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Abstract

Nowadays, it is common to find wireless networks that are based on the IEEE 802.11 standard deployed in an unplanned and unmanaged manner. Moreover, because of the low hardware cost and, trying to obtain optimal coverage and performance, a large number of devices are usually installed in reduced spaces generating high-density deployments. This kind of networks experiment a myriad of problems (e.g., interference, medium access control, etc.) related with the shared nature of the transmission medium. In recent years, different physical-layer- and link-layer-adaptation mechanisms have been proposed to palliate those problems, however, their feedback-loop-based behaviour in a highly complex RF medium makes their performance hard to assess. In this work, we study the problems of high-density networks, experimentally evaluate some existing solutions and propose a new adaptation mechanism, PRCS, that tackles some common weakness of those solutions. PRCS control the transmit power, the data rate, and the carrier sense threshold of APs of a wireless network so as to mitigate the effects of interference in high-density deployments without causing unfairness between links. In simulation-based experiments, PRCS outperforms similar existing mechanisms in various scenarios and in a particular scenario, where most mechanisms fail, duplicates global network throughput.

Resumen

En la actualidad, es muy común encontrar redes inalámbricas basadas en el estándar IEEE 802.11 desplegadas de manera no planificada ni gestionada. Además, debido al bajo costo de los dispositivos y con la intención de obtener una cobertura y rendimiento óptimos, un gran número de dispositivos son instalados en espacios reducidos, generado despliegues de alta densidad. Este tipo de redes experimentan una gran variedad de problemas (por ej., interferencia, control de acceso al medio, etc.) relacionados con el hecho de que utilizan un medio de transmisión compartido. En los últimos años, diferentes mecanismos de adaptación de parámetros de la capa física y de enlace han sido propuestos con el objetivo de mitigar estos problemas. Estas soluciones adaptan parámetros tales como la potencia de transmisión o la tasa de transmisión. En este trabajo, estudiamos los problemas de las redes inalámbricas de alta densidad, evaluamos mediante experimentos algunas de las soluciones existentes y proponemos un nuevo mecanismo de adaptación, PRCS, que aborda algunas de las debilidades de estas soluciones. PRCS controla la potencia de transmisión, la tasa de transmisión y el umbral del mecanismo de sensado de portadora de los puntos de acceso de una red inalámbrica. El objetivo de este mecanismo es mitigar los efectos de la interferencia en despliegues de alta densidad sin causar asimetrías entre los enlaces. En experimentos basados en simulaciones, mostramos que PRCS supera a los mecanismos existentes en varios escenarios y, en un escenario en particular donde la mayoría de los mecanismos fallan, duplica el rendimiento global de la red.

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Nomenclature

P_{MTL} Maximum Tolerable Loss threshold

P_{ORI} Opportunistic Rate Increase threshold

AARF Adaptive Auto Rate Fallback

ACK acknowledgement

AP Access Point

AP-CST Access Point Carrier-Sense-Threshold

APARF Adapting Power-controlled Auto Rate Fallback

ARF Auto Rate Fallback

BEB Binary Exponential Backoff

BER Bit Error Rate

BSA Basic Service Area

BSS Basic Service Set

CA Collision Avoidance

CCA Clear Channel Assessment

CD Collision Detection

CS Carrier Sense

CSMA Carrier Sense Multiple Access

CST Carrier-Sense-Threshold

CTS Clear To Send

NOMENCLATURE

CW Contention Window

ConTPC Conservative Transmit-Power Control

DCF Distributed Coordination Function

DIFS Distributed (coordination function) Inter-Frame Space

DSB Dynamic Spatial Backoff

ECHOS Enhanced Capacity 802.11 Hotspots

ED Energy Detection

EDCA Enhanced Distributed Channel Access

ERF Estimated Rate Fallback

ETT Expected Transmission Time

EWMA Exponential Weighted Moving Average

FLR Frame Loss Rate

HCCA HCF Controlled Channel Access

HCF Hybrid Coordination Function

HD High Density

HP High Performance

IEEE Institute of Electrical and Electronics Engineers

MAC Medium Access Control

MCF Mesh Coordination Function

MIMD Multiplicative Increase Multiplicative Decrease

MP Minstrel-Piano

MTL Maximum Tolerable Loss

ORCCA Optimal-Rate CCA Adaptation

ORI Opportunistic Rate Increase

PARF Power-controlled Auto Rate Fallback

PASA Power Adaptation for Starvation Avoidance

PCAP Power Control for AP Performance enhancement

PCF Point Coordination Function

PERF Power-controlled Estimated Rate Fallback

PH-MAC Power Hopping MAC

PHY physical

PMAC Power control MAC

PRC Power and Rate Control

PRCS Power, Rate and Carrier-Sense-threshold control

PRI Probabilistic Rate Increase

RF Radio Frequency

RNC-SC Radio Network Controller Secondary Channels

RO Rate Only adaptation

RRAA Robust Rate Adaptation Algorithm

RRPAA Robust Rate and Power Adaptation Algorithm

RSS Received Signal Strength

RTS Request To Send

RTT Round Trip Time

RX receive or receptor

SINR Signal to Interference plus Noise Ratio

SNR Signal to Noise Ratio

STA station

TX transmit or transmitter

TXOP transmission opportunity

WLAN Wireless Local Area Network

WiFi Wireless Fidelity

Chapter 1

Introduction

In recent years, wireless networks based on the IEEE 802.11 standard [3] (WiFi) have become very common in offices, university campuses, airports and in almost all urban-area buildings. In most cases these networks are not carefully planned and deployed, and are left unattended without proper management. Moreover, plenty of these deployments are focused on offering full coverage with a small distance from Access Points to terminals (so as to achieve high data rates) but do not consider important aspects such as interference or quality of service. This leads to a high-density (HD) wireless local area network (WLAN) with performance and reliability issues, caused mostly by RF interference and collisions [4].

Given the ubiquity of the IEEE 802.11 standard there is a need to produce a solution to the problem that does not modify that protocol. Currently, there is already a variety of ongoing research trying to improve the performance of HD WLANs, for example, [7, 15, 32] deal with optimal design of WLANs. However, we are interested in reducing planning complexity and costs, so in this work we focus on the novel research area that adapts the IEEE 802.11 MAC- and PHY-layer parameters for infrastructure networks.

This approach to the problem has many advantages (no modification of the network, it can be applied to already defined and deployed networks, it can be distributed and self-managed, no need of previous design) but it also brings in new problems and difficulties. The adaptation of transmit power is a clear example of the difficulties of this approach. Briefly, the transmit power impacts on the strength of the signal at the receiver, so a low transmit power can reduce interference at neighbouring nodes but can also make the receiver to be unable of decoding the signal.

In this work we review a variety of mechanisms to control IEEE 802.11 parameters such as transmit power, data rate or carrier sense threshold, we implement them in a simulator and compare their performance in different scenarios. Our objective is to understand the behaviour of these solutions and to find the pros and cons of each of them. In particular, we study some scenarios where parameter-adaptation techniques are known to have issues and we found that a common problem among many power-control mechanisms is the starvation of some links caused by heterogeneous transmit power or carrier sense thresholds. This problem leads to a performance degradation of the network that is worst than the initial interference problem.

Contribution

Based on the results mentioned previously we propose a novel mechanism: *Power, Rate and Carrier Sense threshold control* (PRCS) that, extending existing solutions, accomplish the objective of reducing interference and improving performance without causing the starvation problem. The mechanism novelty consist on the tuning of the carrier sense threshold based on measurements of the transmission opportunity (TXOP). Using the TXOP the mechanism can detect asymmetries in the network and react accordingly so as to avoid starvation.

Structure of the Document

The document is organized as follows. In Chapter 2 we give some background knowledge and an analyses of the problem of interference in HD-WLANs. In Chapter 3 we present a detailed review of parameter adaptation mechanisms. Then in Chapter 4 we implement and evaluate some of the reviewed mechanisms and in Chapter 5 we propose a new mechanism that deal with the problems found in the evaluation of existing solutions. Finally, Chapter 6 provides some concluding remarks, an overview of the findings of this thesis and future work proposals.

Chapter 2

Problem Analysis

2.1 IEEE 802.11 Standard

2.1.1 Physical (PHY) Layer

We will briefly and partially introduce the PHY-layer specification so as to be able to understand the studied problem.

Currently the are several transmission schemes specified in the IEEE 802.11 standard [3]:

- Direct Sequence Spread Spectrum (DSSS)
- High Rate Direct Sequence Spread Spectrum (HR/DSSS)
- Orthogonal Frequency Division Multiplexing (OFDM)
- Extended Rate PHY (ERP) (use DSSS)
- High Throughput OFDM (HT/OFDM) PHY

These schemes are used by the PHY-layers of the different amendments of the standard. In Table 2.1 we show a summary of the 802.11 amendments characteristics.

Standard	Release	Freq.	Data rate (Mb/s)	PHY-layer
802.11	Jun 1997	2.4 GHz	1, 2	DSSS, FHSS
802.11a	Sep 1999	5 GHz	6, 9, 12, 18, 24, 36, 48, 54	OFDM
802.11b	Sep 1999	2.4 GHz	1, 2, 5.5, 11	DSSS
802.11g	Jun 2003	2.4 GHz	6, 9, 12, 18, 24, 36, 48, 54	DSSS, OFDM
802.11n	Oct 2009	2.4 and 5 GHz	up to 600	OFDM
802.11ac	Dec 2012	5 GHz	up to 3460	OFDM

Table 2.1: IEEE 802.11 Standards (a.k.a Amendments).

In addition to different transmission techniques, there are particular modulation formats defined for the different data-rates allowed by a standard. A modulation format define a transformation of data bits to a sequence of symbols that are, then, mapped to signal waveforms that can be transmitted over an analog channel (such as the wireless channel). These symbols can be encoded varying the frequency, amplitude or phase of the waves.

Moreover, a group of K bits can be represented by a symbol and each symbol is mapped to a different waveform which gives us $M = 2^K$ waveforms. So, the data rate (in bits) is K times the transmitted symbol rate. Hence, if the symbol rate is constant, how much information a modulation format can transmit depends on the possible different values a symbol can take (these different M values a symbol can take is called a constellation). However, as the ways to encode a symbol to waveform variations are limited, when the number of values increases, the decodification becomes harder. It can be demonstrated that the minimum distance (in amplitude, phase or frequency) between two values in a constellation determines the signal-to-noise ratio (SNR) needed to avoid a bit error. In summary, constellations with many values need higher SNR to decode the symbol correctly (see Table 2.2). Additionally, *channel coding* is used as a mechanism to reduce the bit error rate (BER). It consists in adding redundancy by coding blocks of K bits in code words of length $N > K$. The relation $\frac{K}{N}$ is called the *coding rate*. In Table 2.2 we show the modulation formats and coding rate used by data rates in 802.11b and 802.11g [1]. It is also shown the theoretical minimum SNR needed by each data rate to obtain a BER less than $1e-05$.

This theoretical explanation gives an idea of how data rate and transmit power adaptation is beneficial in scenarios where the SNR is variable. Moreover, it can be seen that each modulation format has a SNR for which it is more efficient than the rest. A detailed and formal explanation of these issues can be found in [3, 26, 34].

Another important aspect of the 802.11 PHY layer is the use of the frequency spectrum available. In the case of 802.11b/g, it uses the frequency range between 2400 Mhz and 2500 Mhz separated in 13 channels (14 in some countries) of 22 Mhz as shown in Figure 2.1. Thus, there exist only 3 channels which are non overlapping and so do not interfere between them.

[1] It is important to notice that as OFDM separate a data stream into several parallel streams, in 802.11g in 48 parallel data subcarriers, it can send 48 symbols in parallel.

Data Rate	Standard	PHY-layer	Modulation format	Bits per symbol (and per subcarrier in OFDM)	Coding rate	SNR (dB)
1	b	DSSS	BPSK	1	1/11	-2.92
2	b	DSSS	QPSK	2	1/11	1.59
5.5	b	DSSS	CCK	1	4/8	5.98
11	b	DSSS	CCK	2	4/8	6.99
6	g	OFDM	BPSK	1	1/2	6.02
9	g	OFDM	BPSK	1	3/4	7.78
12	g	OFDM	QPSK	2	1/2	9.03
18	g	OFDM	QPSK	2	3/4	10.79
24	g	OFDM	16-QAM	4	1/2	17.04
36	g	OFDM	16-QAM	4	3/4	18.80
48	g	OFDM	64-QAM	6	2/3	24.05
54	g	OFDM	64-QAM	6	3/4	24.56

Table 2.2: IEEE 802.11b/g PHY Encoding Parameters and Minimum SNRs.

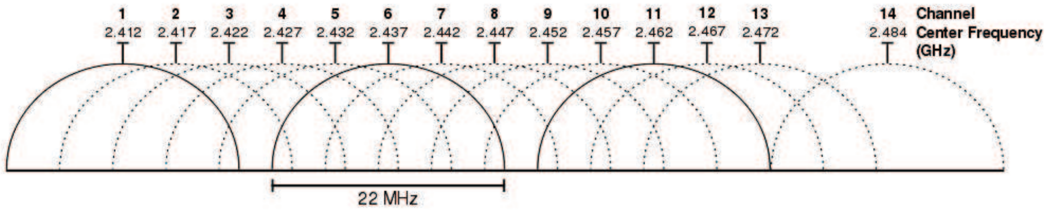


Figure 2.1: 802.11b/g Channels. Source: [13].

2.1.2 Medium Access Control (MAC) Layer

The medium access control in the IEEE 802.11 standard is performed by a logical function (called a coordination function) that determines when a station is allowed to transmit. In the last version of the standard there are defined four coordination functions: 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). Additionally, 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 only consider the latter. For this particular mode, the standard also define the Basic Service Set (BSS) as a group of stations (STAs) which are coordinated by a coordination function and the Basic Service Area (BSA) as the area of a BSS.

DCF uses *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) to regulate the access to the medium. In this protocol, before transmitting, a device must sense the medium to determine if another device is already transmitting (physical carrier sense). If the medium is not busy, the device is able to transmit. More specifically, a transmitting device must sense the medium idle for a period of time (called DIFS) before transmitting. If the medium is determined to be busy (on a transmission attempt), the device has 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 (see Figure 2.2). This back-off time is selected randomly from the interval $[0,CW]$ (the Contention Window). CW is a variable value that duplicates every time the device tries to transmit and can take values between CW_{min} and CW_{max}. This technique is called Binary Exponential Backoff (BEB). It is important to notice that when the node is waiting the BEB time, the medium must be idle for the whole time and, if a signal is detected, the countdown is stopped until the medium is idle again. A transmission is successful when an acknowledge (ACK) frame is received and the lack of reception of an ACK frame indicates to the device that an error has occurred and a retransmission is needed. A refinement of the method, called *virtual carrier sense*, can be used to mitigate the hidden- and exposed-terminal problems (see Section 2.4) to further minimize collisions. This method consists on the exchange of short control frames (Request To Send (RTS) and Clear To Send (CTS) frames) between devices, after determining that the medium is idle, following any deferrals or back off and prior to data transmission. These frames allow a device to reserve the medium for the period of time needed for a transmission.

In detail, the physical carrier sense in IEEE 802.11 standard is performed by the *Clear Channel Assessment* (CCA) function. CCA is defined in the standard as the logical function in the physical layer 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 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

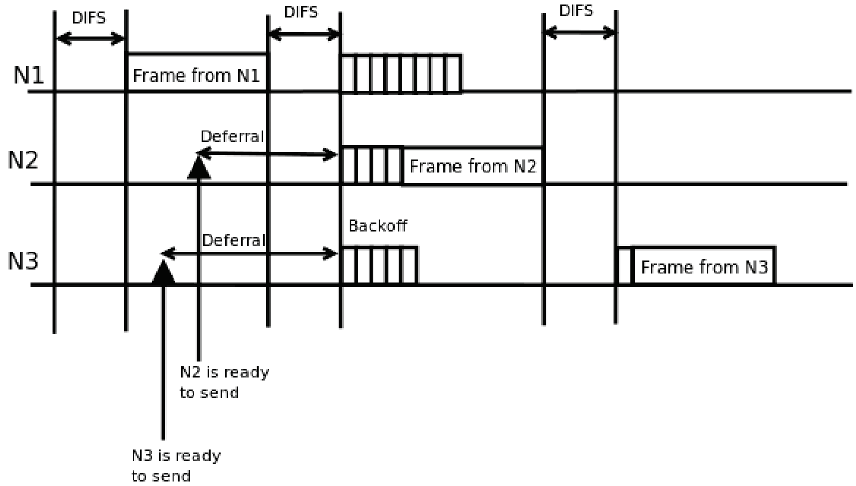


Figure 2.2: DCF Backoff.

Detection can be defined as the ability of a node to sense the energy on the channel, where the source of this energy could be the noise floor, non-WiFi devices causing interference or WiFi devices whose transmissions are too low or corrupted. In this case, the mechanism needs to sense the channel on every time slot because it is not possible to know in advance the amount of time the medium will remain busy. 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. Moreover, the CCA can work in different modes which define how to combine CS and ED to report the medium busy. In the literature is common to find 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.

Finally, another important variable for our following analysis, is the Receiver Sensitivity. It is defined as the minimum signal level required to successfully recovering a frame from the medium. It is dependent on the modulation scheme and the coding rate used. This value is also know as the Signal Detection Threshold.

2.2 Definitions and Models

To better explain the problem we are describing let us define some concepts we will use 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 (in dB) 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 when modeling interference-limited environments.

The difference between P_{TX} and RSS at the receiver has ambiguous names in the literature: path loss, fading, attenuation, channel gain. The suitability of each one depends on the assumptions made. A comprehensive explanation of these terms can be found in [34]. Briefly, in this work we will understand attenuation as any loss of signal strength, path loss (L) as the attenuation due to propagation effects and fading as the temporal and spatial variations of the transmission channel (in particular of the received power) due to multi-path propagation (see [34]).

Another important aspect for understanding the problems (and its solutions) in HD-WLANs is how to model the interference. There exist two important interference models such as the Circle Model [4, 22] and the SINR Model [38]. The Circle Model associates a transmission range and an interference range to each sender. If a node is in the transmission range it can correctly receive data from the sender and if a node is on the interference range means that it will receive high interference and will sense the medium busy. The SINR model consists on determining a threshold where if SINR at a receiver is over the threshold means that the signal can be decoded. This model is often used in a simplified version where only the interference from the strongest source is considered and the noise is ignored (called Protocol Model [38]). So the $SINR$ of the signal from source S at destination D and with an interferer signal from I is:

$$SINR_{SD} = P_{TX}^{S} - L_{SD} - (P_{TX}^{I} - L_{ID})$$

These assumptions are more realistic in the case of interference-dominated scenarios where the power is high enough to ignore noise and the interference is pair-wise.

2.3 The Hidden-Terminal and Exposed-Terminal Problems

In this section we will briefly explain two common problems 802.11 WLANs suffer from. These problems are important for our analysis because, as we will see later, parameter-adaptation mechanisms should take care of not generating or aggravating them. For the explanation of the problems we will use the Circle Model to define three distinct ranges (based on the definitions from [44]):

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.

Interference Range A transmitter inside the interference range of a receiver will cause interference on the receiver.

2.3.1 The Hidden-Terminal Problem

The hidden-terminal problem occurs when a transmitter cannot sense another transmitter signal but both of them are within the interference range of a receiver. In this case, interference is generated at the receiver causing losses. A graphical example can be seen in Figure 2.3. In this figure the continuous green circle is the transmission range of T1, the dotted blue circle is the carrier sense range of T1 and the dashed red circle the interference range of R1. In this example, T2 is outside the carrier sense range of T1 but inside the interference range of R1 causing that both T1 and T2 transmit simultaneously and then generating interference at R1.

2.3.2 The Exposed-Terminal Problem

The exposed-terminal problem is generated when a transmitter is prevented from transmitting because of the carrier sense mechanism but the transmission would have been successful. As depicted in Figure 2.4 this can be produced because the exposed transmitter (T2) is inside the carrier sense range of the other transmitter (T1) but outside the interference range of the receiver (R1).

As we mention early, the idea of the carrier sense mechanism is to prevent simultaneous transmissions and so to avoid interference and collisions. However, this mechanism generates two conflicting problems. It can be notice that increasing the carrier sense range can avoid the case of the hidden-terminal problem, however this increment can increase the possibilities for the exposed-terminal problem to appear.

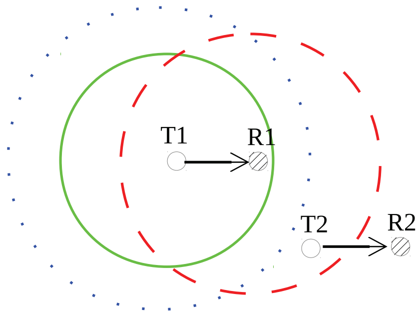


Figure 2.3: The Hidden-Terminal Problem.

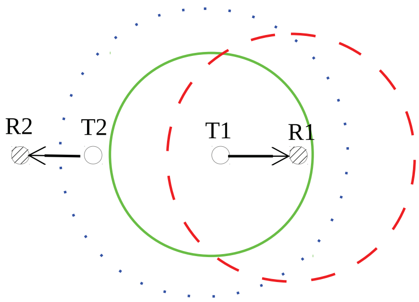


Figure 2.4: The Exposed-Terminal Problem.

2.4 High Density WLANs

In general, when deploying a WLAN the primary objective is to assure total coverage on a predefined area and to provide good performance to users. There exist two performance metrics which are the most important for end-users: throughput and delay, and they are implicitly related to the data rate. As we explain earlier, the data rate at which nodes can communicate depends on the SNR at the receiver, the higher the SNR the higher the possible data rate. However, the SNR is related to the path loss between the sender and the receiver, therefore the distance between two nodes has a major influence in the data transmission rate. HD WLANs are, in part, a result of the effort made to reduce the distance between APs and STAs to increase the SNR and the data transmission rate.

As we mention previously, the 802.11 standard defines a set of channels which can be used by the nodes, and in particular there is a subset of them which do not interfere each other (3 in 802.11g). However, because of the reduced distance between APs in HD WLANs, this quantity could not be enough to isolate all communications.

Then, increasing the network AP density (to cells of 20 to 50 m of radius) makes the distance between APs to decrease and so the interference among co-channel APs increase. This interference impacts in various 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 the reduced distance. For example, in [12] the authors run experiments on a testbed to evaluate the performance degradation of high-density networks. They found that the impact of AP density is more severe than the client density. For example, an increment from 1 AP to 4 AP shows a throughput degradation of about 50%. This characteristic makes HD-WLANs to be interference-limited networks, meaning that the interference is so strong that it affects performance [52, 54], and the noise can be neglected. This is important because there exists a difference between interference and noise, the interference suffer from attenuation but noise is typically constant.

The previous argumentation clearly shows the dependence and trade off between data rate, AP to AP distance and IEEE 802.11 parameters configuration. For example, Kauffmann et. al. [21] explains that the long-term throughput of a user is related with:

- the period of time it (or the AP) can gain access to the medium (MAC parameters).

- the number of users associated with the AP, the AP needs to balance the load between them (density).

- the capacity of the link between the user and the AP (density and PHY parameters).

Additionally, this kind of networks have become very common due to the ease of deployment and low cost. For instance, Akella et. al. [4] presents a study of HD-WLANs in cities and evaluate the impact of interference in these kind of networks for end-client performance. They collect and analyze data from several cities of the United States and then simulate these deployments to measure the clients performance. The authors conclude that most deployments maintain the default configurations of the IEEE 802.11 parameters causing high interference.

An important concept in HD-WLANs is the spatial reuse, which is a measurement of how many concurrent transmissions are possible. As stated in [52]: “The amount of exploitable spatial reuse is closely related to the network topology, the radio propagation model, the communication rate between the transmitter/receiver pair as well as the carrier sense threshold applied to each station.”

2.4.1 Parameter Adaptation Challenges

From the above description of the problem we can argue that after a network is deployed (and the protocols and topology are defined) the nodes behavior depends on the configuration of the protocol; it is possible to tune the protocol to reduce interference and improve network performance dynamically managing its parameters. Most works on the literature choose to configure the following set of parameters from a wide set of configurable parameters:

- Channel.
- Transmit Power.
- Data Rate.
- CCA Sensitivity (Carrier Sense Threshold, CST).
- Receiver Sensitivity (Signal Detection Threshold, SDT).
- Contention Window (CW) Size.

Briefly, the tuning of each one of these parameters affects the network on a different way: CW size and CST in combination with CSMA/CD and CA, isolates the transmissions in time; CST, receiver sensitivity and transmit power achieve space isolation; channel, isolates the transmissions in frequency; and data rate, sets the modulation and coding and affects the error correction and minimum necessary SNR.

As said before, there is a trade-off between these parameters. 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 [11]. It is an important technique for reducing interference in HD-WLANs where co-channel interference is predominant because of the few non overlapping channels available in 802.11 standard. However, 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). Even worst, using low data rates on a link not only affects the local throughput of that link but also the network throughput because links with low data rates occupy the channel for more time to transmit the same amount of data than links with high data rates.

The same dilemma occurs with CST, when it is set to a low value (more sensitive) less concurrent transmissions can happen as it is more likely that the APs hear the channel busy and backoff their transmissions. This generates less interference and so data rates can be increased but the fraction of time each AP is able to transmit becomes smaller. On the contrary, when using high values of CST, more co-channel APs can transmit simultaneously, but the interference at the receiver can be so high that the $SINR$ could not be high enough to decode the signal.

Controlling these parameters not only is complicated because of the trade-offs between them but also because their manipulation can exacerbate innate problems of wireless networks. For example, the hidden- and exposed-terminal problems are common problems that can be produced by heterogeneous transmit powers between nodes. In Figure 2.5 we show the different possibilities where two links interfere (based on findings from [7]). In the figure, 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 ranges of the transmitters (centred on the transmitter), the dashed circles depict the interference range (centred on the receiver) and the dotted circles represent the carrier sense range (centred on the transmitter). In case 1, both senders can hear each other and thus will fairly share the medium. Case 2, is an asymmetric exposed-terminal problem, in this case T1 has reduced its transmit power and so T2 will not sense its transmissions. This is represented by also reducing the carrier sense range of T1. So, T1 can sense T2 and though defer transmission but T2 does not sense T1 and transmits continuously, causing an unfair access to the medium. Cases 3 and 4 are the hidden-terminal problem, as the transmitters cannot sense each other they transmit continuously causing interference on the receivers. Finally, case 5 represents a scenario where simultaneous transmissions can occur without any of those problems by reducing the transmit power of T2.

Related to the problem of hidden- and exposed-terminal appears the concept of starvation. It consists on the inability of a link to transmit as much as it could. In [16] authors identify three kinds of starvation:

- Carrier sense starvation, which occurs when a link has an exposed terminal to many other links but not on the other way.

- Hidden node starvation, suffered when, in a hidden-terminal scenario, only one receiver suffer from interference. For example, in Case 4 the link of T1 will suffer from starvation.

- Asymmetric sense starvation, which happens when exists heterogeneous power, carrier sense threshold or channel conditions like our Case 2.

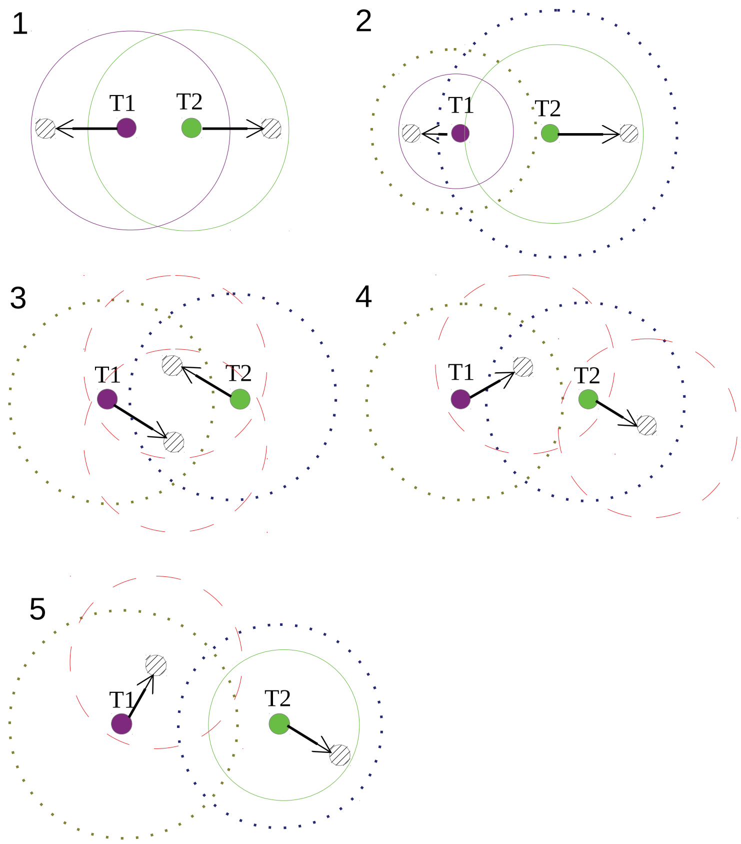


Figure 2.5: Problem Scenarios.

Moreover, another aspect of the problem has to be considered when thinking on controlling IEEE 802.11 parameters, how to detect a performance problem on the network, i.e. how to detect when density is affecting performance. There exist two widely used approaches, the frame loss and the received signal strength. As said in Section 2.1 the IEEE 802.11 standard determines receivers to use acknowledge frames (ACKs) to inform the transmitter of a correctly received data frame. So, this ACK (or the lack of it) can be used to estimate the channel conditions. For example, the absence of a confirmation may be caused either by corrupt frame arrival due to interference, or no frame reception because the signal at the receiver was too low or it collided with another frame. The missing confirmation enables the transmitter to take actions to circumvent the problem. 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. It is important to note that several works [4, 18, 41, 45] claim that this method is difficult to implement because of the complexity of understanding signal propagation and differences in measurements from different hardware. The rationale behind these two approaches is to estimate channel conditions, assuming that bad channel conditions are caused by interference from other nodes.

Chapter 3

State of the Art

The adaptation of IEEE 802.11 MAC and PHY sub-layer parameters has been a topic of research for at least the past fifteen years. In particular, there is mayor work in the areas of data-rate control, power control, and carrier-sense-threshold control. Power control is an important topic in cellular networks and an interesting survey on this topic can be found in [11]. In the area of IEEE 802.11 networks, plenty of research has been done for ad-hoc networks [20, 22, 23, 24, 25, 35, 36, 37, 47, 53], however, the application of these solutions to infrastructure networks (our case of study) is difficult because of the implicit assumption in ad-hoc networks that the communication can be done from any node to any node of the network.

In what follows, we present some of the existing mechanisms for improving performance in high density infrastructure IEEE 802.11 wireless networks through the adaptation of MAC and PHY parameters. The different approaches can be classified in many ways, for example: the parameters controlled, the mechanism used to estimate channel quality or performance degradation, the problems addressed or if the control is done per-link or per-AP (per-cell). In this work we are interested in the mechanisms that try to reduce interference between APs; for achieving this, all existing proposals perform power or carrier-sense-threshold control. Therefore, we present these approaches and classify them distinguishing among those that combine power and rate control (Section 3.1), those that do carrier-sense-threshold control (Section 3.2) and those that combine power and carrier-sense-threshold control (Section 3.3).

Additionally, for an appropriate characterization of the mechanisms we extend and apply to these mechanisms the categories given by Wong et. al. in [50] for rate adaptation algorithms. This classification is based on the concept used to estimate the performance of the channel, as explained in the previous chapter. It takes three aspects of the estimation: which layer it uses, if it send probing messages and how it use the information to estimate.

- The estimation can be done using *physical-layer* information such as the signal strength received, the SINR or other metric; or using *link-layer* information like if frame transmissions were successful or not; or it can follow an *hybrid* approach and use information from both layers.
- If the link-layer approach is used then *probing* frames can be sent using different parameters so as to test the channel conditions or, on the other way, all frames are sent using the defined parameters making a *non-probing* mechanism.
- The information collected in the link-layer approach can be used in a *deterministic* way, meaning that it consider a number of successful or failed transmissions to take a decision or it can use *statistical* approaches to make statistics of successes or failures. The most common statistics among different works are the frame loss rate (FLR) defined as $FLR = \frac{\#failed\ frames}{\#sent\ frames}$.

In Diagram 3.1, following this classification, a taxonomy of the mechanisms reviewed is presented.

Moreover, in Table 3.1 we show a summary of all the mechanisms studied. On the evaluation of the different mechanisms we focus on eight aspects of them:

Power If it does power control.

Rate If it does data-rate control.

CST If it does carrier-sense-threshold control.

Signal If it uses signal strength for estimating channel conditions.

Frame Loss If it uses frame loss to estimate channel conditions.

Per-link If the power, rate or CST control is done per-link or per-AP.

Distributed If the decisions are taken distributed or centralized.

No changes If the implementation of the mechanism do not need to make changes on the IEEE 802.11 standard.

Mechanism	Power	Rate	CST	Signal	Frame Loss	Per-link	Distributed	No changes
PARF	✓	✓			✓	✓	✓	✓
APARF	✓	✓			✓	✓	✓	✓
PASA	✓				✓	✓	✓	✓
ConTPC	✓				✓	✓	✓	✓
Symphony	✓	✓			✓	✓	✓	✓
MP	✓	✓			✓	✓	✓	✓
MiSer	✓	✓		✓		✓	✓	
BasicTPC	✓	✓		✓				
PCAP	✓			✓				
PMAC	✓			✓		✓	✓	✓
PERF	✓	✓		✓	✓	✓	✓	
PRC	✓	✓		✓	✓	✓	✓	
DSB		✓	✓		✓		✓	✓
Zhu			✓		✓			✓
Echos			✓	✓			✓	
ORCCA			✓	✓				✓
Ma	✓		✓		✓	✓	✓	
Mhatre	✓		✓	✓			✓	
Liu	✓		✓	✓			✓	
Fuemmeler	✓		✓	✓			✓	

Table 3.1: Mechanisms Properties.

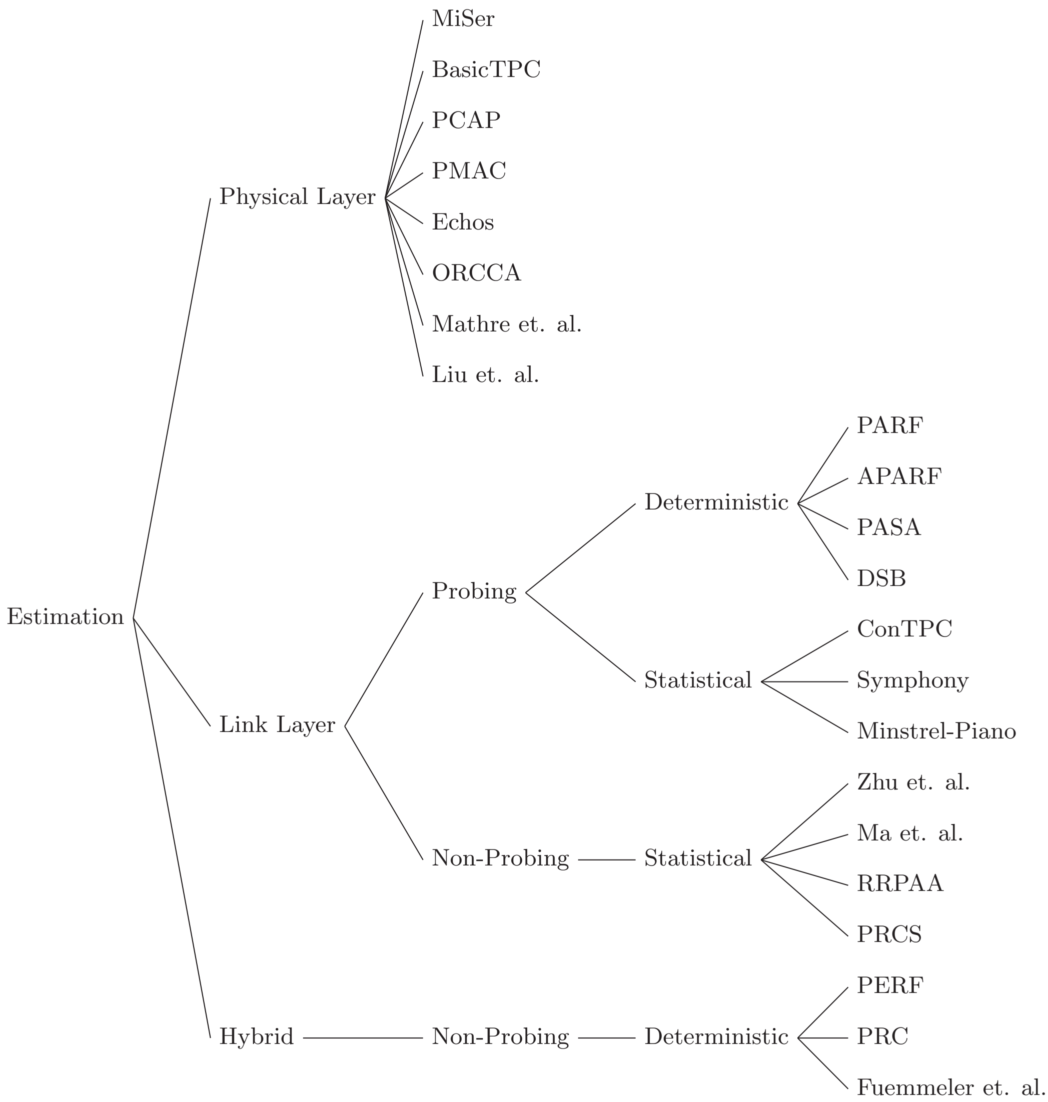


Diagram 3.1: Mechanisms Taxonomy By Channel Quality Estimation Method.

3.1 Power and Rate Control

3.1.1 Link-Layer Estimation

Power-controlled Auto Rate Fallback (PARF) is a self-managing technique presented in [4] that is based on power and rate control. It tries to minimize interference among neighbouring APs based on ARF, a mechanism that only tunes the rate. ARF is based on testing MAC layer ACKs messages to estimate channel conditions. So an ACK loss implies a reduction in rate and a successful reception an increase. Then, PARF adds power control to ARF by reducing the transmission power if at the higher 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 power is increased until a maximum value where, should the fails persist, a rate fallback starts. The evaluation of PARF made in [4] shows this mechanism is very unstable and propose their other mechanism PERF based on signal strength (see Section 3.1.2). However, it has the advantage to be a very simple mechanisms and very easy to implement, and as we will show in Chapter 4 it can improve performance on some scenarios.

Very similar ideas are presented in [9], we call it *Adapting PARF* (APARF). In this work two operation modes for rate and power control are introduced: (i) the High Performance (HP) mode where the idea is the same as PARF, this means to transmit at the higher rate with the lower possible power, and (ii) the Low Power (LP) mode where the transmission is done with the lowest possible power and then the rate is optimized. The most interesting difference from [4] is that the threshold used to decide a change in rate or 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. Authors define the variable S_{max} as the necessary successful sent frames to make a change. It can take two possible values following the mechanism shown in Figure 3.1.

The states correspond to whether the node estimate the change speed of the channel is High or Low. In this article, the mechanisms are evaluated using a discrete-event simulator implemented by the authors. Simulations are executed for three different scenarios and measures are made not only for throughput but also for frame delays and power efficiency and the results are compared with other techniques such as data-rate-only adaptation (RO) and fixed-rate. The authors arrive to the conclusion that the best adaptation technique depends on the scenario (number of devices, traffic type and load) but they show that HP outperforms other mechanisms in many cases.

Power Adaptation for Starvation Avoidance (PASA) is a similar approach pro-

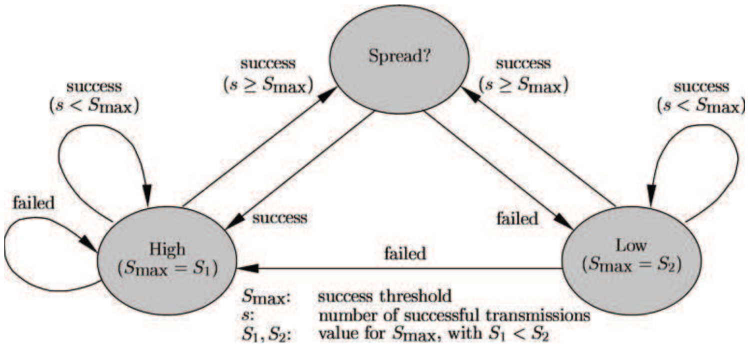


Figure 3.1: Transition Diagram for HP Mode. Source: [9]

posed in [8]. It is a mechanism which principal objective is to mitigate the hidden-terminal problem (and the starvation problem it generates) based only on transmit-power adaptation. It follows the same idea as PARF, to increase power when there are consecutive losses and decrease power on successful transmission. The authors also consider the case of asymmetric links generated when controlling power but, in our opinion, fail to notice that in these scenarios there could be no losses but still starvation. Their mechanism controls power only by frame losses and they suggest that when asymmetry happens there would be more losses and then the power will increase. As we will show in Chapter 4 our simulations show that this is not always the case.

Conservative Transmit-Power Control (ConTPC) [25] differentiates from previous works as it use statistical information of frame losses. It only controls power (rate is not considered), however it is interesting because differently from PARF it exhibits good results. Authors argument that their protocol is more conservative than others because it only reduce power of those links which FLR (they call it delivery ratio) is not adversely impact by this reduction. In ConTPC nodes learn the relation between the FLR and the transmission power of all their links. This is possible because each node broadcasts frames at all available power levels with information of the power used. Then each node selects the best power (the one which do not decrease the FLR more than a configurable threshold) for each link and share this information with the sender. In [25] the mechanism is evaluated on a testbed with real hardware where per packet power control is realized. The most interesting evaluation is conducted on an eleven node testbed where results show a 15% of improvement in the average throughput compared to using maximum power.

Ramachandran et. al. in [41] present *Symphony*, a rate and power control mechanism which is implicitly based on frame loss. The general idea is the same as in other works, to make rate and power control keeping the performance of each link at least as good as the performance when the maximum power is used. 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 broadcast synchronization frames on each phase change. As previously mentioned, the mechanism has two phases, REF (Reference) phase and OPT (Operational) phase. In the REF phase, the rate control is made by all senders for all of its links using maximum power and the performance is recorded to use as reference for power control. Symphony is designed to accept any rate control mechanism in this phase. Then, nodes enter the OPT phase where rate and power control is jointly performed. In this phase, the power is lowered on every link to a value such that the achievable performance is no worse than the performance obtained on the REF phase by more than a given delta. To measure performance, Symphony define three metrics, an Exponential Weighted Moving Average (EWMA) of the data-rate, the utility of RTS and an EWMA of the Expected Transmission Time (ETT). Each one of these metrics is used to prevent or detect some undesirable situations. The data-rate EWMA is used to avoid the power to be decrease excessively and so to make the data-rate to decrease. When the mechanism notice that the data-rate adaptation algorithm decrease the rate to a value lower than that on the REF phase the power is increased. To detect that the power control is not generating a performance degradation (frame losses) due to interference on the receiver (hidden terminal problem) Symphony uses adaptive RTS/CTS (can be turned on and off). Using this mechanism, on a frame-loss event the RTS/CTS mechanism is enabled for a window of frames and the loss rate is measured for that window, then the utility of RTS (URTS) is defined as the ratio between the loss rate using RTS/CTS and the loss rate without RTS/CTS. This means that if the URTS is less than 1 then enabling RTS/CTS was helpful to reduce losses and the mechanisms can induce that losses are a cause of collisions generated by a hidden terminal problem so the power is increased. Finally, to prevent the power control to cause an asymmetric access to the channel (exposed-terminal problem), the ETT is calculated so as to know the time it takes a packet to be transmitted. Then if a sender is starved by another, it gets less access to the channel and so the ETT will increase. Furthermore, the authors implement Symphony on the MadWifi driver [1] (an open source driver for Atheros chipsets no longer used) and make several test on different scenarios. The results show an improvement on the total throughput using Symphony instead of using maximum power on static scenarios. For the problematic scenarios, the techniques for avoiding receiver-side interference and asymmetric channel access also show good results and demonstrate the importance of giving particular attention to these issues.

Minstrel-Piano [18] follows the same idea of power control presented in others works, that is: to transmit at the rate given by the rate control with the minimum power possible. Moreover, to control power, this proposal also use 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 [46] (an enhancement of SampleRate [5] and available in Atheros cards) is a data-rate control algorithm based on throughput to choose the best 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 (probing) part where transmissions are made in other rates. Then, periodically, a statistics table is updated with the inverse of the FLR (the authors define it as success probability, $p = \frac{\#successes}{\#attempts}$) of each rate and for each link. In this table the probabilities of each rate are updated using EWMA as follows.

$$p_{new} = ((1-\alpha) * \frac{successes}{attempts}) + (\alpha * p)$$

Afterwards, for each rate the achievable throughput is calculated as the product between rate and probability. With this information, the rates are classified in three categories: the one with highest throughput as “best throughput”, the one with second-highest throughput as “second-best throughput” and the rate with highest success probability as “highest probability of success”. The classified rates are used in the transmission chain (where the parameters for transmissions and retransmissions can be set) to select the rate for each attempt. The first try is done with the rate classified as “best throughput”, then, if retransmission is needed, the “second best throughput” rate is used and then, if another attempt is needed the “highest probability of success” rate is used. If neither of these attempts work the frame is discarded.

To add power control to Minstrel, Piano send packets at different powers and try to statistically learn the impact of transmission power on throughput. In particular, Piano uses three different packets: reference, sample, and data packets which can be sent using different power levels and record the corresponding success probabilities for each type. The rationale behind this technique is to sample different power values for exploration in order to have a reference power for which the probability of success is near to 1 and then send data packets with the power of sample packets plus a constant. The differences from previous works are: (i) the control is relaxed using probabilities and EWMA (and not the number of failures directly) and (ii) the addition of probe packets for exploration.

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 January 2014) and the evaluation presented in the article does not seems to be deep enough, since the mechanism is only evaluated on a single link varying the channel conditions with different carrier sense modes.

3.1.2 Physical-Layer Estimation

The idea behind all of the mechanisms that make PHY-layer estimation is that there is a relation between the data-rate and the SNR at the receiver, as we explain in Chapter 2. In Table 3.2 we recall this relationship.

Rate (Mbits/s)	SNR (dB)
54	24.56
48	24.05
36	18.80
24	17.04
18	10.79
12	9.03
9	7.78
6	6.02
11	6.99
5.5	5.98
2	1.59
1	-2.92

Table 3.2: Minimum SNR for Data-Rate

MiSer [40] is, to our knowledge, the first work that deals with rate and power control using signal strength measurements for estimating channel conditions. However, the motivation for this work was not to improve performance or reduce interference but to save energy of wireless devices. In this work the authors propose a model to calculate the energy efficiency of a given data-rate and transmit-power based on the data payload length, the channel path loss and the frame retry counters. Then, a table is populated with the optimal data-rate and transmit-power for each possible payload length, path loss and retry counts combinations and the mechanism consists on selecting the appropriate data-rate and transmit-power from that table on each transmission. For calculating the path loss, the authors propose to use the RSS of received frames at the sender and the power at which those frames where sent to calculate the path loss as the difference of these two values. To obtain the transmit-power of received frames authors argue that IEEE 802.11h standard could be used. This standard allows to send the transmit-power used in frames as part of the frame header. The authors present results of simulations that, in summary, show an improvement of 20% in data transmitted per unit of energy in comparison with rate-only adaptation.

A different technique is used in *BasicTPC* [48] where the transmit-power control is applied per-AP (i.e. per-cell) and exists coordination among different APs so as to avoid asymmetric links. In this mechanism rate and power are controlled measuring the SNR at the receiver and follows an iterative algorithm to select the minimal power that ensures a predefined acceptable rate for all the links. For controlling asymmetric links, all adjacent APs use similar powers (the difference between powers is bounded by a defined threshold). The author's implementation of this mechanism consists on a central controller which collects information and calculates the transmit-power for each AP. In this way authors demonstrate by simulations that in dense deployments they can improve throughput without causing asymmetry problems.

Power Control for AP Performance enhancement (PCAP) [28] is another centralized algorithm for controlling power per-AP. In this case, the authors also consider AP association and propose a mechanism to increase performance by selecting the associations that maximize the network utility. The algorithm calculates the utility of each AP (as the weighted bandwidth product of the clients associated to the AP) and selects the transmit-power that maximize this utility. From [28] it is not clear which information the controller needs to calculate these utilities and how it should be use.

Huang et. al. [17] propose *Power control MAC* (PMAC) a power control mechanism to attack the hidden- and exposed-terminal problems based in the exchange of RTS/CTS frames and the measurement of signal strength. The mechanism consists on, before each transmission, exchange a RTS/CTS frame (as proposed by IEEE 802.11) at the lowest rate so as to cover the biggest possible area. Then, using the received signal strength of the CTS frame it estimates the power needed for the transmission of the DATA frame. The calculation of the power is done estimating the channel gain as the difference between the received power and the maximal power (RTS/CTS frames are always sent at maximal power) and using predefined values as in Table 3.2. Simulations carried out by the authors show an improvement in throughput of 80% over no adaptation baseline. An interesting aspect of this work is that it does not need to exchange information to calculate the channel gain and so no modification to the standard. However, in [17] is not clear how to deal with rate adaptation, instead they select power for a already given rate.

In [10] Douros present some ideas for a power control strategy to obtain a fair sharing of the medium. The idea is based on economic social fairness where an income function is defined for each AP and then it is optimized. In this work the authors test two optimization algorithms (FirstMax and BestMax) and found that the best choice is to serve nearer clients and drop bad clients. This strategy (association control) is also present in some other works ([28]) and we think it deserves further study.

A recent work from Patras et. al. [39] presents the *capture effect* phenomenon and the *Power Hopping MAC* (PH-MAC) mechanism which exploits this effect to improve network performance. The capture effect consists in the successful reception of a signal despite the presence of other signals given that the difference in signal strength is sufficiently large. This implies that frame collisions can be avoided even though concurrent transmissions exist. In particular, authors demonstrate that nodes near to the AP can capture the medium and therefore cause a decrease in network performance due to retransmissions of farther APs. PH-MAC consists in making power control to take advantage of this effect by reducing collisions and though reducing retransmissions. The mechanism (implemented on each node) consists in alternate, with equal probability, between two possible power levels P_L and P_H. Then, if the difference between P_L and P_H is large enough, a distant client that uses P_H can capture the medium instead of a closer client that is using P_L. In high-density scenarios (where collisions are common), the authors demonstrate that, setting P_H to the maximum available power and P_L to the minimum available power, the network throughput improves by a 25%.

3.1.3 Hybrid Estimation

The *Power-controlled Estimated Rate Fallback* (PERF) technique [4] follows the same idea that PARF, it extends a rate-adaptation mechanism called *Estimated Rate Fallback* (ERF). ERF uses an estimate of the SNR at the receiver to select the appropriate rate (the optimal for that SNR). It estimates the SNR at the receiver by including channel information in the frames. Each node includes the transmission power of the frame, the estimated path loss and the estimated noise of the last received packet. Then with this information and the measured RSS the sender can calculate the SNR. If the SNR is in the limit of two possible rates, it uses the frame losses to decide, assuming that the estimation may have errors. If there are no losses it will increase the rate and will decrease it if there are failures. The power control in PERF is done similarly as in PARF: if the SNR is as high that a power reduction would keep the same rate, then the power is reduced. In summary, this technique uses the SNR for a first approximation to the best rate and then control fine grain differences with frame losses. The evaluations of these mechanisms made by the authors are, in our opinion, too simple, as they only consider a single node configuration. For the test they use two pairs of nodes, one pair (the victim) transmits a TCP flow while the other realize another transmission used to cause interference in the first one. These tests are made in a laboratory with nodes communicating over coaxial cables and in a testbed with wireless devices. The results show that PERF is able to improve the throughput of the victim pair by reducing the power of the aggressor. For instance, in the wireless deployment the improvement is of 50% with respect to not using any mechanism.

Power and Rate Control (PRC), described in [23], is a very similar mechanism which is based on the RSS but also uses frame losses. In this work, it is also addressed the tuning of the carrier-sense-threshold but it is not incorporated to the algorithm. In their theoretical analysis the authors found that spatial reuse only depends on the ratio between transmit-power and carrier-sense-threshold, this means that one parameter can be controlled while fixing the other (similar results will be exposed in Section 3.3). Moreover, they found that controlling the transmit-power has some advantages over tuning the carrier-sense-threshold when the channel allows different rates. Based on these results, a rate and power control mechanism is designed with the idea of allowing the maximum possible rate and to keep minimal the interference in other nodes. The first part of the mechanism consists of setting the carrier-sense-threshold to a fix value derive from the analytic study for all the APs. The power control mechanism results very interesting and consists of three steps (on each AP):

1. Measure the RSS of all the APs in range and consider it as the *received interference*, then using this information the transmitter estimates the maximum transmit-power which would also allow the closest interferer to transmit at the lowest data-rate and select this power for transmission.

2. Each transmitter finds the maximum $SINR$ that will perceive the receiver based on the selected transmit-power and, using a table (like Table 3.2), finds the highest rate supported for that $SINR$ and select it. To find out what is the $SINR$ at the receiver the mechanism makes all nodes to inform through the frame headers which is the perceived interference-level and uses the protocol model to estimate the $SINR$.

3. If the $SINR$ at the receiver permits a reduction in the transmission power without affecting the rate, this reduction is done.

To update these values when some change occur in the environment the mechanism count the failures and successes of the frame transmissions and if these values exceed some threshold the PRC mechanism is activated. Though, this mechanism maximizes the transmission distance while minimizing power and data-rate.

The simulations made by the authors in randomly generated scenarios show an increase in the number of concurrent transmission compared to *fixed power*. Also PRC can achieve an improvement of 22% of the total throughput compared to the DSB algorithm (an algorithm that adjust carrier-sense-threshold and rate).

3.2 Carrier-Sense-Threshold Control

As mentioned before, the carrier-sense-threshold (CST) is an important parameter not only for improving performance but also to avoid undesired scenarios such as asymmetric sense starvation. Many works have studied the impact of carrier-sense-threshold on performance and propose controlling it for improving spatial reuse.

3.2.1 Link-Layer Estimation

In [51] Yang propose a simple algorithm for controlling CST and data-rate called DSB (*Dynamic Spatial Backoff*). The algorithm is based on successful and failed transmissions of data frames to make a decision. The idea of the algorithm is that as a high rate needs the signal at the receiver to be high (or the interference to be low) then a low CST is needed. Following the same idea of the mechanisms based on signal strength, authors create a table that associates data-rates with CST. Briefly, the mechanisms consists on:

- Start at the minimum data-rate and maximum CST.
- On consecutive successful transmissions increase the data-rate until failure occurs or the maximum rate is reached.
- On consecutive failure three decisions can be made:
  - If the CST us higher than the one assigned to the data-rate in the table, the CST is decreased.
  - If the CST is the same as the indicated in the table for the data-rate then the data-rate is decreased.
  - If the data-rate used is the lowest then the CST is decreased.

In this work, the table of rates and carrier-sense-thresholds appears to be an important drawback because these values depend on channel conditions (for example path loss) and this has to be estimated to populate the table.

A very simple mechanism is proposed in [54] by *Zhu et. al.* to balance the hidden- and exposed-terminal problems controlling the CST. The idea is based on the assumption that a low FLR suppose there is few collisions and then a small number of hidden terminal and that there is a duality between exposed-terminal problem and hidden-terminal problem. This means that, when there are many hidden terminal there are few exposed terminals and vice versa. So, the mechanism consists on decreasing the CST when the FLR is high (so as to detect possible hidden nodes) and increasing the threshold when the FLR is too low. There is no suggestion for the right values for low and high FLR and in the author's experiments these values are calculated empirically. The authors propose a centralized deployment where all APs cooperate and use the same CST and a distributed deployment. Testbed experimentation results show that the cooperative approach where the maximum FLR of all links is used for taking decisions outperforms the distributed and the no adaptation case. No cooperation generates new hidden nodes and cause some links to degrade performance.

3.2.2 Physical-Layer Estimation

Enhanced Capacity 802.11 Hotspots (ECHOS) is an architecture design to improve the performance of 802.11 networks working as hotspots. It introduces two algorithms *Access Point Carrier-Sense-Threshold* (AP-CST) and *Radio Network Controller Secondary Channels* (RNC-SC). The AP-CST mechanisms consists on CST control in a distributed manner so as to allow as concurrent transmissions as possible. For the implementation of the algorithm each node of the network must sense all incoming signals and separate them as signals from the same basic service area (BSA) and from outside the BSA. This information is shared to the rest of the nodes piggybacked in beacon frames. With this information each client knows the strength of its signal at the AP and then choose the minimal CST that would allow the signal to be received correctly. The AP, knowing the strength of it signal at each client and the interference from other BSAs, can calculate the minimum SNR of all the clients. If the minimum SNR is high enough it can choose a high value of CST so as to always transmit. Otherwise, it decrease it CST to the minimal CST of all the clients. The rationale of this is that these value makes the carrier sense range to cover the interference range of the receiver.

Optimal-Rate CCA Adaptation (ORCCA) is a mechanism presented in [32] which controls CST to increase network throughput and uses a central controller for selecting a global CST. Each AP register the RSS of all the co-channel APs using the beacons received and the RSS of the associated clients. With the RSS of the clients and knowing the power used in transmissions, each AP calculates the interference allowed at the farther client for all the possible rates and use this value to select the CST for each rate. Then using the information obtained from beacons it calculates the number of competing APs and find the maximum allowable throughput for each rate. All this information (a triplet of rate, throughput and CST for each rate) is sent to the central controller which choose the CST that maximizes the network throughput. This mechanism does not require any modification of the standard and to our opinion its implementations appears to be simple. The author's evaluation in simulations show an important improvement over the default CST option and also over the *Echos* mechanism. We consider the central controller to be the major drawback, which could be difficult to implement in networks with heterogeneous operators or managers.

3.3 Power and Carrier-Sense-Threshold Control

3.3.1 Link-Layer Estimation

In [31], *Ma et. al.* propose a method to differentiate the cause for frame losses and then, based on this differentiation, suggest a mechanism to control transmit-power and carrier-sense-threshold to increase performance. The differentiation method consists on determining if the losses are caused by interference or by collision. In detail, authors argue that can differentiate between three types of interference as described in Figure 3.2. Implementing this method seems not trivial and need some measurements difficult to obtain.

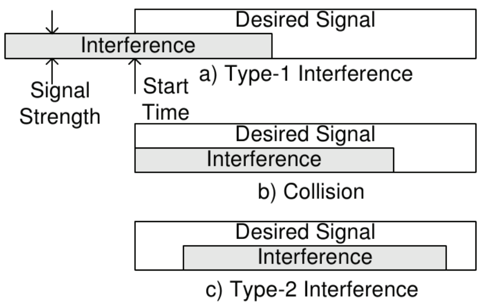


Figure 3.2: Types of Interference. Source: [30]

The adaptation mechanism consists on tuning power and carrier-sense-threshold to eliminate type I1 and I2 of interference. This interference is generated by the hidden-terminal problem so we can say that this mechanism is aimed at mitigating this problem. For eliminating I1 interference the authors arrive to the conclusion that CST should be decrease (and then becoming more sensible). So the mechanism acts decreasing the CST when the FLR caused by I1 is over a certain value. To eliminate losses caused by I2 interference the mechanism increase power so as to increase the $SINR$ at the receiver and then mitigate the effect of the interference signal. The whole mechanism works defining a maximal and minimal acceptable FLR and controls power and carrier sense to maintain FLR among these values.

3.3.2 Physical-Layer Estimation

Mhatre et. al. [33] use a cross-layer approach for power control to attack the interference among APs in HD wireless networks. The problem of throughput starvation because of asymmetric links is addressed and sufficient conditions are given to obtain power control without starvation. This work consider the concepts of contention domain and symmetry so as to analyse the problem. The contention domain of a node i (S_i) is defined as the set of nodes in the network that can generate sufficient interference to suppress the node's transmissions, this means the nodes which power received at node i is higher than a certain threshold. On the other hand, a network $\mathcal{N}$ is symmetric if $i \in S_j \leftrightarrow j \in S_i \, \forall i, j \in \mathcal{N}$. This is important because when a network is symmetric there is no starvation. The authors demonstrate that it is possible to maintain the symmetry of a network if power control goes along with control of the CST. In particular they arrive to the relation

$$P_{TX}^i \alpha_i = K \, \forall i \in \mathcal{N}$$

where $\mathcal{N}$ are the nodes of the network, P_{TX} is the transmit-power and α satisfies this relation $CST^i = (\alpha_i + 1)N$. Thus, the conclusion is that if the transmit-power of a node is high, then its CST should be low (the same result as in [14]).

Afterwards, an optimization framework is presented so as to minimize the potential delays (the inverse of throughput) of all users in the network using power control per-AP. The authors found an objective function which depends on the transmit-power of the AP, the channel gain, the noise power and the interference level. This function is approximated so as to be able to solve it and a distributed algorithm based on Gibbs sampler [6] is used to solve the problem. Finally, an optimum transmit-power vector and CST vector are calculated so as to give each AP in the network the power level and CST to use in order to minimize the potential delay.

For the implementation of the algorithm there must exist communication between neighbouring APs, so the mechanism makes each AP to send information on beacon frames. The mechanism is evaluated by simulations where, after finding the optimum vector with the algorithm proposed and after applied the values to eight APs and 26 clients, the average throughput of the network improves 290% in comparison with fixed power and CST. Also, a small testbed-evaluation is performed but running the algorithm offline, in this case the improvement in total throughput is almost 250%. The huge increase in throughput compared to other proposals could be explained by various factors, for example, a particular topology, but more important is the fact that this mechanism uses total knowledge of the network and an optimization technique. An important drawback of this mechanism is the convergence time which, for the evaluation exposed, is of 30s, a time that can be crucial in mobile networks scenarios.

A similar idea is presented by *Liu et. al.* [29] based on a *iterative greedy algorithm* to optimize power and carrier-sense threshold. The mechanism consists of two steps: first, collect environment information and create a conflict graph and second, apply an algorithm which removes as many edges as possible of the graph. In a conflict graph there is a node for each link in the network and an edge between two nodes if the links they represent cannot transmit concurrently. For creating this graph authors use the protocol model and define a threshold ($SINR_{thrsh}$) which determines the minimum $SINR$ to allow a correct reception. The algorithm consists on selecting the power that would remove the biggest quantity of edges from the graph by determining for each link the power that would allow simultaneous transmissions. For that, the algorithm uses the P_{TX} of the other links and the RSS. To be able to apply this mechanism on a distributed manner each node creates the entire graph and for achieving this all nodes need a complete knowledge of the P_{TX} and the RSS of all other nodes. So, the information of the used P_{TX} and the estimated path loss ($L = RSS - P_{TX}$) is added to each frame, and nodes are allowed to sniff for transmissions of other nodes to learn the topology faster.

3.3.3 Hybrid Estimation

In the work of *Fuemmeler et. al.* [14] a vague practical mechanism is presented but it is worth mentioning it because of its analysis about the conditions for improving spatial reuse. The analysis is based on the idea that more spatial reuse implicates collision prevention and though, they found conditions for this. The most important result of this analysis is that the product between transmit-power and carrier-sense-threshold should be constant, as later works also found.

$$P_{TX}CST = \beta$$

This conclusion leads the authors to an interesting reasoning: if a node select a high power it should be more sensitive for transmissions that are farther away (there is a bound in the interference a node can make) and so, the transmit-power on a given link impacts on the collisions on that link. Thus, the authors propose that is reasonable to think that a collision could be avoided with the correct transmit-power and arrive to these two functions for controlling power and carrier-sense-threshold:

$$P_{TX}(x) = \frac{\gamma\eta + \sqrt{\gamma^2\eta^2 + 4k\gamma\beta g(x)}}{2g(x)}$$

$$CST(x) = \frac{\beta}{P_{TX}(x)}$$

where P_{TX} is the transmit-power, x the distance to the receiver, $g()$ the gain function, η the thermal noise, γ the $SINR$ threshold at which the transmission is successful and k, a constant from authors analysis representing the quantity of interferer nodes. The authors also suggest to bound β by the following formula:

$$\beta \leq \frac{P_{TX}^{max}}{k_{max}}\left(\frac{P_{TX}^{max} g(x_{max})}{\gamma} - \eta\right)$$

The mechanism consist in using these functions to select the transmit-power and the carrier-sense-threshold, for achieving this, some of the parameters in the formulas need to be estimated. For the estimation of the gain function to the receiver $g(x)$, the authors suggest to add the information of the power used to DATA and RTS frames. Then, the receiver estimates the gain using the RSS and some interference model and adds it to the ACK and CTS frames. The value of η and γ are supposed to be known (similarly to other works).

Then power and carrier-sense-thresholds are selected varying the value of k. The mechanism to vary k consists on frame losses, a failure generates an increase and a successful transmission a decrease. Summarizing, this work uses a combination of link-layer estimation and physical-layer estimation plus a mathematical model to jointly tune the transmit-power and the carrier-sense-threshold so as to increase spatial reuse.

3.4 Conclusions

Within the parameter-adaptation mechanisms we can identify three categories depending on how to estimate channel conditions: based on link-layer estimation, based on physical-layer estimation and based on hybrid estimation (see Diagram 3.1). When considering a distributed implementation which does not modify the IEEE 802.11 standard the link-layer estimation appears as the most appropriate choice, as eight out of the nine link-layer-estimation based mechanisms evaluated do not need modifications to the standard. On the other hand, from the eleven physical-layer-estimation and hybrid-estimation based mechanisms reviewed only one (PMAC) does not need modifications to the standard.

Trying to compare the mechanisms based only on their description from the articles results very difficult. Additionally, the evaluations made by different authors differ between each other in setup and scenarios. Even worst, only a few compare their results with previous work. May be, this is caused because non of the mechanisms have their source code publicly available. A thorough and reproducible comparison where all the mechanisms are evaluated on the same conditions is needed so as to obtain some conclusions.

Chapter 4

Experimental Comparison

Based on the conclusions from the state-of-the-art evaluation, in this chapter, we implemented and compare some of the mechanisms presented previously. We focus on the mechanisms that use link-layer information to estimate channel conditions. Our goal is to evaluate and compare their performance and behaviour on a set of scenarios taking special care in particular scenarios which are known to be problematic.

4.1 Experimental Setup

We have experimentally compared the performance of the following mechanisms in some representative scenarios: PARF, Adapting PARF (APARF) and Minstrel-Piano (MP). We disregard PASA because its similarity with PARF, ConTPC because it needs standard modifications and let Symphony aside because its requirement of synchronization between APs, a difficult and uncommon task in current networks. To compare these mechanisms with an ideal solution we have also experimented with different base-line optimal solutions that we explain later.

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.
- *Average transmit power*, which measures the power per second used by a node to transmit.
- *Power efficiency*, as the ratio between the link throughput and the *average transmit power* that link uses.

- *Throughput fairness*, which measures the fairness (with the Jain's fairness index [19]) between each per-link throughput.
- *Per-link transmission opportunity*, which is defined as the fraction of time that the medium is available for transmission on a particular node.
- *Transmission opportunity fairness* (with the Jain's fairness index), as the fairness between the per-link transmission opportunities.

The evaluation was conducted on the NS3 Network Simulator [2] which we extend to add 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 online in [43].

4.2 Scenarios

For the evaluation, we consider three different scenarios: i) a simple wireless link between one AP and one STA where we study the impact of signal attenuation on the performance of the link; ii) a scenario with two interfering AP to STA links (two different APs and two different STAs); and iii) a more realistic scenario with 4 APs deployed on a 50 meters side square, and 10 STAs disposed randomly inside the square. For the second case we consider four different deployments following the cases mentioned in Chapter 2 (remember that cases 3 and 4 are equivalent). Then the deployments defined are:

- Overlapping (Case 1)
- Exposed terminal (Case 2)
- Hidden terminal (Case 3 and 4)
- Possibly disjoint (Case 5)

All the experiments use the IEEE 802.11b/g standard which provides 12 different data rates: 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48 and 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 modeled 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 configured to generate frames of 1500 bytes of size.

4.3 Simple Link Scenario

In this section, we vary the distance between the AP and the STA in order to have different attenuation levels and we calculate the performance of each mechanism. Besides the transmit-power-control mechanisms we also experiment with two baseline mechanisms: fixed maximum transmit power with data rate adaptation (AARF [27]) and fixed data rate (6 Mbps) with maximum transmit power. We start with the STA and the AP in the same spot and then move the STA 10 meters every 100 seconds. We show the results for *per-link throughput*, *average transmit power* and *power efficiency*.

Setup

All of the experiments are executed 20 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 90% probability. In what follows we will show all the results graphically but the numerics results can be found in Appendix A.

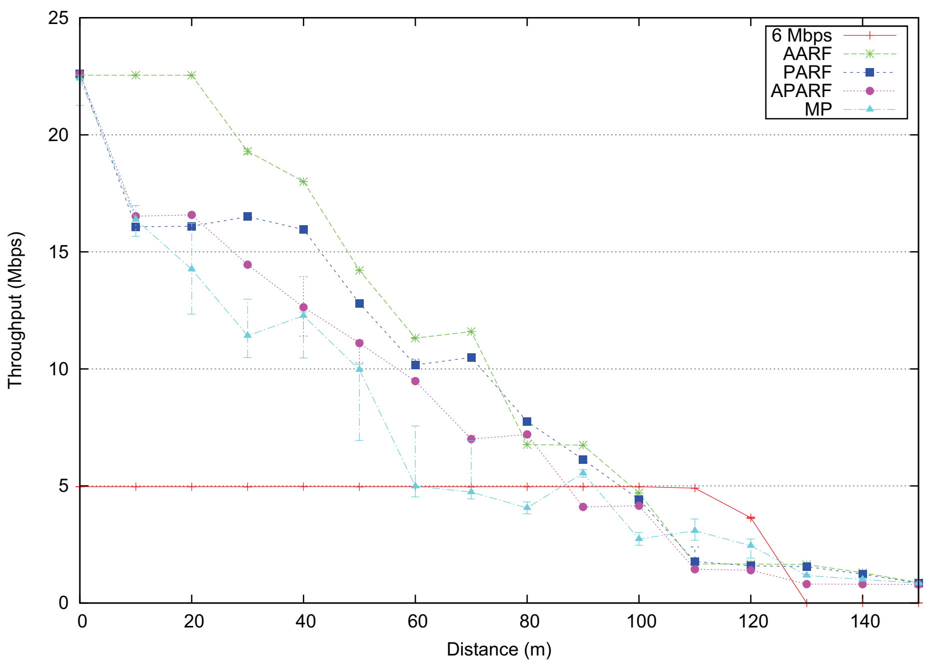


Figure 4.1: Throughput vs. Distance Between AP and STA

Results

Figure 4.1 shows the average per-link throughput during 100 seconds for each distance. It can be seen that, as expected, the throughput decreases with distance and all transmit-power-control mechanisms behave in a very similar manner. The difference between data-rate-only adaptation (AARF) and transmit-power and data-rate adaptation (PARF, APARF, and MP) can be explained by the overhead generated by power control when trying other powers (remember that the three mechanisms are probing based). Figure 4.2 shows the *average transmit power* (ATP) consumed by each mechanism. To obtain this value we calculate the power consumed by each frame transmitted as the product of the transmit power (P_{TX}) and the transmission time of the frame (T_{TX}). Then we sum this value for all transmitted frames (N) and divided by the total transmission time (T), $ATP = \frac{\sum_{i=1}^{i=N} P_{TX}^i * T_{TX}^i}{T}$. As the transmission times depend on the data rates, when the data rate decreases the power consumed will increase. So, as depicted in the figure, when the distance between transmitter and receiver increases (and data rate decreases) the power consumed is higher. We can clearly see the difference obtained by the transmit-power-control algorithms (PARF, APARF, and MP). In particular, APARF and MP considerably decrease the power used in transmissions, meaning they achieve to choose a better (higher) data rate.

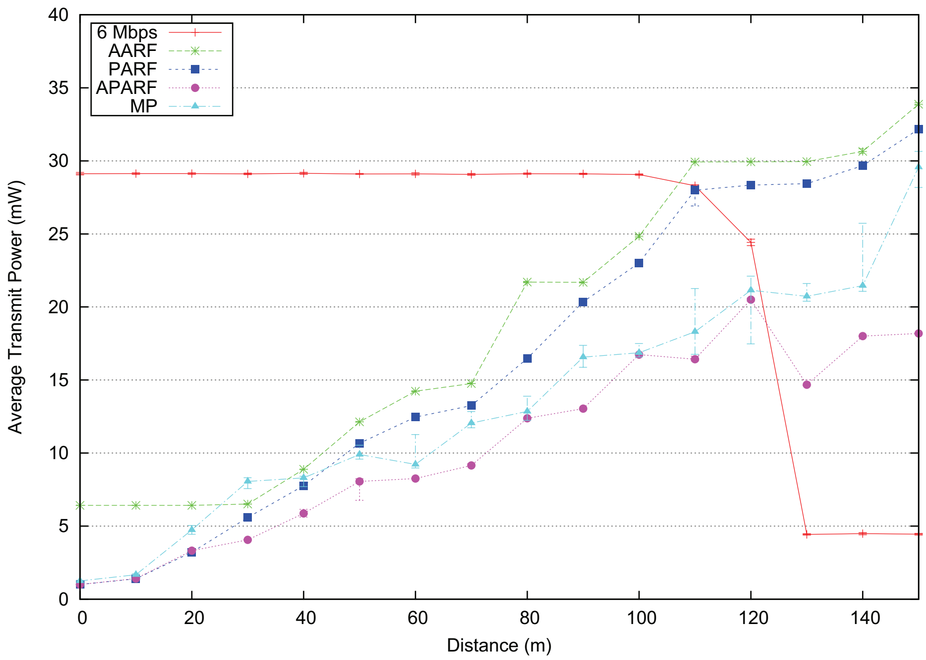


Figure 4.2: Average Transmit Power vs. Distance Between AP and STA

The last metric studied for this scenario is *power efficiency*. In this case, we calculate the ratio between the per-link throughput obtained and the power consumed for the transmissions. Figure 4.3 shows that, as expected, the transmit-power-control mechanisms (PARF, APARF, and MP) consume much less power to transmit at shorter distances. Beyond approximately 50 m, the efficiency drops and is very similar to data-rate-only mechanism (AARF).

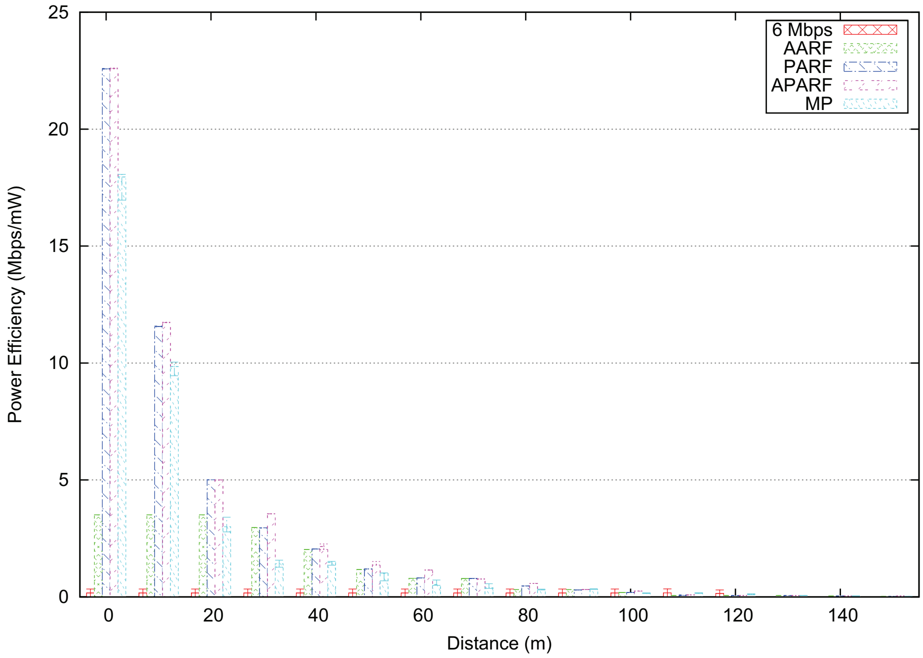


Figure 4.3: Power Efficiency vs. Distance Between AP and STA

Discussion

As all the evaluated mechanisms try to first maximize throughput and then minimize transmit power, when the medium does not allow a transmit power reduction at the current data rate (in this case, when the distance is bigger than 50 m) maximum transmit power is always used. The transmit power can be reduced –and so the interference– if the used mechanisms allows a transmit power reduction, even if that has an impact on the throughput. In some cases, a mechanism like this can improve the global network performance.

These results show us the capabilities of the transmit-power-control mechanisms for short distances but also their limitations. Moreover, these experiments operate as a validation of our implementations given that our results are consistent with those in [9].

4.4 Two Links Scenario

In the two-link scenario, we show how the different mechanisms behave in the presence of interference, how this behaviour impacts on the global network throughput and how fair is the channel distribution between both links. In particular, we want to stand out four configurations: APs with possibly disjoint ranges, with overlapping ranges, the well-known case of the hidden terminal and the case of the exposed terminal. These different configurations where chosen because they represent possible problematic cases which are commonly found in real deployments.

Setup

For all the experiments in this scenario, 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 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. In Appendix A we show the numeric results of all the experiments.

For each of the four configurations, we show the performance of the three transmit-power- and data-rate-control mechanisms (PARF, APARF and MP), the data-rate-only adaptation mechanism (AARF), and two base-line solutions: the optimal transmit power selection for higher global network throughput (*NetTh*) and the optimal transmit power for best throughput fairness (*Fair*). Additionally, we also depict the no-interference case (*NoInterf*) as a throughput upper bound.

The optimal values for the base-line solutions are obtained trying all the possible transmit power combinations for each link and using AARF for rate control. To calculate fairness we use the Jain's fairness index and we consider optimal the solution with the highest global network throughput and a fairness index greater than 0.95. 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.

4.4.1 Results for Possibly Disjoint Coverage

This configuration consists of two links with very good throughput that are separated at a distance such that the transmit power can be set in a level that eliminates interference between both links. For the simulation the distance between each AP and its STA is 5 m and the APs are separated by a distance of 200 m (see Figure

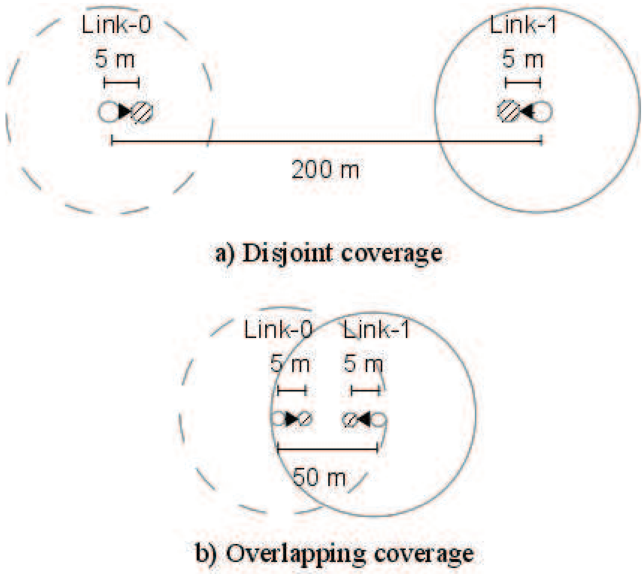


Figure 4.4: Disjoint and Overlapping Coverage Configurations.

4.4a).

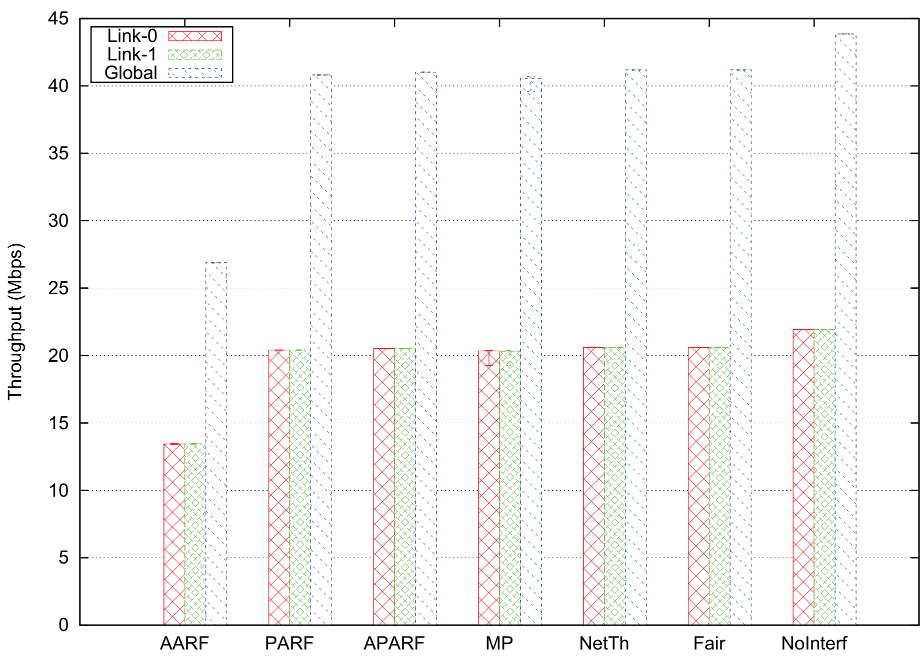


Figure 4.5: Throughput in Possibly Disjoint Configuration.

In Figure 4.5 we can see the *per-link throughput* and the *global network throughput* obtained by each mechanism. The transmit-power-control mechanisms (PARF, APARF, and MP) improve global network throughput by a 52% getting very close to the optimum solution. This scenario can be considered the best-case for the transmit-power-control mechanisms because they can manage to isolate the links.

4.4.2 Results for Overlapping Coverage

This scenario is the opposite of the previous one; in this case there is no place for improvement because the two links are very close. In our simulation we place the APs at a distance of 50 m and the distance between the AP and it corresponding STA is of 5 m, as we show in Figure 4.4b.

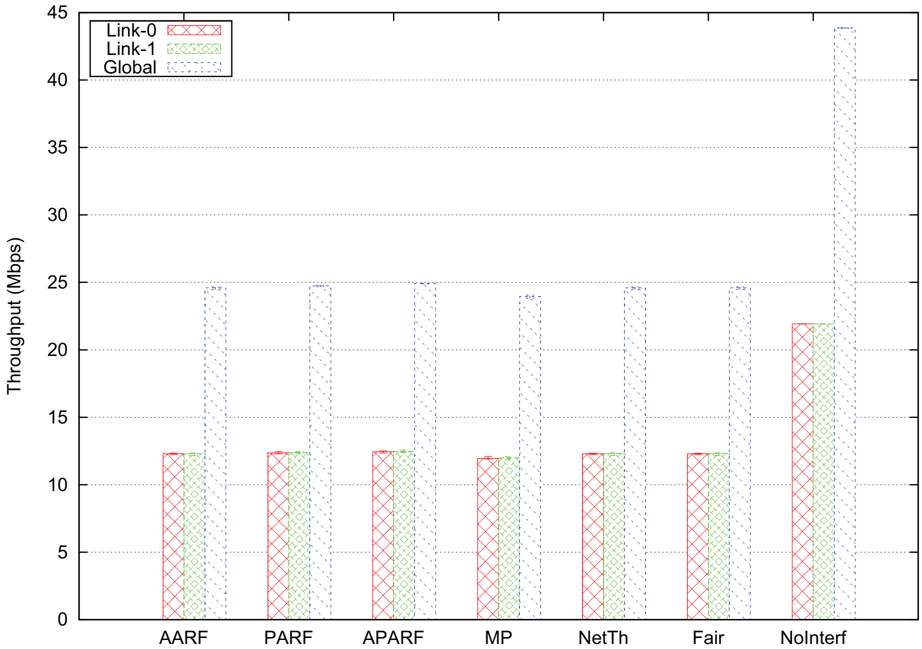


Figure 4.6: Throughput in the Overlapping Ranges Configuration.

The results depicted in Figure 4.6 show that power control cannot cause any throughput improvement on those links, but, it can also be seen, by the result of the base-line solution *NetTh*, that there is no better solution either. However, it is important to note that all power control mechanisms reach the minimal power, hence, the interference generated to the surroundings and the power consumed is much lower than without making power control.

Summarizing, Figures 4.5 and 4.6 show that the transmit-power-control mechanisms evaluated do not reduce performance in the simplest scenarios and moreover, make improvements when possible.

4.4.3 Results for the Hidden Terminal Case

In this experiment we evaluate the mechanisms in a configuration that reproduces the hidden-terminal problem. As we mention before, this problem is generated when an AP cannot sense the signal transmitted by the other AP, assumes that the medium is free and transmits, interfering both signals at the STA (Case 3 and 4 from Figure 2.5). A solution to this problem is given by the IEEE 802.11 standard with the definition of the RTS/CTS frames. This solution has a known issue: the overhead caused by sending the RTS/CTS frames before transmitting reduces the global network throughput. We performed an experiment to see how the mechanisms behave in this scenario without using RTS/CTS and, in particular, if transmit power control can solve this problem. Our simulation setup consists of the APs and STAs placed as shown in Figure 4.7a.

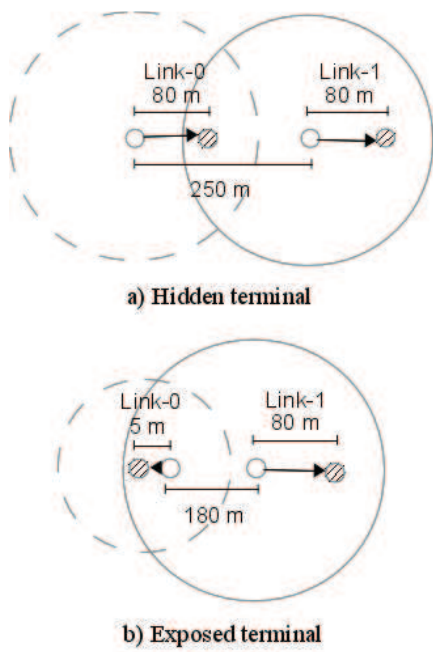


Figure 4.7: Hidden and Exposed Terminal Configurations.

Figure A.3 shows the per-link and global network throughputs obtained by the different mechanisms. AARF, PARF and APARF have all similar results where the Link-0 has a very bad throughput caused by the interference at the STA. As can be seen, using RTS/CTS improves the throughput of Link-0, minimizing the problem but causing a degradation of the global network throughput. This result is consistent with the experiments in [49] which show that RTS/CTS mechanism, when used in high-speed networks degrade performance even in the case of hidden-terminal.

The MP mechanism show an interesting performance. It allows the Link-0 to

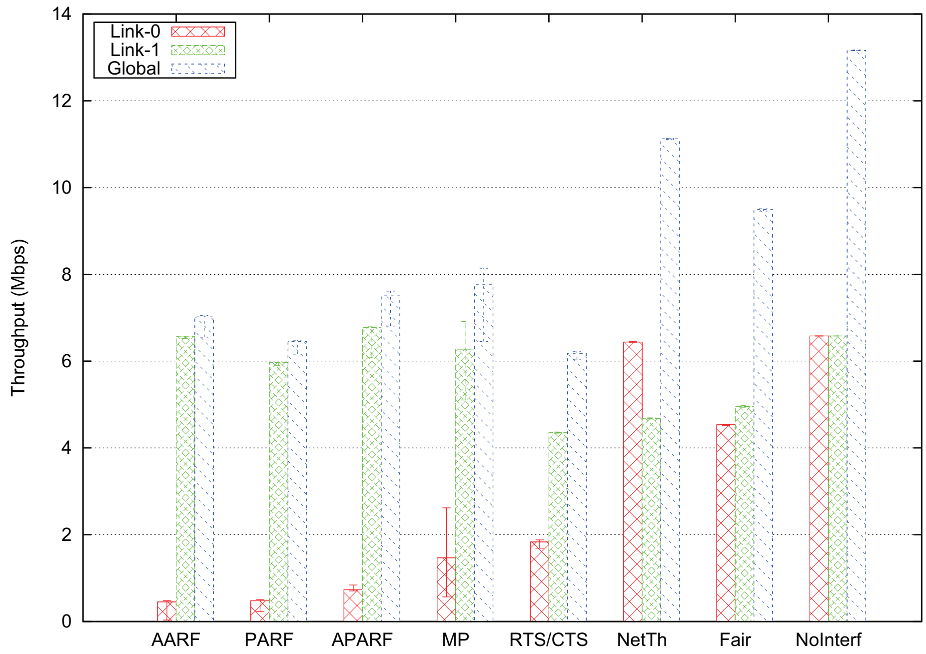


Figure 4.8: Throughput in Hidden Terminal Configuration.

obtain a better throughput but with the cost of throughput reduction on Link-1 making the obtained global network throughput similar to the other transmit-power-control mechanisms. By a deep study of this algorithm we believe that the improvement on the Link-0 throughput is caused by the procedure of probing lower transmit power levels, what reduces the interference on the station. The results of experimenting with the base-line solution *NetTh* show that there is room for improvement by doing the appropriate transmit power control or, all the more, a hypothetically better transmit-power-control mechanism could supply a solution to the hidden-terminal problem. The optimal solution is reached when the power level in Link-1 is reduced to a level such that it does not generate interference in the problematic station. The mechanisms studied fail to find this solution because all of them are based on reaching the best local throughput and then reducing the transmit power. A mechanism where it is allowed to reduce link throughput in order to improve global throughput would be more suitable for this case.

4.4.4 Results for the Exposed Terminal Case

Finally, we consider a problem generated by the transmit-power-control mechanisms, the exposed-terminal problem caused by asymmetric links. This problem appears when there are links with different quality and therefore the power control choose different power for each one. This causes the scenario described as Case 2 in Figure 2.5. The link with the higher power uses the medium every time it needs because it cannot sense the link with lower power and, the lower-power link sense busy the medium more often and therefore reduces its transmissions. Figure 4.7b shows the experiment setup and the results can be seen in Figure 4.9.

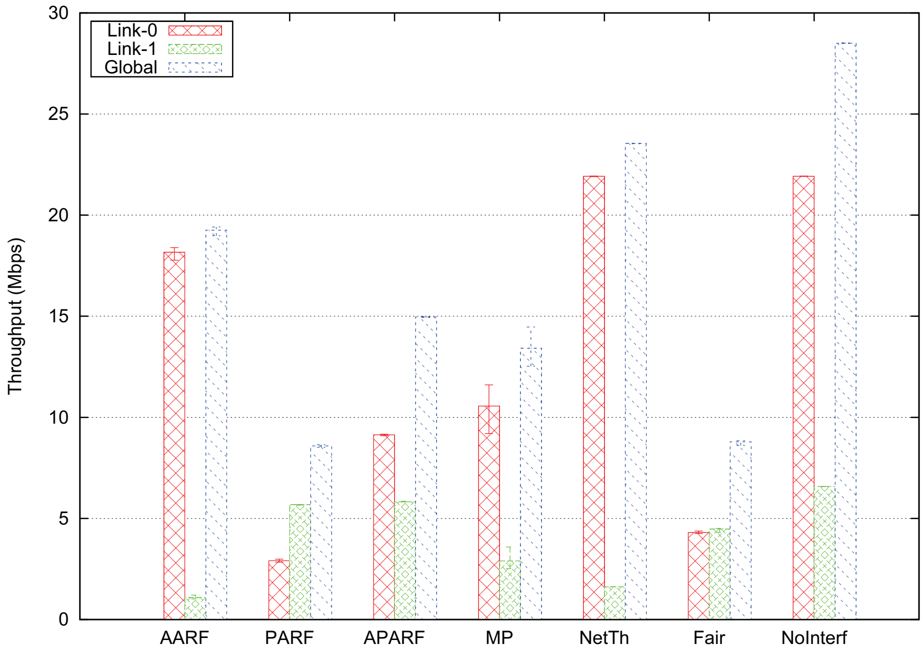


Figure 4.9: Throughput in the Exposed Terminal Configuration.

The first thing we can notice in Figure 4.9 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 almost 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 exposed-terminal problem. In Figure 4.10 we can see how most of the mechanisms reduce the average transmission opportunity for Link-0. The different performances among the mechanisms can be explained by the strategy to reduce the transmit power of each one. In this case, the more dependent on loss rate is the mechanism, the worse is its performance because the throughput degradation is not caused by the frame losses but by the reduced probability of finding the medium available. For example, as MP uses an estimate of the throughput to make its decisions, it obtains a better performance for Link-0 than the others.

Defining an optimum solution for this case is not easy as the links qualities are not symmetric. For example, we could want to maximize global network throughput

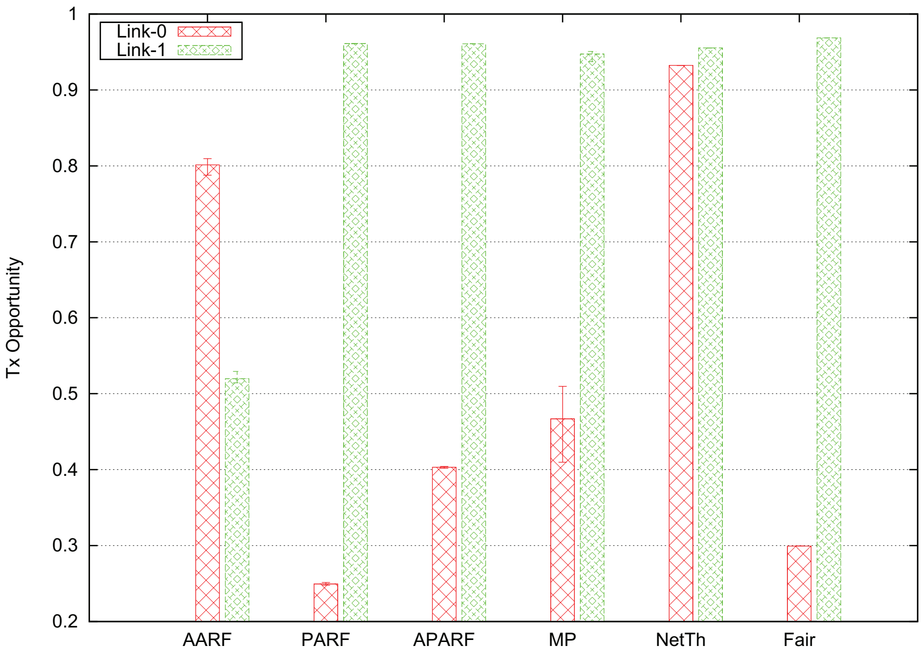


Figure 4.10: TX Opportunity in the Exposed Terminal Configuration.

by making the better-quality link to get a higher throughput than the poor-quality link or, we could try to maximize the throughput fairness. For the case of maximizing global network throughput, it is clear that the transmit-power-control strategy does not help and, even more, generates a problem.

4.5 Random Scenario

Finally, in this experiment we test the behaviour of the mechanisms evaluated in a more realistic scenario of a HD wireless network. It consist of 4 APs disposed on the middle of each side of a 50m side square and 10 STAs placed randomly inside the square. The STAs are configured to associate to the closer AP and the APs send 54Mb/s CBR traffic to each client connected. In Figure 4.11 we depict a possible deployment of this configuration.

For each mechanism the experiment was run 50 times varying the position of the clients. In Figure 4.12 we show the median of the total network throughput, the 25% and 75% quantiles and the minimal and maximal total 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 Minstrel-Piano outperforms the rest of the algorithms and surprisingly APARF has a very bad performance. We let for future work the study of this particular

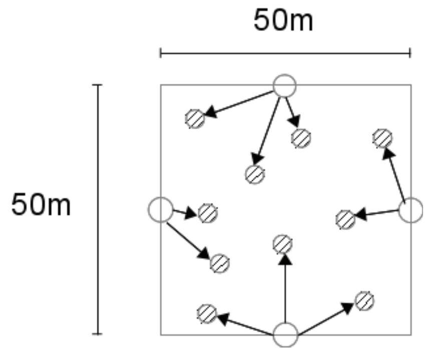


Figure 4.11: A Possible Deployment of the Random Scenario.

result of APARF mechanism, however, we validate that the result is not because of an experimentation error.

Another important aspect to consider in this scenario is the fairness between the different links. For example, a mechanism can achieve good total network throughput but by suppressing some links and giving high throughput to others. In Figure 4.13 we show that this is not the case. Minstrel-Piano, the one that achieves best throughput maintains the same fairness as the other mechanisms. However, it is important to notice that fairness is not excellent in any of the mechanisms (in this case the fairness can take values between 0.1 and 1) giving us the idea that in all scenarios exist good links and bad links.

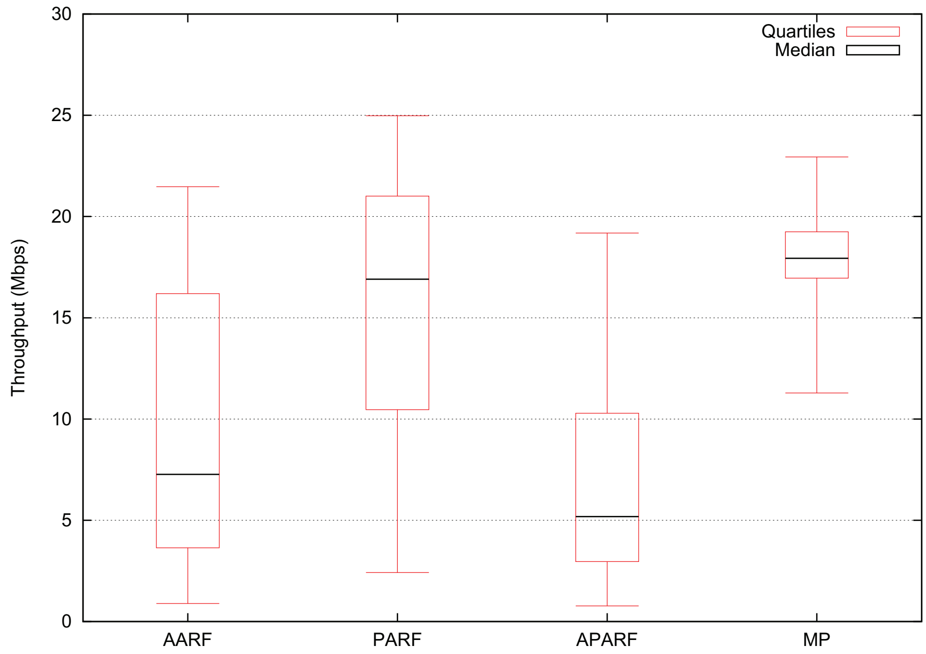


Figure 4.12: Throughput in the Random Scenario.

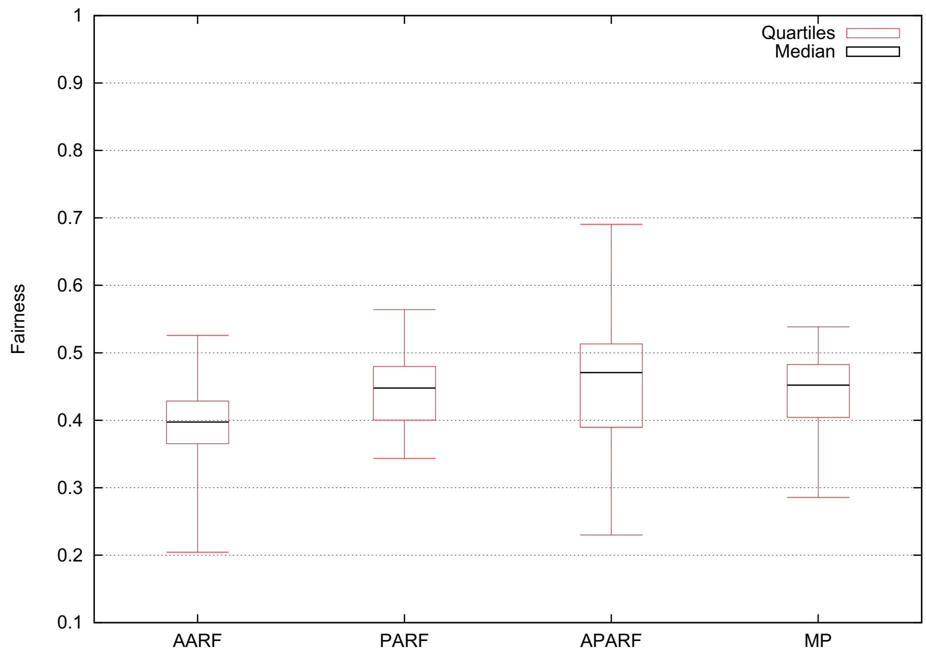


Figure 4.13: Fairness in the Random Scenario.

4.6 Conclusions

The 2-link scenario experiments were designed to show the strengths of parameter adaptation mechanisms but also to evidence the problems of the mechanisms studied. This scenario does not represent a high-density WLAN, and we are conscious of that, but it fulfill our purpose to show parameter adaptation challenges. On the other hand, the random scenario with only 4 APs in a 50m square can be considered a small high-density deployment if we take into account that in the scenario can be more APs working in different channels, for example 16 APs in total, working in 4 different channels.

In our opinion, two interesting conclusions can be drawn from the results of these experiments. The first one is that, as suggested by the results in the three scenarios studied, a good approach to power control can considerably improve performance in HD wireless networks. It is important to notice that, surprisingly, in the majority of works that present new mechanisms, experiments with the Random Scenario are not performed. So, we consider these results are an important contribution to the evaluation of power-control mechanisms.

The second conclusion we arrive to is that there exist two particular node configurations where power-control mechanisms fail to improve performance: the hidden-terminal and the exposed-terminal configurations. In particular, we believe that the exposed-terminal configuration is the most problematic, as in this case, power-control mechanisms generates starvation which results on an important degradation of throughput.

Chapter 5

A Starvation Free Mechanism

Considering the starvation problem caused by existing power-control mechanisms that we found in Chapter 4, we propose to solve this problem by implementing a power, rate and carrier-sense-threshold control mechanism based on link-layer estimation. The idea of controlling carrier-sense-threshold has been suggested in many works (as we show in Chapter 3) as a way to avoid asymmetries caused by power control. However, to the best of our knowledge, does not exists a mechanism that jointly adapts power, rate and carrier-sense-threshold based on link-layer estimations.

Though, in this chapter we present two novel mechanisms for controlling IEEE 802.11 parameters with the objective of avoiding starvation in the network. Both mechanisms are based on an existing rate adaptation algorithm called *Robust Rate Adaptation Algorithm* (RRAA) [50] and on a modification of it done in [42] called RRAA+. In Section 5.1 we present *Robust Rate and Power Adaptation Algorithm* (RRPAA) an adaptation where power control is added to RRAA+. We show that this mechanism has some advantages over previous mechanisms but still suffer from starvation. Then, in Section 5.2 we extend RRPAA to also control carrier-sense-threshold and mitigate the starvation problem. *Power, Rate and Carrier-Sense-threshold control* mechanism consist in controlling data-rate, transmit-power and carrier-sense threshold so as to avoid asymmetric links and reduce starvation. Finally, in the last section we evaluate both mechanisms and compare them with existing solutions.

5.1 RRPAA: A New Power Control Mechanism

5.1.1 RRAA+ Basic

As we mention before, our new power control mechanism (RRPAA) is based on a rate adaptation mechanism called RRAA+ and, in particular, on a simplification of it called RRAA+ Basic. RRAA+ Basic uses a link-layer statistical approach for estimating channel conditions and do not uses probing frames. This mechanism calculates the frame loss rate (FLR) on a window of frames and adapt data rate to maintain FLR on certain values. It is similar to Minstrel [46] but simpler and without using probing frames. The RRAA+ Basic mechanism has two interesting ideas that make it different from almost all other mechanisms. The first one consist on the thresholds used for deciding a rate increase or decrease.

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 authors define the *critical* FLR of a rate R_i 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.

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

then

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

This means that, $FLR_{critical}(R_i)$ 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 $P_{MTL}(R_i) = \alpha * FLR_{critical}(R_i)$ with $\alpha \geq 1$. For calculating the $FLR_{critical}$ for each rate, we need the transmission time for each rate, which assuming a fixed frame size is very easy to calculate.

For selecting the values of P_{ORI} the authors suggest to use 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. This mechanism, as said by its name, is an opportunistic method and can generate rate fluctuations if β is chosen too small or it can never find a better rate if β is to high.

Hence, Ramachandran et. al. [42] introduce the other idea we mentioned, to use a *Probabilistic Rate Increase* (PRI) mechanism so as to help the algorithm to converge. The PRI mechanisms consist on maintaining for each data rate the probability to move to this rate from the next lower rate. These probabilities are reduced when the mechanisms 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.

In next subsection we explain our extension to add power control to this mechanism and provide deeper explanation of these ideas.

5.1.2 Adding Power Control to RRAA+

For RRPAA we took the ideas described earlier 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 RRPAA 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.

The algorithm considers three different cases (see Figure 5.1). 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.

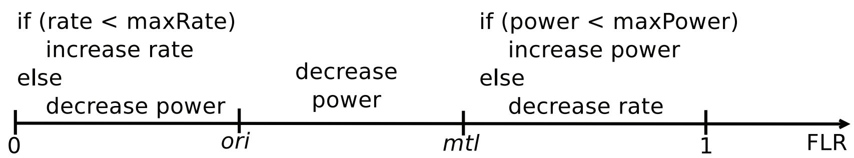


Figure 5.1: RRPAA Decisions

We also took the idea of the PRI mechanism so as to improve the convergence of the algorithm. The implementation consist on a table (priTable) where for each rate and power combination we save the PRI probability. These probabilities are modified following a *Multiplicative Increase Multiplicative Decrease* (MIMD) mechanism with the parameters γ and δ. When the power is increased or the rate decreased the probability for the current rate and power combination is decreased by the γ factor (see lines 2 and 5 of Algorithm 5.1). On the other side, when the conditions for a rate

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

Algorithm 5.1: RRPAA Power and Rate Adaptation Algorithm

increase or power decreased are satisfied, the probability of all the lower rates or the higher powers are increased using the δ value (see lines 10 and 16 of Algorithm 5.1). 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. When these conditions satisfy a random variable is draw and if the value is lower than the PRI probability the action is taken. It is important to note that this algorithm is executed on a per-link basis, so the current power, rate and priTable are maintained for each existent link.

For the thresholds parameters we use the same values as in [50] ($\alpha = 1.25$ and $\beta = 2$) and we calculate the $FLR_{critical}$ for a frame size of 1500 bytes, the results are shown in Table 5.1. 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.

Rate (Mbits/s)	Critical FLR (%)	P_{MTL}	P_{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 5.1: Thresholds for RRPAA

This mechanism has some advantages over previous works. The most important is the usage of two different thresholds for rate and power increase or decrease. This generates a zone where the mechanism uses an intermediate rate with an intermediate power. This characteristic permits us to reduce power (and therefore, interference) in cases where most other algorithms would not be capable. Another existing mechanism that also allows this is Minstrel-Piano, and as we will show later is the only one whose results are very similar to those of our mechanism. However, RRPAA has two important differences from Minstrel-Piano. MP use long-term smoothed (EWMA) estimation for the FLR while in RRPAA we use only the last FLR calculated. The applicability of one or other mechanism are to be studied yet, nevertheless, while using EWMA adds complexity and consumes resources, experiments done in some works [5, 50] show that the long-term estimation does not provide any gain. 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 optimal rate and power estimations given the low statistical significance of a probe frame sent every 10 frames (the default value in MP). Moreover, another drawback we found when using MP in our experiments is that is has many configurable parameters (mainly caused by the complexity of the mechanism itself) making the usage of the mechanism very difficult.

5.2 PRCS: Power, Rate and Carrier-Sense-Threshold 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 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.

5.2.1 Starvation and Transmission Opportunity

As we mention previously 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.

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. 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 two ideas to detect starvation using TXOP. One is to detect TXOP variations due to power control, if when PRCS decrease the power the TXOP increases means the mechanism is generating starvation. The other idea is to estimate the value of the expected TXOP based on some local measurements. This idea was introduced by Hua and Zheng in [16], it is proposed for a single interferer link and follows the reasoning bellow.

Lets define the transmission probability as $P_{TX} = \frac{T_{TX}}{T}$, the busy probability as $P_{BUSY} = \frac{T_{RX}+T_{BUSY}}{T}$ and idle probability as $P_{IDLE} = \frac{T_{IDLE}}{T}$. Then, as a node only transmits when the medium is free, the transmission probability can be written as $P_{TX} = P_{IDLE} * \tau * RTT$ where τ is the probability to transmit on an idle slot and RTT is the time needed for a transmission and the reception of the corresponding ACK (the time occupied by a transmission). In the case of asymmetric sensing, where we have two nodes a and b, the majority of frame losses in a are produced by collisions (the nodes transmit simultaneously) because transmitter b do not sense a. So, the loss probability in a can be calculated as the transmission probability of node b and then the FLR can be estimated by $FLR_a = P_{IDLE_b} * \tau_b * T_D$ where T_D is the time for the transmission of the data frame (the time both transmissions would overlap). Then $P_{TX_b} = \frac{RTT}{T_D} * FLR_a$ and by definition $P_{TX_b} = P_{BUSY_a}$ (because as we only have two nodes $P_{IDLE_a} = P_{IDLE_b}$). So by measuring FLR we can find the expected P_{BUSY} and then, if the measured TXOP is higher than the expected P_{BUSY} we have starvation.

5.2.2 Carrier-Sense-Threshold Control

As mentioned before, PRCS adds carrier-sense-threshold control to RRPAA to deal with asymmetric links. This approach is motivated by the works of Fuemmeler et. al. [14] and Mhatre et. al. [33] which propose to maintain the product $P_{TX} * CST$ constant so as to avoid asymmetries and the 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 way, when the losses increase more than P_{MTL} and we are using a CST higher than the minimal 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 5.2 we depict a pseudocode of the carrier-sense-threshold control, the rest of the algorithm is identical to RRPAA.

```
if sentFrames >= ewnd then
    P_BUSY = busyTime/ett
    if P_BUSY > busyTh then
        cst+ = η
    end if
end if
if loss > pmtl(rate) and power < maxPower then
    priTable[rate][power] / = γ
    power + +
else if loss > pmtl(rate) and power == maxPower then
    if cst > minCst then
        cst− = η
    else
        priTable[rate][power] / = γ
        rate − −
    end if
end if
```

Algorithm 5.2: PRCS Carrier-Sense-Threshold Adaptation Algorithm

As we want to control CST per link we need to measure the P_{BUSY} for each link. To achieve this we have a counter where we accumulate the periods of times the 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. Because, for each frame sent we can access the destination MAC of the fame and so all the busy periods between the previous frame sent and the current correspond to the link which STA has that destination MAC (see Algorithm 5.3).

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

Algorithm 5.3: T_{BUSY} Measurement Algorithm

5.3 Evaluation and Comparison

In this section we will show the results of executing RRPAA and PRCS in the same scenarios and setups of Chapter 4 where we tested the existent mechanisms. For each scenario we compare RRPAA and PRCS with the mechanism that shows the best performance on it and with the base-line solutions.

5.3.1 RRPAA Evaluation for the Simple Link Scenario

For the Simple Link Scenario we only show the performance of RRPAA because it behaves identically to PRCS (as there is no interferer the CST is not modified). In this case we compare RRPAA with all the other power control mechanisms (PARF, APARF and MP) and with the rate-only adaptation AARF as they all show similar results. Remember that in this scenario we start with the STA and the AP in the same spot and then move the STA 10 meters every 100 seconds. We show the results for *per-link throughput*, *average transmit power* and *power efficiency*.

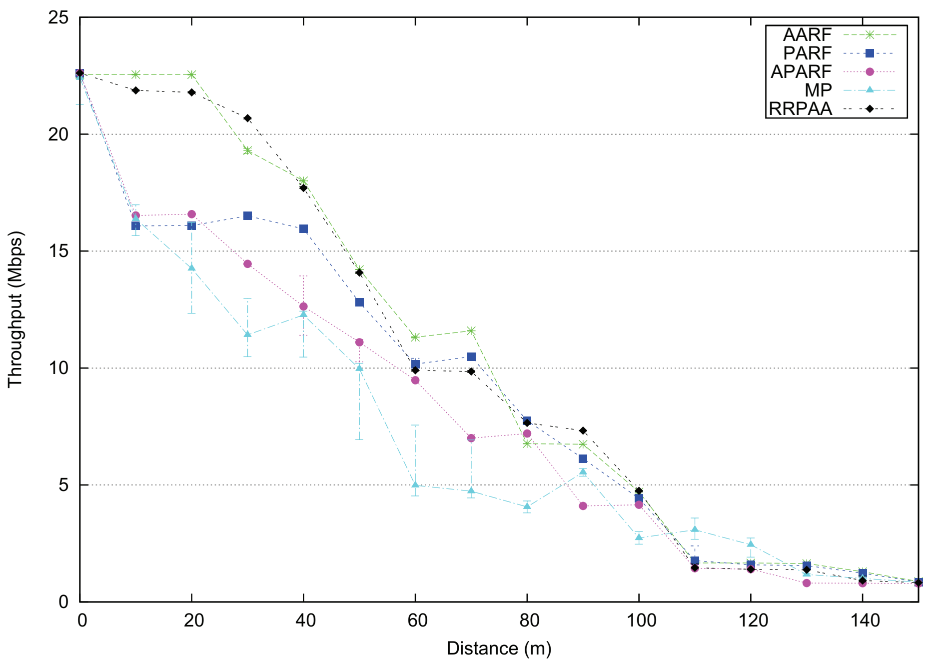


Figure 5.2: Throughput vs. Distance Between AP and STA for the Simple Link Scenario

As we can see in Figures 5.2 and 5.3, RRPAA shows very good results in *average per-link throughput*, reaching the values obtained by the rate-only adaptation, and similar results to MP and APARF in *average transmit power*. A better comparison of the mechanisms can be seen in Figure 5.4 where we show the *power efficiency*

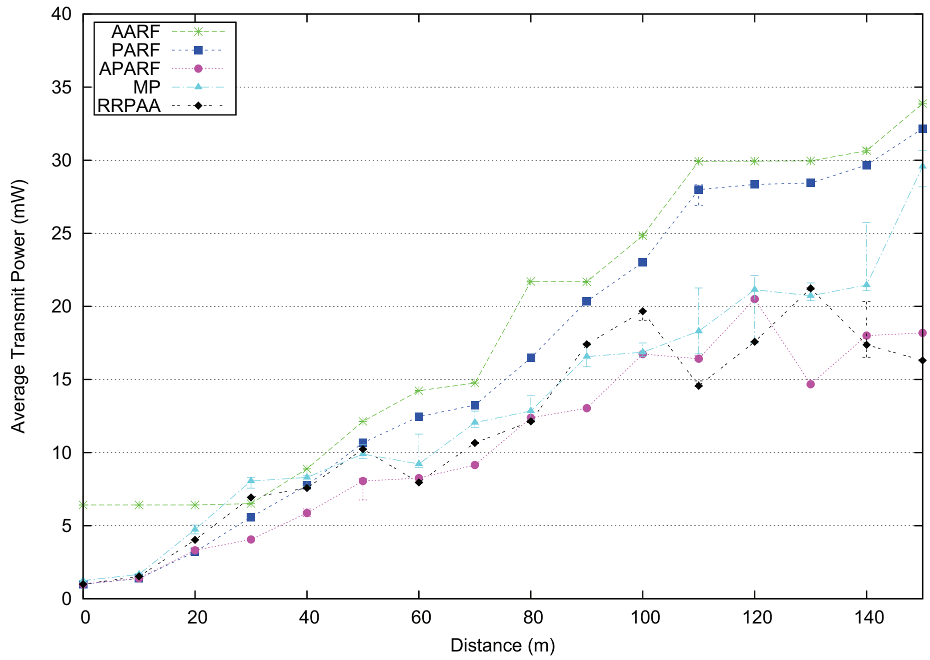


Figure 5.3: Average Transmit Power vs. Distance Between AP and STA for the Simple Link Scenario

(the ratio between the per-link throughput obtained and the power consumed in transmissions). Examining Figure 5.4 we can see that RRPAA achieves a very good power efficiency, outperforming in many cases all the other mechanisms. From these results we can argue that RRPAA is more effective when selecting the optimal rate and power and therefore do not suffer from the overhead of the other power control mechanisms. To confirm this hypothesis we register the rate and power modifications of APARF, MP and RRPAA.

In Figures 5.5 and 5.6 we show the power and rate changes of APARF, MP and RRPAA for a scenario where the STA starts at 40m from the AP and after 100 seconds it is moved 10m farther from the AP until 60m. We can clearly appreciate how RRPAA rapidly converge to a combination of power and rate. On the other hand, APARF and MP keeps varying power or rate, and probing with values very different from current selection. In particular, MP has a very unstable behaviour which explains the low performance we saw previously. Even more, the not-probing approach RRPAA implements does not jeopardize the speed to react to a change in channel conditions, as it can be seen in rate and power decrease at 100 and 200 seconds.

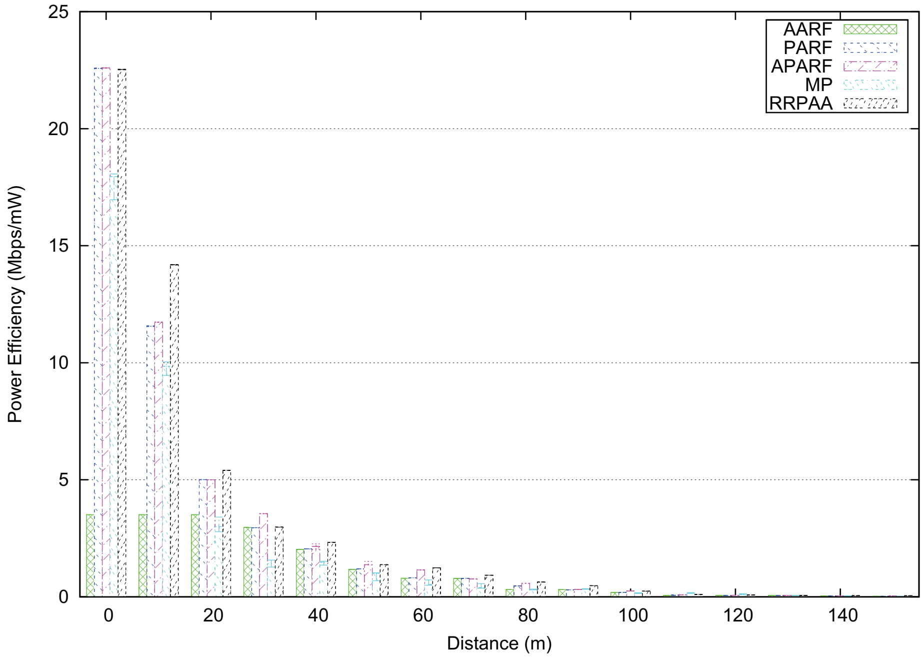
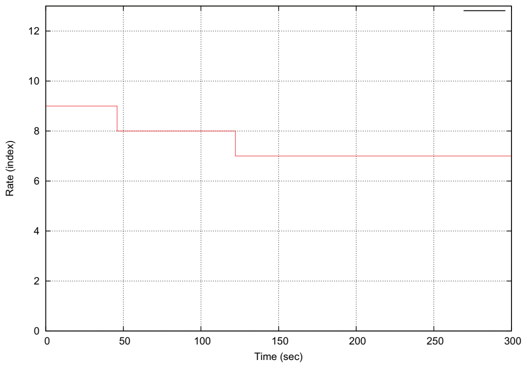
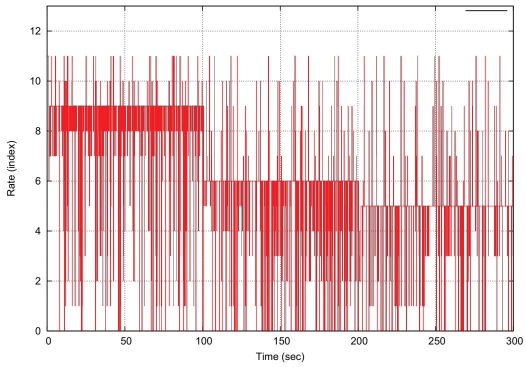


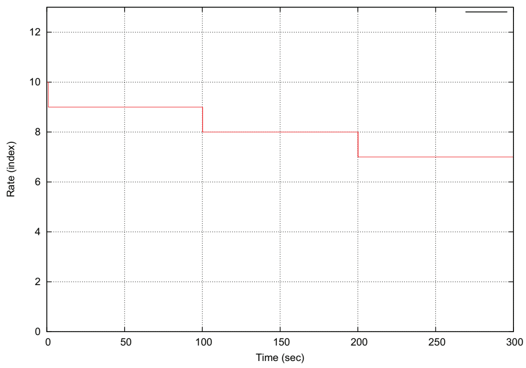
Figure 5.4: Power Efficiency vs. Distance Between AP and STA for the Simple Link Scenario



(a) Aparf Rates

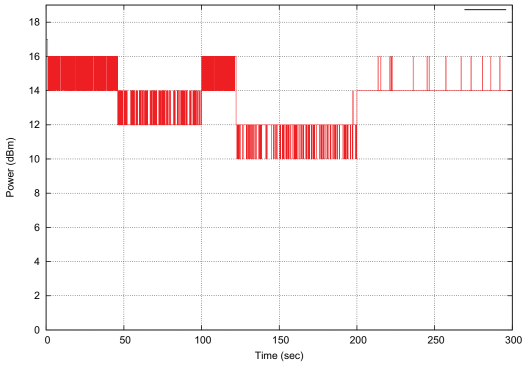


(b) MP Rates

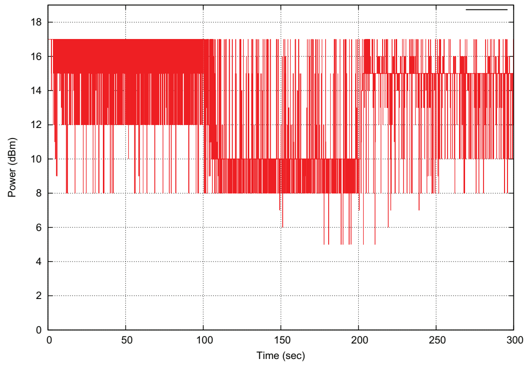


(c) RRPAA Rates

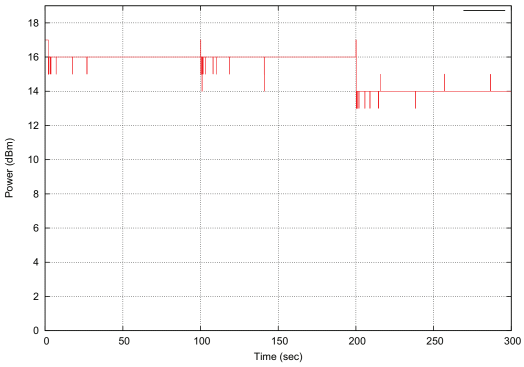
Figure 5.5: Rate Variations vs. Time for the Simple Link Scenario



(a) Aparf Powers



(b) MP Powers



(c) RRPAA Powers

Figure 5.6: Power Variations vs. Time for the Simple Link Scenario

5.3.2 RRPAA and PRCS Evaluation for the Two-Link Scenario

For this scenario we are only showing the results for the exposed terminal case. The behaviour on the other scenarios is very similar to existent mechanisms and do not contribute to the comparison, nevertheless the results can be found in Appendix A.

In Figure 5.7 we compare RRPAA and PRCS with the rate-only-adaptation mechanism (AARF), with the power control mechanism that shows better performance in previous experiments for the Two-Link Scenario (APARF) and with the base-line solutions *NetTh*, *Fair* and *NoInterf*. It can clearly be seen that PRCS achieves a significant performance improvement (83% over APARF in total network throughput) getting the same throughput as the *NoInterf* solution.

Moreover, in Figure 5.8 it is shown how the transmission opportunity of both links are increased over 0.9 getting a fair access to the medium.

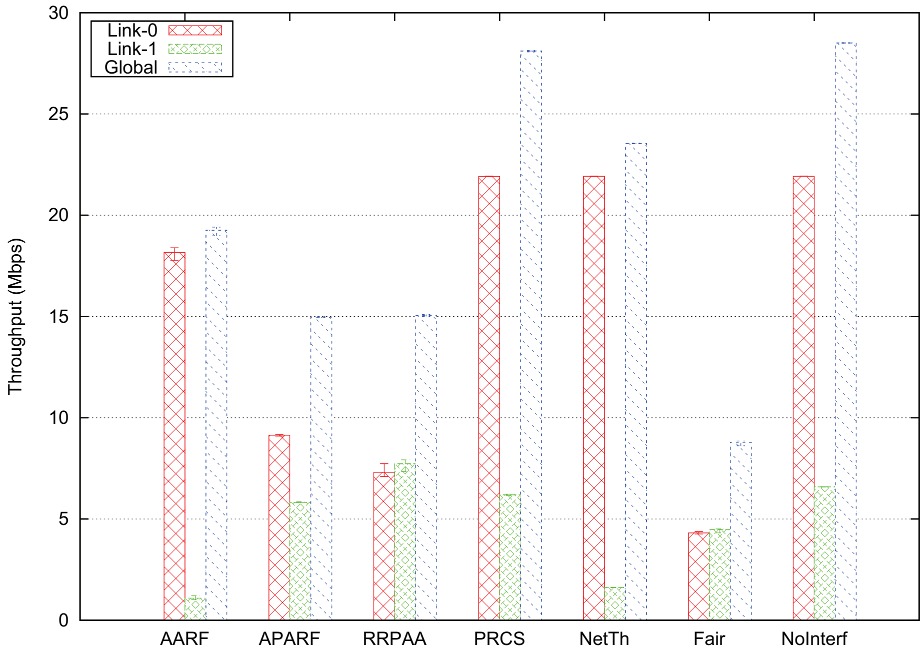


Figure 5.7: Throughput in the Exposed Terminal Configuration.

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.

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.

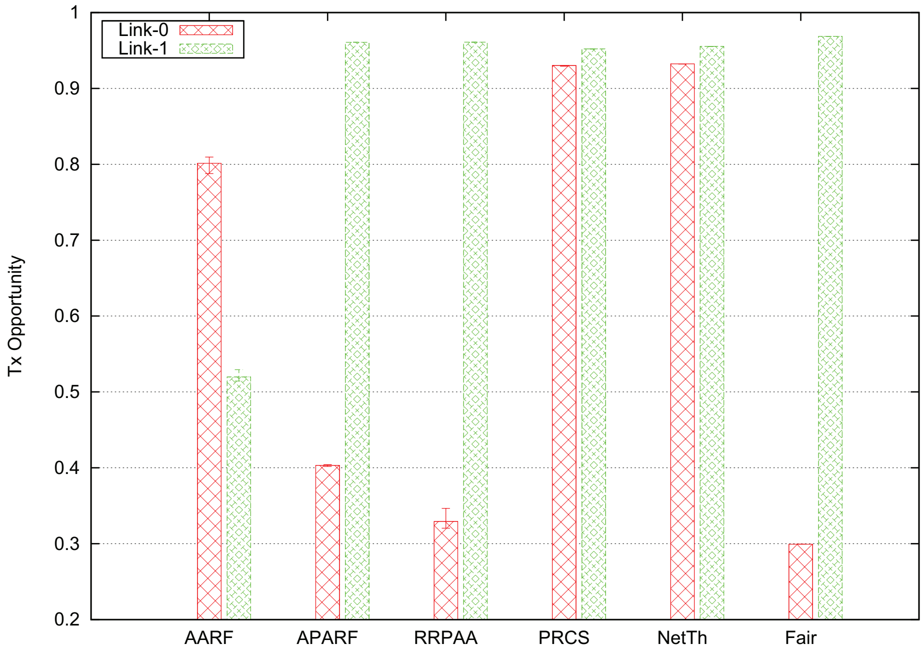


Figure 5.8: TX Opportunity in the Exposed Terminal Configuration.

5.3.3 RRPAA and PRCS Evaluation for the Random Scenario

Finally, we compare RRPAA and PRCS with MP (the mechanism with best performance) and with the rate-only adaptation mechanism (AARF) in the Random Scenario. We execute the same experiment as in Chapter 4 doing 100 independent runs where the position of the stations on the scenario is varied. In Figures 5.9 and 5.10 it is shown the median, the quartiles and the best and worst case of all the executions. The worst and best case gives us a prediction interval of 98% probability.

From the figures it can be notice that RRPAA and PRCS have a similar performance which is better than MP. We consider this performance improvement is due to the robustness of RRPAA because of using separated thresholds for low losses and high losses, because of not using probing frames and because of a correct usage of frame loss statistics.

This experiment, closer to real deployments, show us again the importance of power control in high-density scenarios. It can be seen from results that power control mechanisms not only improve the median of results but also the worst case is significantly improved in comparison to not using power control.

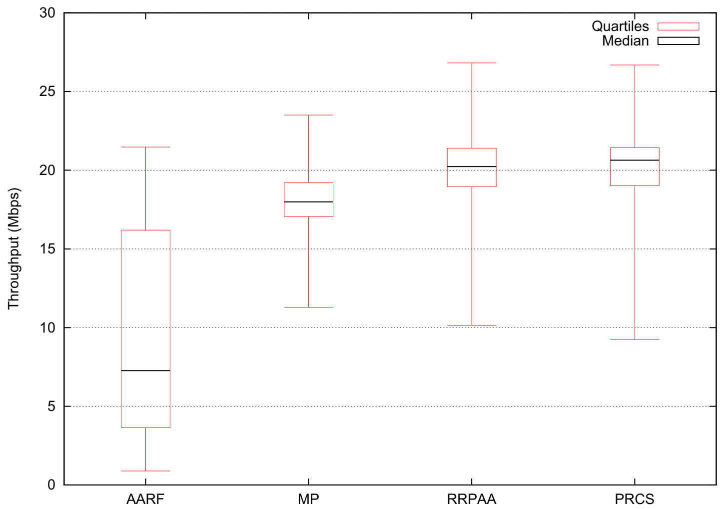


Figure 5.9: Throughput in the Random Scenario.

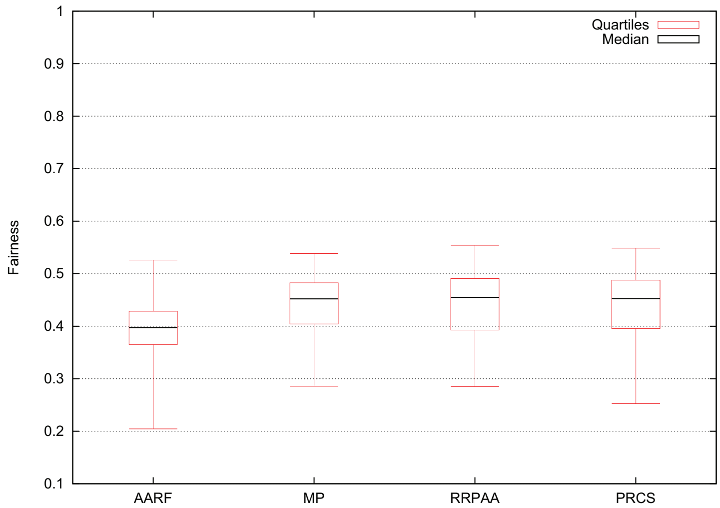


Figure 5.10: Fairness in the Random Scenario.

Chapter 6

Conclusions

In this work we describe the main interference and loss problems that the IEEE 802.11 networks experiment in high-density environments. We analyse how network-parameters control can improve the performance of HD wireless networks by adapting to dynamic channel and scenario conditions. We also experiment with the solutions that address those interference issues manipulating the transmit power and data rate using the frame loss rate as a measure of the problem magnitude. The implemented solutions have shown to be very good on the situations where the AP cells can be completely disjoint, but where not useful at all when they must overlap. We have also seen that the treatment of hidden-terminal and the exposed-terminal situations left a big space for global network throughput improvement.

Our premise is that those particular situations in which the surveyed work has its main weaknesses are not exceptional, but common situations in the context of HD wireless networks where it is common to reduce the cell size without reaching the point of completely disjoint cells, increasing the occurrence probability of the hidden-terminal problem or causing the problems seen when the APs coverage-overlap occurs.

To address these problems we develop PRCS, a novel mechanism which adapts data rate, transmit power and carrier sense threshold. For its implementation we extend an starvation identification algorithm based on local measurements of transmission opportunity and frame loss rate. Similarly to existent power control mechanisms, our solution reduce transmit power generating less interference but it also reduce carrier sense sensitivity when reducing power. This technique avoids asymmetrical links and even more allows for more spatial reuse.

We have implemented PRCS on the NS3 network simulator and compare it with some existent power control mechanisms PARF, APARF and MP. In our experiments with different scenarios, where we try to simulate real possible configurations, we show how PRCS has a similar performance to other mechanisms but outperforms all of them in the problematic scenario of exposed terminal. We believe that our mechanism has all the benefits from previous works but additionally it does not suffer from the problem of starvation caused by asymmetric links.

6.1 Contribution

The body of research work on high-density WiFi networks is yet small and somehow rudimentary. In most cases the proposed algorithms are just published, not widely or independently implemented and their existent implementations are not publicly available. Moreover, non off-the-shelf commercial hardware implements any kind of power control. Therefore, we contribute with: (i) implementations of published algorithms that we made available to everyone through public git repositories [43], making all our experiments reproducible and verifiable; (ii) a proper investigation on the validity of the assumptions and asseverations made by the investigated work; (iii) an investigation on the not yet completely understood behaviour of dense WiFi networks and (iv) a proposal for a novel mechanism that mitigates the problem of starvation caused by power control.

6.2 Future Work

With the knowledge gained on the evaluation of existing solutions, we are currently developing a solution that addresses the interference problem from an autonomic perspective in which the APs share information and collaborate to perform a transmit-power- and data-rate-based mechanism with the aim to get closer to the throughput optimums depicted in Chapter 4. In particular, we are interested on finding an effective solution to the hidden-terminal problem.

Although our evaluation of RRPAA and PRCS shows important performance improvements, the presented experiments do not take into account 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.

Furthermore, how often should we adjust power, rate and carrier sense threshold so as to be robust enough while detecting channel variations is an important topic to consider. For example, we should take into account time-varying fading channels and mobility. Currently the 802.11g standard is getting out-of-date and the new 802.11n and 802.11ac are becoming more common in wireless network deployments.

The extension of current mechanisms to these standards is a challenging work as they incorporate a very large spectrum of data rates (up to 32 rates with two different guard intervals and channel width) as well as new capabilities like multiple input multiple output (MIMO). In this case seems also more important to know how to select the correct parameters as the number of possible values increase considerably.

Appendix A

Results

A.1 Simple Link Scenario

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	22.5334	22.5448	22.5485	22.5564	22.5638
10	22.5304	22.5417	22.5456	22.5533	22.5610
20	22.5274	22.5388	22.5426	22.5501	22.5580
30	19.1791	19.2733	19.2954	19.3260	19.3936
40	17.9934	18.0013	18.0052	18.0103	18.0195
50	14.2027	14.2059	14.2091	14.2119	14.2201
60	11.2889	11.3082	11.3161	11.3214	11.3368
70	11.5853	11.5896	11.5933	11.5957	11.6029
80	6.75829	6.76474	6.76795	6.76974	6.77329
90	6.73466	6.74074	6.74290	6.74355	6.74557
100	4.65908	4.68737	4.70032	4.70580	4.71804
110	1.66663	1.66685	1.66703	1.66722	1.66765
120	1.66606	1.66625	1.66651	1.66700	1.66742
130	1.64141	1.64459	1.64646	1.64890	1.64924
140	1.26766	1.28658	1.29589	1.30146	1.32810
150	0.874720	0.876225	0.876538	0.877219	0.878355

Table A.1: AARF Throughput Results (Mbps)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	22.5908	22.6027	22.6064	22.6149	22.6224
10	16.0399	16.0538	16.0744	16.0825	16.1078
20	16.0703	16.0843	16.0923	16.1097	16.1443
30	16.4906	16.5004	16.5061	16.5171	16.5288
40	15.9426	15.9501	15.9533	15.9566	15.9632
50	12.7942	12.7984	12.8000	12.8054	12.8119
60	10.4195	10.1651	10.1686	10.1758	10.1829
70	10.4835	10.4893	10.4929	10.4946	10.5024
80	7.74150	7.74596	7.74923	7.75218	7.76683
90	6.11702	6.12650	6.13060	6.13622	6.17336
100	4.41904	4.42301	4.42558	4.42674	4.43051
110	1.59710	1.70704	1.76818	1.85617	2.39923
120	1.58767	1.58921	1.58995	1.59077	1.59199
130	1.54666	1.55356	1.55661	1.55780	1.56166
140	1.22324	1.23054	1.23194	1.24341	1.26051
150	0.850182	0.851773	0.85325	0.854726	0.857453

Table A.2: PARF Throughput Results (Mbps)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	22.5908	22.6027	22.6064	22.6149	22.6224
10	16.5124	16.5197	16.5241	16.5383	16.5578
20	16.5398	16.5698	16.5809	16.5958	16.6120
30	14.4325	14.4412	14.4515	14.4566	14.4716
40	11.4034	12.1659	12.6329	13.0709	13.9393
50	10.2621	10.8479	11.1001	11.2013	11.2269
60	9.46322	9.47495	9.48123	9.49341	9.50082
70	6.98595	7.00077	7.00583	7.03875	7.15941
80	7.19156	7.19664	7.19906	7.20210	7.21485
90	4.08721	4.09707	4.10323	4.11102	4.12209
100	4.14401	4.15123	4.15464	4.15825	4.16424
110	1.40126	1.41643	1.43977	1.46161	1.60619
120	1.39694	1.40018	1.40194	1.40416	1.40671
130	0.804970	0.807043	0.809116	0.813149	0.832688
140	0.804515	0.804970	0.805310	0.805907	0.806901
150	0.790997	0.792474	0.793383	0.793950	0.795541

Table A.3: APARF Throughput Results (Mbps)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	21.2592	22.3942	22.4042	22.5469	22.5568
10	15.6649	15.9475	16.3767	16.8064	16.9817
20	12.3395	13.8417	14.2556	16.0857	16.2228
30	10.4844	10.8016	11.4196	11.6817	12.9755
40	10.4656	12.2087	12.2738	12.3417	12.4286
50	6.93926	9.25510	9.96420	10.1140	10.2036
60	4.53094	4.63440	4.98278	5.11635	7.56088
70	4.44948	4.55380	4.73536	5.20706	6.92846
80	3.81128	3.86962	4.06677	4.15311	4.31771
90	5.37714	5.49194	5.54385	5.58575	5.69670
100	2.46944	2.66216	2.73720	2.83168	3.01085
110	2.68005	2.84718	3.08890	3.16572	3.58783
120	1.91677	2.34868	2.44576	2.55881	2.73344
130	1.14963	1.16571	1.17633	1.18476	1.22290
140	0.960829	0.999282	1.00417	1.01212	1.07511
150	0.839390	0.844361	0.848365	0.849415	0.853818

Table A.4: MP Throughput Results (Mbps)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	22.5908	22.6027	22.6064	22.6149	22.6224
10	21.8414	21.8546	21.8679	21.8741	21.8891
20	21.7587	21.7757	21.7864	21.7946	21.8172
30	20.6443	20.6651	20.6791	20.6923	20.7035
40	17.6688	17.6840	17.6961	17.7104	17.7641
50	14.0525	14.0755	14.0824	14.0941	14.1084
60	9.86559	9.88227	9.90007	9.90941	9.93761
70	9.81095	9.83856	9.84963	9.85684	9.88956
80	7.63028	7.64466	7.65261	7.66155	7.67016
90	7.31404	7.31927	7.32529	7.33023	7.33915
100	4.70792	4.75458	4.75519	4.75658	4.75870
110	1.43999	1.44889	1.46181	1.46672	1.62618
120	1.38512	1.39086	1.39365	1.39739	1.40694
130	1.36718	1.37260	1.37360	1.37706	1.38524
140	0.857907	0.875174	0.91732	0.94160	1.10658
150	0.824736	0.826497	0.827179	0.828854	0.830416

Table A.5: RRPAA Throughput Results (Mbps)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	6.41325	6.419207	6.4212	6.425315	6.42928
10	6.41163	6.417565	6.4197	6.423695	6.42772
20	6.41014	6.416105	6.41806	6.422007	6.42617
30	6.46315	6.49895	6.508915	6.524037	6.54746
40	8.87463	8.884048	8.88809	8.893298	8.9029
50	12.1186	12.12575	12.1328	12.13905	12.1563
60	14.1941	14.221075	14.23295	14.246575	14.2642
70	14.7397	14.75025	14.75955	14.77035	14.7965
80	21.6626	21.683375	21.7089	21.7252	21.7486
90	21.6458	21.662175	21.68255	21.692	21.7189
100	24.7457	24.804875	24.8456	24.900575	24.9461
110	29.9059	29.9174	29.9255	29.935675	29.9567
120	29.9091	29.9279	29.93735	29.94345	29.9615
130	29.9233	29.940625	29.9481	29.958375	29.9724
140	30.5124	30.614425	30.64835	30.72545	30.8309
150	33.8161	33.847075	33.87655	33.9307	33.9865

Table A.6: AARF Power Results (mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	1.0013	1.0013	1.0013	1.0013	1.0013
10	1.38914	1.38998	1.39017	1.39068	1.39142
20	3.21153	3.213258	3.2148	3.21642	3.22234
30	5.57488	5.582365	5.587815	5.59263	5.59683
40	7.75362	7.762107	7.765325	7.77091	7.77534
50	10.6643	10.670575	10.6734	10.68457	10.6954
60	12.4244	12.4521	12.4635	12.4767	12.5017
70	13.2291	13.235025	13.2489	13.2562	13.2727
80	16.4416	16.461025	16.476	16.48967	16.5564
90	20.2896	20.336225	20.35135	20.37525	20.3893
100	22.9314	22.994875	23.0202	23.04373	23.1162
110	26.9158	27.843525	27.9898	28.0891	28.3175
120	28.3145	28.327525	28.3444	28.35708	28.377
130	28.3936	28.43215	28.4398	28.45367	28.4814
140	29.5027	29.597675	29.6731	29.70157	29.7781
150	32.0817	32.14045	32.1725	32.20375	32.2229

Table A.7: PARF Power Results (mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	1.00071	1.00071	1.00071	1.00071	1.00071
10	1.40838	1.408635	1.40906	1.409495	1.41
20	3.30758	3.314518	3.315505	3.31747	3.32014
30	4.06182	4.062773	4.06493	4.067735	4.06984
40	5.61467	5.775903	5.86839	5.96543	6.14692
50	6.7691	7.630645	8.059125	8.222862	8.24576
60	8.24361	8.249715	8.256015	8.261317	8.28206
70	9.13569	9.147545	9.15317	9.180585	9.27328
80	12.3702	12.3744	12.38385	12.3929	12.4228
90	12.9638	13.000225	13.03685	13.044975	13.0608
100	16.7112	16.725175	16.742	16.755525	16.7744
110	16.3065	16.3832	16.42225	16.504525	16.6332
120	20.3976	20.481225	20.5016	20.5386	20.6069
130	14.6156	14.652325	14.6746	14.731425	15.0162
140	17.9863	17.9974	18.00195	18.009325	18.018
150	18.1463	18.170475	18.18345	18.2089	18.2366

Table A.8: APARF Power Results (mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	1.24417	1.2484	1.250325	1.25255	1.25899
10	1.63974	1.646203	1.6768	1.688382	1.74014
20	4.4368	4.697237	4.739355	4.814762	5.04514
30	7.56804	7.893257	8.06049	8.15041	8.3082
40	7.70545	8.275388	8.29925	8.32077	8.41403
50	9.58398	9.77344	9.90435	9.971815	10.54
60	8.98115	9.124438	9.22347	9.361622	11.2723
70	11.7264	11.9462	12.05335	12.1986	12.8442
80	12.2351	12.377525	12.85125	13.337475	13.8883
90	15.8687	16.019525	16.56995	17.070075	17.3735
100	16.5807	16.7134	16.86665	16.960425	17.4984
110	16.7587	17.8882	18.3058	18.53155	21.2595
120	17.4742	19.50475	21.1422	21.47635	22.1105
130	20.3938	20.6037	20.7286	20.8671	21.6043
140	21.0716	21.24125	21.4595	22.6147	25.7317
150	28.1838	29.341925	29.5753	30.108275	30.6456

Table A.9: MP Power Results (mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	1.00357	1.00357	1.00357	1.00357	1.00357
10	1.54057	1.54074	1.541125	1.541502	1.54169
20	4.02869	4.031865	4.033925	4.035567	4.04128
30	6.92481	6.933553	6.939095	6.9445	6.95185
40	7.56806	7.577357	7.582875	7.590155	7.62759
50	10.2052	10.227075	10.23475	10.24845	10.2684
60	7.93182	7.951097	7.96084	7.972912	7.98704
70	10.6083	10.647625	10.66245	10.668225	10.6966
80	12.1018	12.1202	12.1348	12.156	12.1833
90	17.373	17.39535	17.4075	17.42375	17.4575
100	19.0594	19.6487	19.66715	19.68575	19.7034
110	14.5035	14.533625	14.57045	14.6036	14.9037
120	17.5502	17.563275	17.57695	17.5936	17.6065
130	21.1447	21.218725	21.23865	21.2449	21.2707
140	16.5259	16.7755	17.3734	17.7409	20.3488
150	16.2858	16.301675	16.30865	16.318275	16.3289

Table A.10: RRPAA Power Results (mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	3.50954	3.51055	3.51157	3.51208	3.51357
10	3.50995	3.51095	3.51194	3.51250	3.51399
20	3.51033	3.51137	3.51236	3.51284	3.51434
30	2.96160	2.96283	2.96345	2.96549	2.96745
40	2.02400	2.02515	2.02578	2.02629	2.02751
50	1.16977	1.17075	1.17114	1.17155	1.17198
60	0.794303	0.794615	0.794843	0.795309	0.795480
70	0.784165	0.785076	0.785487	0.785835	0.786137
80	0.311357	0.311608	0.311705	0.311877	0.312068
90	0.310575	0.310865	0.310988	0.311138	0.311389
100	0.187418	0.188338	0.189055	0.189345	0.189954
110	0.0556647	0.0556964	0.0557038	0.0557145	0.0557327
120	0.0556380	0.0556581	0.0556697	0.0556919	0.0557078
130	0.0548160	0.0549247	0.0549981	0.0550286	0.0551082
140	0.0411677	0.0418950	0.0422650	0.0425370	0.0435266
150	0.0258075	0.0258312	0.0258821	0.0259002	0.0259368

Table A.11: AARF Power Efficency Results (Mbps/mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	22.5615	22.5733	22.577	22.5855	22.5930
10	11.5457	11.5495	11.5607	11.56790	11.5813
20	5.00299	5.00549	5.00598	5.00793	5.01345
30	2.95172	2.9531	2.9536	2.95587	2.95823
40	2.05267	2.05339	2.05447	2.05476	2.05615
50	1.19789	1.19842	1.19919	1.19946	1.19983
60	0.814305	0.815395	0.81583	0.816415	0.817032
70	0.791165	0.791689	0.792025	0.792458	0.792955
80	0.469113	0.470141	0.470279	0.470555	0.470976
90	0.300479	0.300740	0.301142	0.301632	0.304262
100	0.191618	0.192094	0.192237	0.192391	0.192707
110	0.0563998	0.0607737	0.0631709	0.0666658	0.0891384
120	0.0559654	0.0560477	0.0561142	0.0561316	0.0562137
130	0.0543042	0.0545875	0.0547408	0.0547908	0.0549155
140	0.0410785	0.0414349	0.0414741	0.0419990	0.0427252
150	0.0263915	0.0264584	0.0265134	0.0265897	0.0267272

Table A.12: PARF Power Efficency Results (Mbps/mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	22.5748	22.5866	22.5903	22.5988	22.6063
10	11.7206	11.7254	11.7297	11.73430	11.7441
20	4.99807	5.00024	5.00158	5.00254	5.00454
30	3.55203	3.55280	3.55378	3.55523	3.55878
40	2.02835	2.10631	2.15299	2.19412	2.26769
50	1.36069	1.36151	1.37795	1.42162	1.51602
60	1.14654	1.14778	1.14841	1.14923	1.15000
70	0.763753	0.764904	0.765813	0.766738	0.772047
80	0.580588	0.580959	0.581441	0.581784	0.582416
90	0.314578	0.314891	0.315072	0.315359	0.315714
100	0.247044	0.248072	0.248204	0.248350	0.248761
110	0.0855705	0.086426	0.0875294	0.0887278	0.0965653
120	0.0679331	0.0682549	0.0684004	0.0685910	0.0687027
130	0.0550031	0.0550824	0.0551180	0.0551722	0.0555466
140	0.0446793	0.0447195	0.0447471	0.0447661	0.0447926
150	0.0433990	0.0435426	0.0436344	0.0436770	0.0438404

Table A.13: APARF Power Efficency Results (Mbps/mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	16.9643	17.9185	17.9544	18.0124	18.0661
10	9.45626	9.65229	9.8476	9.95017	10.0409
20	2.78117	2.93243	3.00334	3.32549	3.40942
30	1.27128	1.34287	1.41746	1.47449	1.57001
40	1.35821	1.47103	1.47673	1.48687	1.52016
50	0.690354	0.943983	1.00640	1.01954	1.02648
60	0.496272	0.510976	0.533430	0.548808	0.722147
70	0.367565	0.383267	0.393037	0.421812	0.566912
80	0.298129	0.304597	0.311160	0.316748	0.334357
90	0.321396	0.327348	0.335438	0.342785	0.352282
100	0.147681	0.157636	0.162185	0.167789	0.176822
110	0.147159	0.157139	0.167215	0.172415	0.178215
120	0.0877156	0.113407	0.119042	0.1283600	0.137582
130	0.0558328	0.0564259	0.0565581	0.0568481	0.0571751
140	0.0373403	0.0449776	0.0469115	0.0474217	0.0478669
150	0.0275496	0.0281042	0.0285784	0.0288676	0.0301213

Table A.14: MP Power Efficency Results (Mbps/mW)

Distance	0%-quantile	25%-quantile	Median	75%-quantile	100%-quantile
0	22.5104	22.5222	22.5259	22.5344	22.5419
10	14.1746	14.1830	14.1883	14.19490	14.1981
20	5.39799	5.40008	5.40083	5.40133	5.40387
30	2.97813	2.97916	2.98028	2.98082	2.98168
40	2.32893	2.33275	2.33353	2.33415	2.33547
50	1.37396	1.37522	1.37573	1.37644	1.37732
60	1.24196	1.24282	1.243430	1.24384	1.24529
70	0.922357	0.923804	0.924197	0.924546	0.924934
80	0.628388	0.630080	0.630568	0.630955	0.631423
90	0.477455	0.477917	0.478172	0.478353	0.478958
100	0.241425	0.241583	0.241798	0.242012	0.247013
110	0.0971994	0.0996552	0.100340	0.100584	0.109202
120	0.0787246	0.0791614	0.0793185	0.0794787	0.0799343
130	0.0644323	0.0646360	0.0646957	0.0647954	0.0652275
140	0.0518455	0.0522390	0.0527327	0.0530931	0.0543806
150	0.0505681	0.0506910	0.0507378	0.0507951	0.0508693

Table A.15: RRPAA Power Efficency Results (Mbps/mW)

A.2 Two Link Scenario

	Mechanism	Median	95% CI	0%-quantile	100%-quantile
Link-0	AARF	13.4391	[13.4310, 13.4471]	13.4050	13.4756
Link-0	PARF	20.4049	[20.3939, 20.4089]	20.3899	20.4215
Link-0	APARF	20.5117	[20.5049, 20.5147]	20.4975	20.5273
Link-0	MP	20.3363	[20.2208, 20.3487]	19.2631	20.3724
Link-0	RRPAA	20.508	[20.5010, 20.5107]	20.4865	20.5174
Link-0	PRCS	21.9685	[21.9640, 21.9716]	21.9500	21.9820
Link-0	NetTh	20.5911	[20.5853, 20.5952]	20.5758	20.6024
Link-0	Fair	20.5911	[20.5853, 20.5952]	20.5758	20.6024
Link-0	NoInterf	21.9246	[21.9163, 21.9286]	21.9154	21.9379
Link-1	AARF	13.4493	[13.4365, 13.4601]	13.3859	13.4815
Link-1	PARF	20.4032	[20.3992, 20.4115]	20.3865	20.4233
Link-1	APARF	20.5143	[20.5058, 20.5206]	20.4972	20.5304
Link-1	MP	20.3238	[20.2160, 20.3362]	19.2455	20.3651
Link-1	RRPAA	20.5048	[20.5002, 20.5123]	20.4942	20.5219
Link-1	PRCS	21.9708	[21.9671, 21.9793]	21.9580	21.9866
Link-1	NetTh	20.5928	[20.5873, 20.5974]	20.5799	20.6134
Link-1	Fair	20.5928	[20.5873, 20.5974]	20.5799	20.6134
Link-1	NoInterf	21.9246	[21.9163, 21.9286]	21.9154	21.9379
Global	AARF	26.8868	[26.8743, 26.9000]	26.8587	26.9142
Global	PARF	40.8100	[40.8011, 40.8160]	40.7788	40.8330
Global	APARF	41.0242	[41.0184, 41.0333]	41.0035	41.0418
Global	MP	40.5436	[40.1592, 40.6657]	39.6017	40.6924
Global	RRPAA	41.0126	[41.0064, 41.0194]	40.9896	41.0312
Global	PRCS	43.9395	[43.9317, 43.9504]	43.9147	43.9595
Global	NetTh	41.1837	[41.1781, 41.1928]	41.1557	41.2042
Global	Fair	41.1837	[41.1781, 41.1928]	41.1557	41.2042
Global	NoInterf	43.8491	[43.8326, 43.8572]	43.8308	43.8758

Table A.16: Disjoint Case Throughput Results (Mbps)

	Mechanism	Median	95% CI	0%-quantile	100%-quantile
Link-0	AARF	12.2969	[12.2779, 12.3131]	12.2302	12.3543
Link-0	PARF	12.3595	[12.3434, 12.3877]	12.2802	12.4600
Link-0	APARF	12.4510	[12.4229, 12.4831]	12.3513	12.5131
Link-0	MP	11.9504	[11.9339, 11.9800]	11.9120	12.1025
Link-0	RRPAA	12.4520	[12.4381, 12.4676]	12.3897	12.5473
Link-0	PRCS	11.9364	[11.5652, 12.0986]	11.1432	12.7044
Link-0	NetTh	12.2880	[12.2302, 12.3162]	12.2222	12.3434
Link-0	Fair	12.2880	[12.2302, 12.3162]	12.2222	12.3434
Link-0	NoInterf	21.9246	[21.9163, 21.9286]	21.9154	21.9379
Link-1	AARF	12.3028	[12.2815, 12.3241]	12.1637	12.3481
Link-1	PARF	12.3799	[12.3544, 12.3913]	12.2851	12.4517
Link-1	APARF	12.4598	[12.4110, 12.4904]	12.3986	12.5759
Link-1	MP	11.9763	[11.9548, 12.0033]	11.8835	12.0776
Link-1	RRPAA	12.4538	[12.4379, 12.4666]	12.3584	12.5181
Link-1	PRCS	12.4384	[12.0712, 12.5009]	11.2982	12.6863
Link-1	NetTh	12.3178	[12.2784, 12.3494]	12.1611	12.3583
Link-1	Fair	12.3178	[12.2784, 12.3494]	12.1611	12.3583
Link-1	NoInterf	21.9246	[21.9163, 21.9286]	21.9154	21.9379
Global	AARF	24.5952	[24.5610, 24.6358]	24.4520	24.6595
Global	PARF	24.7398	[24.7119, 24.7550]	24.6791	24.7859
Global	APARF	24.9139	[24.9067, 24.9180]	24.8875	24.9272
Global	MP	23.9414	[23.9147, 23.9779]	23.8262	24.0663
Global	RRPAA	24.9107	[24.8960, 24.9139]	24.8723	24.9239
Global	PRCS	24.0716	[24.0108, 24.3096]	23.8202	24.5418
Global	NetTh	24.5883	[24.5525, 24.6519]	24.4608	24.6656
Global	Fair	24.5883	[24.5525, 24.6519]	24.4608	24.6656
Global	NoInterf	43.8491	[43.8326, 43.8572]	43.8308	43.8758

Table A.17: Overlapping Case Throughput Results (Mbps)

	Mechanism	Median	95% CI	0%-quantile	100%-quantile
Link-0	AARF	0.450396	[0.442615, 0.455970]	0.0340846	0.480238
Link-0	PARF	0.478077	[0.470809, 0.483361]	0.224931	0.511966
Link-0	APARF	0.730842	[0.724058, 0.746987]	0.703966	0.840600
Link-0	MP	1.46713	[1.43527, 1.53168]	0.566407	2.61975
Link-0	RTS/CTS	1.83337	[1.78336, 1.85198]	1.69072	1.88045
Link-0	RRPAA	0.40701	[0.403150, 0.410972]	0.229138	0.440248
Link-0	PRCS	0.407513	[0.404526, 0.410801]	0.2941720	0.440248
Link-0	NetTh	6.43972	[6.43571, 6.45038]	6.43528	6.45649
Link-0	Fair	4.53582	[4.52477, 4.54201]	4.52046	4.54346
Link-0	NoInterf	6.58091	[6.57821, 6.58446]	6.57698	6.58490
Link-1	AARF	6.57467	[6.57340, 6.57524]	6.51993	6.57845
Link-1	PARF	5.97116	[5.97002, 5.97260]	5.90502	5.97566
Link-1	APARF	6.77645	[6.77144, 6.78018]	6.07807	6.79080
Link-1	MP	6.27676	[6.20981, 6.33620]	5.10445	6.91704
Link-1	RTS/CTS	4.35045	[4.34059, 4.35526]	4.34008	4.36761
Link-1	RRPAA	8.21143	[8.20628, 8.21703]	8.11896	8.23285
Link-1	PRCS	8.21200	[8.20491, 8.21777]	8.12510	8.24173
Link-1	NetTh	4.67987	[4.67283, 4.68699]	4.66697	4.69232
Link-1	Fair	4.95281	[4.93799, 4.97381]	4.93719	4.97944
Link-1	NoInterf	6.58091	[6.57821, 6.58446]	6.57698	6.58490
Global	AARF	7.02077	[7.01255, 7.02914]	6.55402	7.05163
Global	PARF	6.44844	[6.43901, 6.45470]	6.16258	6.48222
Global	APARF	7.50356	[7.48060, 7.51302]	6.81018	7.61456
Global	MP	7.77364	[7.73181, 7.84607]	6.45259	8.14210
Global	RTS/CTS	6.18024	[6.12526, 6.20636]	6.03131	6.22798
Global	RRPAA	8.61723	[8.60521, 8.62580]	8.43665	8.64414
Global	PRCS	8.61653	[8.60252, 8.62421]	8.44997	8.64517
Global	NetTh	11.1233	[11.1121, 11.1300]	11.1077	11.1313
Global	Fair	9.49059	[9.47327, 9.50291]	9.45845	9.51260
Global	NoInterf	13.1618	[13.1564, 13.1689]	13.1540	13.1698

Table A.18: Hidden Case Throughput Results (Mbps)

	Mechanism	Median	95% CI	0%-quantile	100%-quantile
Link-0	AARF	18.1638	[18.1141, 18.2748]	17.7761	18.3974
Link-0	PARF	2.90538	[2.88032, 2.92372]	2.83571	2.98461
Link-0	APARF	9.13444	[9.12692, 9.14239]	9.09039	9.16969
Link-0	MP	10.5574	[10.2467, 10.8613]	9.20360	11.6045
Link-0	RRPAA	7.30792	[7.21203, 7.41799]	7.09334	7.72967
Link-0	PRCS	21.9177	[21.9119, 21.9206]	21.8999	21.9345
Link-0	NetTh	21.9248	[21.9206, 21.9286]	21.9064	21.9379
Link-0	Fair	4.30620	[4.28871, 4.32497]	4.25233	4.37682
Link-0	NoInterf	21.9246	[21.9163, 21.9286]	21.9154	21.9379
Link-1	AARF	1.09090	[1.05022, 1.10470]	1.01778	1.20771
Link-1	PARF	5.67723	[5.67160, 5.67850]	5.66136	5.68794
Link-1	APARF	5.82482	[5.82056, 5.83329]	5.81437	5.84961
Link-1	MP	2.90229	[2.79558, 3.05263]	2.52158	3.58616
Link-1	RRPAA	7.72336	[7.62963, 7.81498]	7.33564	7.91851
Link-1	PRCS	6.18774	[6.18335, 6.19212]	6.16169	6.22736
Link-1	NetTh	1.62160	[1.62151, 1.62168]	1.62120	1.62218
Link-1	Fair	4.47599	[4.45676, 4.49431]	4.30953	4.50904
Link-1	NoInterf	6.58091	[6.57821, 6.58446]	6.57698	6.58490
Global	AARF	19.2547	[19.2188, 19.3302]	18.9838	19.4152
Global	PARF	8.58351	[8.55859, 8.59860]	8.52365	8.64597
Global	APARF	14.9610	[14.9529, 14.9785]	14.9368	14.9881
Global	MP	13.4147	[13.3243, 13.5855]	12.5254	14.4646
Global	RRPAA	15.0327	[15.0270, 15.0413]	15.0036	15.0933
Global	PRCS	28.1038	[28.0985, 28.1122]	28.0649	28.1388
Global	NetTh	23.5463	[23.5422, 23.5503]	23.5276	23.5595
Global	Fair	8.78980	[8.76054, 8.79775]	8.61573	8.84503
Global	NoInterf	28.5057	[28.4966, 28.5111]	28.4924	28.5214

Table A.19: Exposed Case Throughput Results (Mbps)

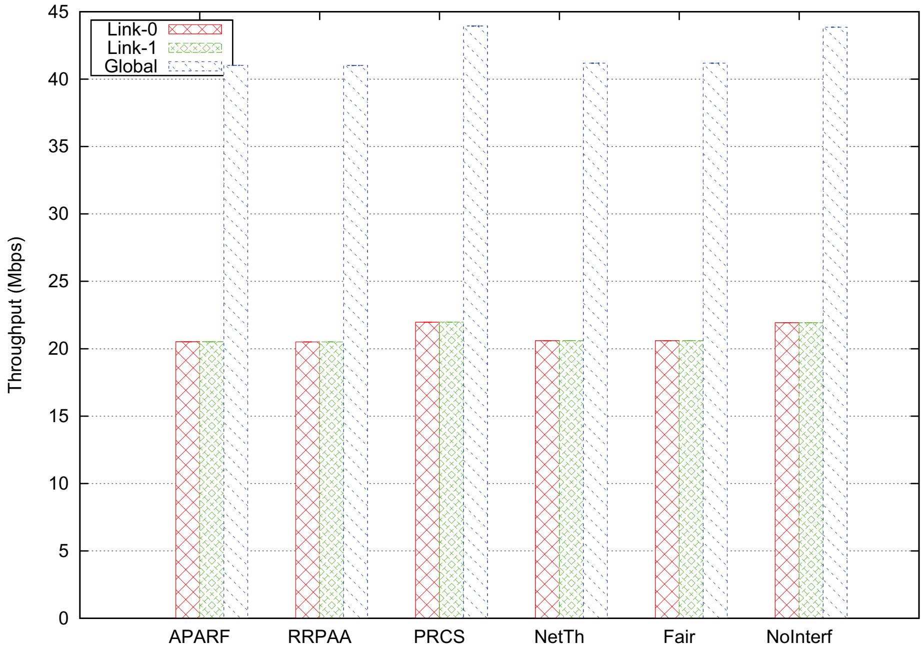


Figure A.1: Throughput in Possibly Disjoint Configuration.

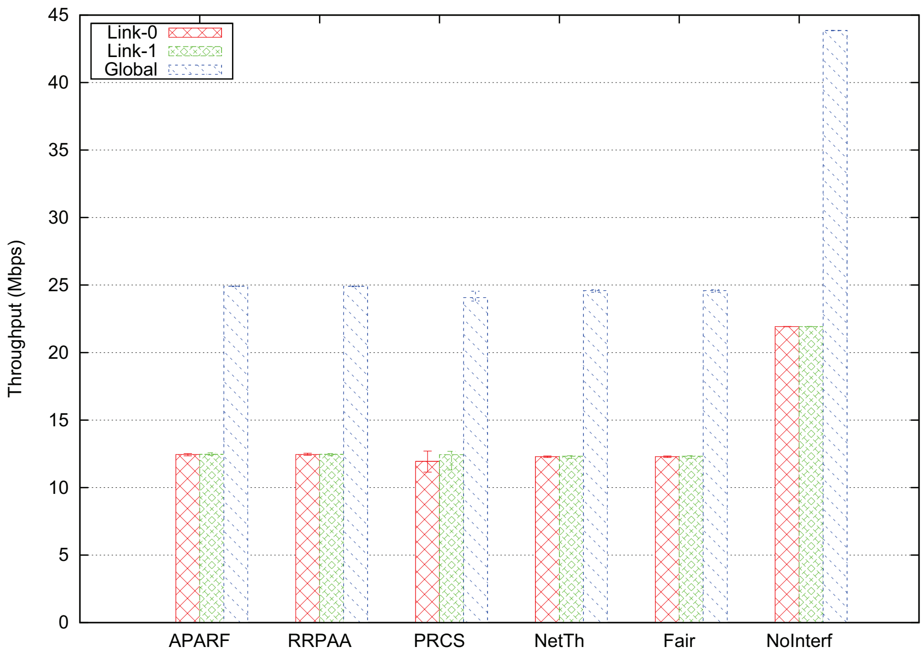


Figure A.2: Throughput in the Overlapping Ranges Configuration.

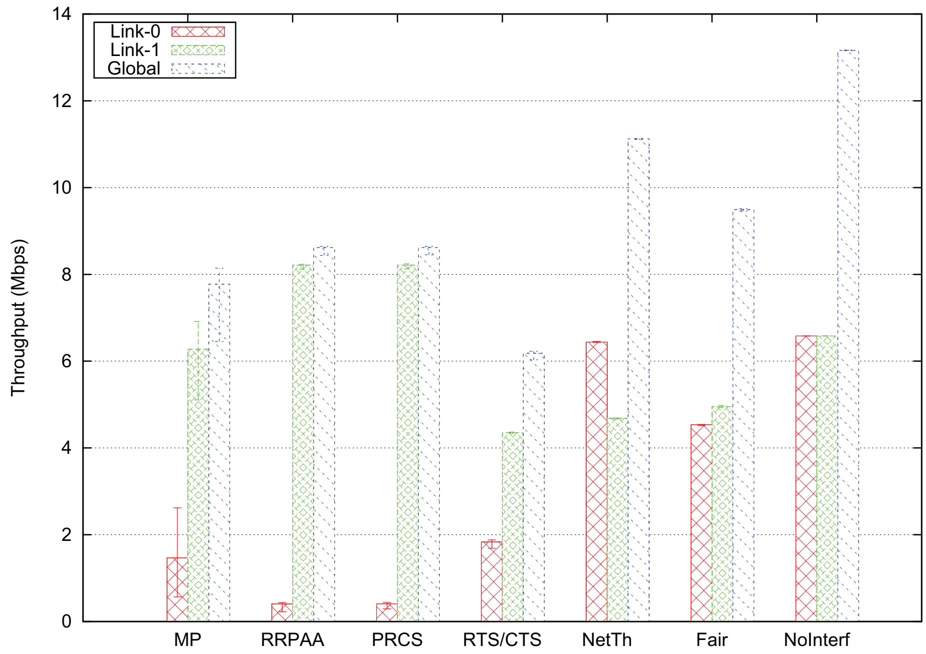


Figure A.3: Throughput in Hidden Terminal Configuration.

A.3 Random Scenario

Mechanism	Median	95% CI	25%-quantile	75%-quantile	0%-quantile	100%-quantile
AARF	7.26772	[3.84076, 15.9460]	3.63713	16.1948	0.888782	21.4753
PARF	16.9079	[14.1318, 20.4894]	10.4644	21.0079	2.41806	24.9747
APARF	5.18059	[3.82848, 6.74883]	2.95784	10.2877	0.772974	19.1859
MP	17.9387	[17.4869, 18.3738]	16.9555	19.2454	11.2856	22.9456
RRPAA	20.2285	[19.8993, 20.9044]	18.9514	21.4004	10.1456	26.8169
PRCS	20.6344	[19.7288, 21.3190]	19.0206	21.4240	9.22412	26.6867

Table A.20: Randmom Scenario Throughput Results (Mbps)

Mechanism	Median	95% CI	25%-quantile	75%-quantile	0%-quantile	100%-quantile
AARF	0.365148	[0.525904, 0.365623]	0.204417	0.397430	0.204417	0.428628
PARF	0.400327	[0.564012, 0.415737]	0.343385	0.447797	0.343385	0.479720
APARF	0.389723	[0.690613, 0.409422]	0.229888	0.470736	0.229888	0.513162
MP	0.404202	[0.538481, 0.443218]	0.285603	0.452107	0.285603	0.482576
RRPAA	0.392758	[0.554215, 0.441534]	0.284855	0.455087	0.284855	0.490850
PRCS	0.395629	[0.548682, 0.415857]	0.252448	0.452246	0.252448	0.487819

Table A.21: Randmom Scenario Throughput Fairness Results

References

[1] The madwifi project. 23

[2] Ns-3 network simulator. 38

[3] IEEE Std 802.11^{TM}-2012, IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: WLAN MAC and PHY specifications. Online, March 2012. 1, 3, 4, 7

[4] Aditya Akella, Glenn Judd, Srinivasan Seshan, and Peter Steenkiste. Self-management in chaotic wireless deployments. *Wireless Networks*, **13**[6]:737–755, 2007. 1, 8, 11, 14, 21, 27

[5] John Charles Bicket. *Bit-rate selection in wireless networks*. PhD thesis, Massachusetts Institute of Technology, 2005. 24, 57

[6] Pierre Bremaud. *Markov chains: Gibbs fields, Monte Carlo simulation, and queues.*, **31**. Springer, 1999. 32

[7] Ioannis Broustis, Jakob Eriksson, Srikanth V Krishnamurthy, and Michalis Faloutsos. Implications of power control in wireless networks: A quantitative study. In *Passive and Active Network Measurement*, pages 83–93. Springer, 2007. 1, 13

[8] Jiancong Chen, S-HG Chan, Qian Zhang, Wen-Wu Zhu, and Jin Chen. Pasa: power adaptation for starvation avoidance to deliver wireless multimedia. *Selected Areas in Communications, IEEE Journal on*, **21**[10]:1663–1673, 2003. 22

[9] Pierre Chevillat, Jens Jelitto, and Hong Linh Truong. Dynamic data rate and transmit power adjustment in ieee 802.11 wireless lans. *International Journal of Wireless Information Networks*, **12**[3]:123–145, 2005. v, 21, 22, 41

[10] Vaggelis G Douros, Pantelis A Frangoudis, Konstantinos Katsaros, and George C Polyzos. Power control in wlans for optimization of social fairness. In *Informatics, 2008. PCI'08. Panhellenic Conference on*, pages 239–243. IEEE, 2008. 27

[11] Vaggelis G Douros and George C Polyzos. Review of some fundamental approaches for power control in wireless networks. *Computer Communications*, **34**[13]:1580–1592, 2011. 12, 17

[12] Mesut Ali Ergin, Kishore Ramachandran, and Marco Gruteser. Understanding the effect of access point density on wireless lan performance. In *Proceedings of the 13th annual ACM international conference on Mobile computing and networking*, pages 350–353. ACM, 2007. 11

[13] Rob Flickenger. *Wireless networking in the developing world.* Hacker Friendly LLC, 2006. v, 5

[14] Jason Fuemmeler, Nitin H Vaidya, and Venugopal V Veeravalli. Selecting transmit powers and carrier sense thresholds for csma protocols. Technical report, University of Illinois at Urbana-Champaign, 2004. 32, 33, 59

[15] Alex Hills. Large-scale wireless lan design. *Communications Magazine, IEEE*, **39**[11]:98–107, 2001. 1

[16] Cunqing Hua and Rong Zheng. On link-level starvation in dense 802.11 wireless community networks. *Computer Networks*, **54**[17]:3159–3172, 2010. 13, 59

[17] Caishi Huang, Chin-Tau Lea, and Albert Kai-Sun Wong. A joint solution for the hidden and exposed terminal problems in csma/ca wireless networks. *Computer Networks: The International Journal of Computer and Telecommunications Networking*, **56**[14]:3261–3273, 2012. 26, 27

[18] Thomas Huehn and Cigdem Sengul. Practical power and rate control for wifi. In *Computer Communications and Networks (ICCCN), 2012 21st International Conference on*, pages 1–7. IEEE, 2012. 14, 24

[19] Raj Jain, Dah-Ming Chiu, and William R Hawe. *A quantitative measure of fairness and discrimination for resource allocation in shared computer system.* Eastern Research Laboratory, Digital Equipment Corporation, 1984. 38

[20] Eun-Sun Jung and Nitin H Vaidya. A power control mac protocol for ad hoc networks. *Wireless Networks*, **11**[1-2]:55–66, 2005. 17

[21] Bruno Kauffmann, François Baccelli, Augustin Chaintreau, Vivek Mhatre, Konstantina Papagiannaki, and Christophe Diot. Measurement-based self organization of interfering 802.11 wireless access networks. In *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*, pages 1451–1459. IEEE, 2007. 11

[22] Vikas Kawadia and PR Kumar. Principles and protocols for power control in wireless ad hoc networks. *Selected Areas in Communications, IEEE Journal on*, **23**[1]:76–88, 2005. 8, 17

[23] Tae-Suk Kim, Hyuk Lim, and Jennifer C Hou. Improving spatial reuse through tuning transmit power, carrier sense threshold, and data rate in multihop wireless networks. In *Proceedings of the 12th annual international conference on Mobile computing and networking*, pages 366–377. ACM, 2006. 17, 28

[24] Ramana Rao Kompella and Alex C Snoeren. Practical lazy scheduling in sensor networks. In *Proceedings of the 1st international conference on Embedded networked sensor systems*, pages 280–291. ACM, 2003. 17

[25] Karol Kowalik, Marek Bykowski, Brian Keegan, and Mark Davis. Conservative transmit power control mechanism for 802.11 mesh. In *e-Business and Telecommunications*, pages 399–411. Springer, 2009. 17, 22

[26] Anurag Kumar, D Manjunath, and Joy Kuri. *Communication networking: an analytical approach.* Access Online via Elsevier, 2004. 4

[27] Mathieu Lacage, Mohammad Hossein Manshaei, and Thierry Turletti. Ieee 802.11 rate adaptation: a practical approach. In *Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, pages 126–134. ACM, 2004. 39

[28] Wei Li, Yong Cui, Xiuzhen Cheng, Mznah A Al-Rodhaan, and Abdullah Al-Dhelaan. Achieving proportional fairness via ap power control in multi-rate wlans. *Wireless Communications, IEEE Transactions on*, **10**[11]:3784–3792, 2011. 26, 27

[29] Xi Liu, Srinivasan Seshan, and Peter Steenkiste. Interference-aware transmission power control for dense wireless networks. In *In Proceedings of the Annual Conference of ITA*. Citeseer, 2007. 33

[30] H Ma, J Zhu, and Sumit Roy. On loss differentiation for csma-based dense wireless network. *Communications Letters, IEEE*, **11**[11]:877–879, 2007. v, 31

[31] Hui Ma, Jing Zhu, Sumit Roy, and Soo Young Shin. Joint transmit power and physical carrier sensing adaptation based on loss differentiation for high density ieee 802.11 wlan. *Computer Networks*, **52**[9]:1703–1720, 2008. 31

[32] Vivek P Mhatre and Konstantina Papagiannaki. Optimal design of high density 802.11 wlans. In *Proceedings of the 2006 ACM CoNEXT conference*, page 8. ACM, 2006. 1, 30

[33] Vivek P Mhatre, Konstantina Papagiannaki, and Francois Baccelli. Interference mitigation through power control in high density 802.11 wlans. In *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*, pages 535–543. IEEE, 2007. 32, 59

[34] Andreas F Molisch. *Wireless communications*, **15**. Wiley. com, 2010. 4, 8

[35] Jeffrey P Monks, Vaduvur Bharghavan, and W-MW Hwu. A power controlled multiple access protocol for wireless packet networks. In *INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, **1**, pages 219–228. IEEE, 2001. 17

[36] Alaa Muqattash and Marwan Krunz. Powmac: a single-channel power-control protocol for throughput enhancement in wireless ad hoc networks. *Selected Areas in Communications, IEEE Journal on*, **23**[5]:1067–1084, 2005. 17

[37] Swetha Narayanaswamy, Vikas Kawadia, Ramavarapu S Sreenivas, and PRe Kumar. Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the compow protocol. In *European wireless conference*, **2002**. Florence, Italy, 2002. 17

[38] Jitendra Padhye, Sharad Agarwal, Venkata N Padmanabhan, Lili Qiu, Ananth Rao, and Brian Zill. Estimation of link interference in static multi-hop wireless networks. In *Proceedings of the 5th ACM SIGCOMM conference on Internet Measurement*, pages 28–28. USENIX Association, 2005. 8

[39] Paul Patras, Hanghang Qi, and David Malone. Exploiting the capture effect to improve wlan throughput. In *World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2012 IEEE International Symposium on a*, pages 1–9. IEEE, 2012. 27

[40] Daji Qiao, Sunghyun Choi, Amit Jain, and Kang G Shin. Miser: an optimal low-energy transmission strategy for ieee 802.11 a/h. In *Proceedings of the 9th annual international conference on Mobile computing and networking*, pages 161–175. ACM, 2003. 25

[41] Kishore Ramachandran, Ravi Kokku, Honghai Zhang, and Marco 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*, pages 132–145. ACM, 2008. 14, 22

[42] Kishore Ramachandran, Ravi Kokku, Honghai Zhang, and Marco Gruteser. Symphony: synchronous two-phase rate and power control in 802.11 wlans. *IEEE/ACM Transactions on Networking (TON)*, **18**[4]:1289–1302, 2010. 53, 54

[43] Matias Richart. Ns-3-power-control project. 38, 70

[44] Bahareh Sadeghi. On hidden and exposed terminal problems. *IEEE 802.11-05/0065r0*, 2005. 9

[45] Anant Sahai, Niels Hoven, and Rahul Tandra. Some fundamental limits on cognitive radio. In *in Forty-second Allerton Conference on Communication, Control, and Computing*, 2004. 14

[46] Derek Smithies. Minstrel rate control algorithm. The code of the Minstrel Rate Control Algorithm at the linux kernel sources., 2006. 24, 54

[47] Dongjin Son, Bhaskar Krishnamachari, and John Heidemann. Experimental study of the effects of transmission power control and blacklisting in wireless sensor networks. In *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*, pages 289–298. IEEE, 2004. 17

[48] Suhua Tang, Akio Hasegawa, Riichiro Nagareda, Akito Kitaura, Tatsuo Shibata, and Sadao Obana. Improving throughput of wireless lans with transmit power control and slotted channel access. In *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*, pages 834–838. IEEE, 2011. 26

[49] Ilenia Tinnirello, Sunghyun Choi, and Youngsoo Kim. Revisit of rts/cts exchange in high-speed ieee 802.11 networks. In *World of Wireless*

Mobile and Multimedia Networks, 2005. WoWMoM 2005. Sixth IEEE International Symposium on a, pages 240–248. IEEE, 2005. 45

[50] Starsky HY Wong, Hao Yang, Songwu Lu, and Vaduvur Bharghavan. Robust rate adaptation for 802.11 wireless networks. In *Proceedings of the 12th annual international conference on Mobile computing and networking*, pages 146–157. ACM, 2006. 17, 53, 56, 57

[51] Xue Yang. *Efficient packet scheduling in wireless multihop networks*. PhD thesis, University of Illinois at Urbana-Champaign, 2005. 29

[52] Xue Yang and Nitin Vaidya. On physical carrier sensing in wireless ad hoc networks. In *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, **4**, pages 2525–2535. IEEE, 2005. 11

[53] Yong Yang, Jennifer C Hou, and Lu-Chuan Kung. Modeling of physical carrier sense in multi-hop wireless networks and its use in joint power control and carrier sense adjustment. In *Proc. of IEEE INFOCOM Miniconferences*, pages 6–12, 2007. 17

[54] Jing Zhu, B. Metzler, Xingang Guo, and Y. Liu. Adaptive csma for scalable network capacity in high-density wlan: A hardware prototyping approach. In *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, pages 1–10, 2006. 11, 30