate so 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. 2). When the FLR is between the values accepted for a given rate the mechanism decrease the power while the FLR do not exceed the P_{MTL} threshold. When the FLR surpasses the P_{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 P_{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 P_{ORI} threshold takes the value of 0 and the P_{MTL} threshold the value of 1 respectively.

To improve convergence the algorithm uses a *Probabilistic Rate Increase* (PRI) mechanism. The PRI mechanism consists on maintaining for each data rate and transmit power the probability to move to a higher rate or a lower power. These probabilities are reduced when the mechanism decides to move to a lower rate because the losses are higher than the threshold, so as to make more difficult to return to this data rate. These probabilities are then used when the conditions are given for a rate increase or power decrease (when the FLR is low) to decide if taking the action. It is important to note that this algorithm is executed on a per-link basis. For the implementation details, please refer to [10]

B. Carrier-Sense-Threshold Control

PRCS adds carrier-sense-threshold control to the power and rate adaptation algorithm to deal with asymmetric links. This approach is motivated by previous works 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 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 asymmetric sense starvation as the lack of transmission opportunity. Following we will 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 and 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:

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

Hence, asymmetric sense 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. Then, PRCS measures the TXOP to detect starvation and, if starvation is detected just after lowering transmit power, it increases the CST. The system, then, becomes less vociferous and less sensitive at the same time. In particular, our implementation only considers 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.

So, the algorithm works this way: it measures T_{BUSY} every a given number frames and if the value is considered high it increases the CST. On the other hand, when losses increase more than P_{MTL} and it is using a non-minimal CST, it decreases CST. This is done because losses can be caused by collisions which are produced by terminals hidden by an increased CST.

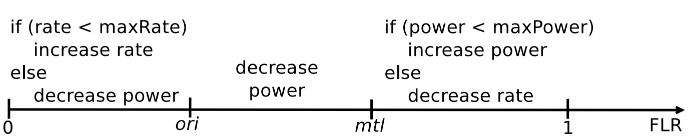

Fig. 2. PRCS Decisions for Power and Rate Adaptation

V. EVALUATION

We have experimentally compared the performance of PRCS with the following mechanisms in a scenario prone to starvation: PARF [1], Adapting PARF (APARF) [4] and MP [6]. It is important to notice that, to the best of our knowledge, non of the existing works that deal with the starvation problem are only based 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.

The evaluation was conducted on the NS3 Network Simulator 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 done can be found in [10].

All the experiments use the IEEE 802.11g standard which provides 12 different data rates: 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, 54 Mbps. The transmit-power-control mechanisms use 18 power levels form 0 to 17 dBm and the fixed power techniques use 17 dBm. The medium is modelled such that the propagation delay is equal to a constant, the speed of light and the propagation loss is a log distance model with a reference loss of 46.6777 dB at a reference distance of 1.0 m. For all the cases we generate a UDP constant-bit-rate flow at 54 Mbps 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 simulation setup consist of two links, Link-0 and Link-1, each one established between one AP generating traffic and one STA receiving it with a duration of 100 seconds. The links are deployed so that Link-0 is a link with short AP-Client distance and Link-1 with larger distance. 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.

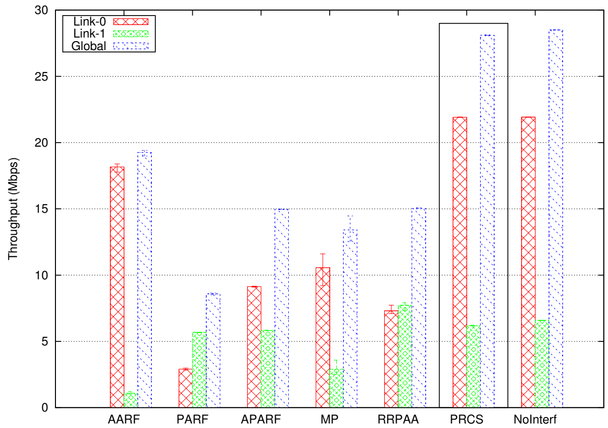

Fig. 3. Throughput in the Exposed Terminal Configuration.

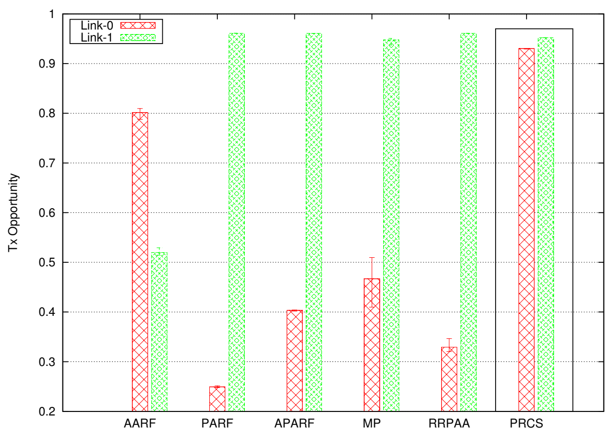

Fig. 4. Average TX Opportunity in the Exposed Terminal Configuration.

A. Results

We show the performance of PRCS and RRPAA (PRCS without CST control), the transmit-power- and data-rate-control mechanisms PARF, APARF and MP, the data-rate-only adaptation mechanism AARF, and the no-interference case (NoInterf) as a throughput upper bound. The throughput upper-bound for each configuration is the throughput that each link would obtain if it uses the maximum transmit power and there is no interference from the other link.

The first thing we can notice in Fig. 3 is how all the power-control mechanisms reduce the global network throughput. 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 Fig. 4. In this graph we can clearly see how all of the power and rate control mechanisms reduce the average transmission opportunity for Link-0.

It can be seen that PRCS (boxed in the figures) achieves a significant performance improvement (83% over the best mechanism in total network throughput) getting the same throughput as the *NoInterf* solution. Moreover, in Fig. 4 it is shown how the TX opportunity of both links are increased over 0.9 getting a fair access to the medium.

Although more experimentation is needed, with this 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.

VI. Conclusions

In this work we describe the main interference and loss problems that the IEEE 802.11 networks experiment in high-density environments. We experiment with the solutions that address those interference issues manipulating the transmit power and the data rate using the frame loss rate as a measure of the problem. We show that the related work neglects the starvation problem in situations that are not exceptional in the context of HD wireless networks. To address the starvation problem we developed PRCS, a novel mechanism which 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, even more, allows for more spatial reuse. Comparing PRCS with PARF, APARF and MP in 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 [10].

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References

[1] A. Akella, G. Judd, S. Seshan, and P. Steenkiste, "Self-management in chaotic wireless deployments," *Wireless Networks*, vol. 13, no. 6, pp. 737–755, 2007.

[2] "IEEE Std 802.11-2012," Online, IEEE Computer Society, March 2012.

[3] K. Kowalik, M. Bykowski, B. Keegan, and M. Davis, "Conservative transmit power control mechanism for 802.11 mesh," in *e-Business and Telecommunications*. Springer, 2009, pp. 399–411.

[4] P. Chevillat, J. Jelitto, and H. L. Truong, "Dynamic data rate and transmit power adjustment in ieee 802.11 wireless lans," *International Journal of Wireless Information Networks*, vol. 12, no. 3, pp. 123–145, 2005.

[5] K. Ramachandran, R. Kokku, H. Zhang, and M. Gruteser, "Symphony: synchronous two-phase rate and power control in 802.11 wlans," in *Proceedings of the 6th international conference on Mobile systems, applications, and services*. ACM, 2008, pp. 132–145.

[6] T. Huehn and C. Sengul, "Practical power and rate control for wifi," in *Computer Communications and Networks (ICCCN), 2012 21st International Conference on*. IEEE, 2012, pp. 1–7.

[7] V. P. Mhatre, K. Papagiannaki, and F. Baccelli, "Interference mitigation through power control in high density 802.11 wlans," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*. IEEE, 2007, pp. 535–543.

[8] X. Liu, S. Seshan, and P. Steenkiste, "Interference-aware transmission power control for dense wireless networks," in *In Proceedings of the Annual Conference of ITA*. Citeseer, 2007.

[9] S. H. Wong, H. Yang, S. Lu, and V. Bharghavan, "Robust rate adaptation for 802.11 wireless networks," in *Proceedings of the 12th annual international conference on Mobile computing and networking*. ACM, 2006, pp. 146–157.

[10] M. Richart, "Ns-3-power-control project." [Online]. Available: http://mrichart.github.io/ns-3-dev-git/