RATE PRIORITIZED POWER ADAPTATION: A THROUGHPUT MAXIMIZING POWER CONSERVATION ALGORITHM FOR IEEE 802.11 WLANS

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Summary

If the rate and power of WLAN transmissions are kept constant, they have to be designed for the worst case channel condition, thus resulting in the wastage of bandwidth and power. Effective utilization of these limited resources is crucial in wireless communications and hence the rate/power adaptations have become the focus of many research works. Methods proposed involve techniques for either power minimization, throughput maximization or a trade off between the conservation of these two resources. In this work, we propose and design a Rate Prioritized Power Adaptation (RPPA) technique for adapting both rate and power with an objective of conserving the power while achieving the best possible bandwidth utilization by maximizing the transmission throughput.

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P_{min}	Minimum power allowed by the RPPA system
P_{max}	Maximum power allowed by the RPPA system
N	Number of power levels in the RPPA system
P_i	Refers to i^{th} power level of the RPPA system
P_{avg}	Average power used by an RPPA system
$P(r)$	Average power required by an RPPA mobile at a distance r from AP
$f_R(r)$	Probability density function of nodes with distance from AP
R_{max}	The maximum radius till which an AP can communicate with a node
$R_{max_{i,j}}$	The outer radii of i^{th} power level in j^{th} mode
$R_{min_{i,j}}$	The inner radii of i^{th} power level in j^{th} mode

List of Abbreviations

AP	Access Point
BER	Bit Error Rate
DCF	Distributed Coordination Function
MAC	Medium Access Control
QoS	Quality of Service
RM	Rate Maximization
RPPA	Rate Prioritized Power Adaptation
RSSI	Received Signal Strength Indicator
SNR	Signal to Noise Ratio
WLANs	Wireless Local Area Networks

Chapter 1

Introduction

In today's world, the usage of wireless LANs (WLANs) has become very common and widespread. Hence the conservation of the resources used by the WLAN devices has gained significant interest among the scientific community. The resources refer to the bandwidth, which has to be utilized effectively in order to accommodate more users and allow higher bit rates, and the power used by the WLAN devices, the conservation of which requires focus as many of the WLAN devices are mobile. The use of these resources in WLANs is optimized by either modifying the physical layer design, which deals with modulation, interleaving, channel coding, diversity techniques employed etc., or by redesigning the data link layer using optimized algorithms (Higher OSI layers focus on end-to-end transmissions and so they are modified only to optimize the network performance; They do not focus on problems caused by individual channels). This work focusses on improving the data link layer used by WLANs. It involves study and design of a particular functionality of the data link layer, namely the rate/power adaptation.

This chapter states the contributions of this work and also discusses the fundamentals of rate/power adaptations. The next chapter discusses the different methods proposed in the current literature for implementing the adaptations. Chapter 3 introduces the Rate Prioritized Power Adaptation (RPPA) algorithm proposed in this work. The simulations performed for an unoptimized RPPA system are discussed in chapter 4. As the next natural step would be to design an optimized system to utilize this algorithm, chapter 5 gives details on the optimization of a general RPPA system. Chapter 6 describes the optimization of RPPA for IEEE 802.11a/g [1], the numerical simulations involved and the results obtained. The next two chapters discuss the simulation results and draw the conclusions of the work. The final section points to possible future directions to be followed to improve upon this work.

1.1 Introduction to Rate/Power Adaptation

1.1.1 The Time-Varying Wireless Channel

The radio propagation channel exhibits many different forms of channel impairments, as a result of time varying signal reflections, blockage and motion. These impairments are broadly classified into three components - Path Loss, Long Term

Fading and Short Term Fading. Diagram to depict these are shown in Figs. 1.1 and 1.2[1]. Figure 1.1 shows, as an example, some points along distances where power may be measured and marks them as H or L based on whether the power measured is greater or lower then the path loss component at that point. This is shown to illustrate the effect of fading and shadowing on received signal. Figure 1.2 follows to explain how the path loss component is the average power at any distance and shadowed component is the average of faded power at that distance.

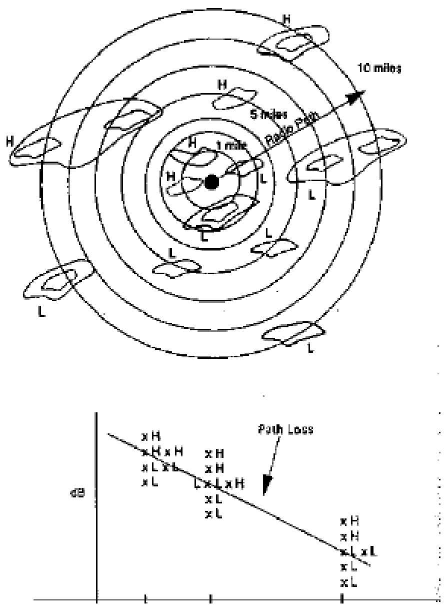

Figure 1.1: Diagram to depict radio environment and Path loss

The path loss is the average decrease in power of signal received as compared to

[1]Figures 1.1 and 1.2 are taken from *Mobile Communications Engineering: Theory and Applications* by William C.Y. Lee [2].

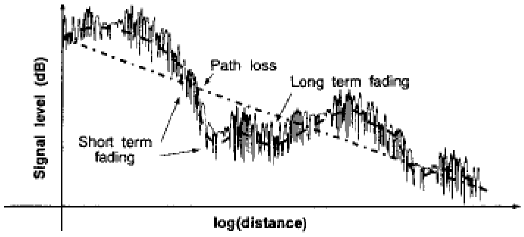

Figure 1.2: Diagram to depict Path loss, Long Term and Short Term Fading in measured power levels

the power transmitted. It is the component which explains the decrease in the received signal with its distance from the transmitter. The long term and short term fading components are attributed to the time varying loss observed in received signal measurements. As the name implies, the long term fading component changes slowly with time and the rapid variation of losses with time is associated to the short term fading component. Long term fading is also referred to as shadowing and is caused by the terrain in which the transmissions take place. The short term fading, on the other hand, takes place due to the receiver capturing not only the transmitted wave, but also its delayed and weakened copies that are reflected by the radio environment. Thus the wireless channel causes the received signal power to be time varying and in turn results in varying signal to noise ratio (SNR) at the receiver.

1.1.2 Fundamentals of Rate and Power Adaptation

This section explains the effect of rate and power adaptation algorithms on the bandwidth utilization and power conservation. All transmissions are constrained by a maximum allowed bit error rate (BER) and transmissions resulting in BER above the limit are declared as unacceptable. For any given BER, the channel defines the minimum received power required given a transmission rate and also defines the maximum rate to be used given a received power. This is because the transmission rate is varied by increasing or decreasing the redundancy in the transmitted packet and with higher received SNR (i.e. for higher transmitted power), redundancy required is lesser (thus allowing higher rate) for achieving the same BER.

As the wireless channel used by the WLAN devices is time-varying, the received power and so the SNR at the receiver keeps varying with time. Hence, for a given BER, the rate has to be decreased if SNR reduces and vice-versa. To efficiently utilize the allocated bandwidth, transmission rate has to be adapted according to the channel condition (with power constant), rather than designing the system rate for the worst case condition. The design for worst case channel condition requires selection of the rate that can be used even in bad channels. So, even when the channel condition improves, a higher rate cannot be used though the channel can accommodate it. Thus the worst case design results in poor utilization of the channel and adapting the rate according to the channel condition improves the utilization. Basically, the rate adaptation scheme is a process of automatically switching the data transmission rate to match the channel conditions, with the goal of maximizing the link utilization.

Alternatively, as the channel condition varies, it is also possible to adapt power accordingly, with the goal of minimizing the power used while keeping the rate constant. In this case, when channel condition improves, the rate is kept constant and the power is decreased based on the decrease in the loss observed. Since many WLAN devices are mobile, power is also an important resource and hence many research works focus on power adaptation and minimization. There are some algorithms that are focussed in their joint adaptations as well. These algorithms are concerned with cases where transmission power would have an impact on throughput and trade-off is possible between the conservation of the two resources. Examples of such scenarios are code vision multiple access (CDMA) (where power affects the interference and hence the throughput) or multi-hop networks (where an increase in power can save hops).

1.2 Contributions

The contributions of this project are as follows.

- This project proposes RPPA algorithm for minimizing power while maximizing throughput in WLAN devices.
- The design parameters for the proposed algorithm are identified and simulations are performed for the different values of the parameters in this project. These simulations are used to prove the superiority of the proposed method.
- The design parameters are optimized using part analytical and part brute force approach and thus the optimized RPPA algorithm is designed.
- Simulations are performed for the optimal RPPA system and it is shown that up to 9% power can be saved while the devices operate at maximum throughput.

Chapter 2

Rate and Power Adaptation Techniques: An Overview

This chapter discusses the various rate, power and joint adaptation techniques proposed in literature.

2.1 Survey of Rate Adaptation Techniques

The first documented bit-rate selection algorithm, Auto Rate Fallback (ARF) [3], was developed for WaveLAN-II 802.11 cards. These cards were one of the earliest multi-rate 802.11 cards and could send at 1 and 2 megabits. ARF aims to adapt to changing conditions and take advantage of higher bit-rates when opportunities appear. It was also designed to work on future WaveLAN cards with more than 2 bit-rates. For a particular link, ARF keeps track of the current bit-rate as well as the number of successive transmissions without any re-transmissions. Most 802.11 wireless cards offer feedback about packet transmission after the transmission has either been acknowledged or exceeded the number of retries without an acknowledgment. When the ARF algorithm starts for a new destination, it selects the initial bit-rate to be the highest possible one. Given the number of retries that a transmission used and whether or not it was successfully acknowledged, ARF adjusts the bit-rate for the destination based on the following criteria:

1. Move to the next lowest bit-rate if the packet was never acknowledged.
2. Move to the next highest bit-rate if 10 continuous transmissions have occurred without any retransmissions.
3. Otherwise, continue at the current bit-rate.

As can be seen, this algorithm is very simple and easy to implement.

Adaptive Auto Rate Fallback (AARF) [4] is an extension of ARF where the step-up parameter is doubled every time the algorithm tries to increase the bit-rate and the subsequent packet fails. This can increase throughput dramatically if packet failures take up a large amount of transmission time. This occurs with the higher bit-rates of 802.11g and 802.11a since the back-off penalty is so high. AARF will instead wait exponentially longer before increasing the bit-rate if no other packet failures occur, which allows it to avoid the throughput reduction resulting from trying high bit-rates that do not work.

But the above algorithms make decisions on individual acknowledgements. ONOE [5] also uses count of acknowledgements for selection of rate. But rather than making decision on individual packets, it uses the failure of a batch of packets to make a decision. Thus it is not prone to individual packet failures, as opposed to its predecessors.

The algorithm proposed in [6] uses signal strength measurements for selecting the rate, as opposed to earlier methods. In this paper, they present a link adaptation algorithm which aims to improve the system throughput by adapting the transmission rate to the current link condition. Their algorithm is simply based on the received signal strength measured from the received frames, and hence it does not require any changes in the current IEEE 802.11 WLAN medium access control (MAC) protocol. Based on the simulation and its comparison with a numerical analysis, it is shown that the proposed algorithm closely approximates the ideal case with the perfect knowledge about the channel and receiver conditions.

The thesis [7] presents the SampleRate bit-rate selection algorithm. It uses combination of throughput computation and count of acknowledgement to determine the rate. SampleRate sends most data packets at the bit-rate it believes will provide the highest throughput. SampleRate periodically sends a data packet at some other bit-rate in order to update a record of that bit-rate's loss rate. SampleRate switches to a different bit-rate if the throughput estimate based on the other bit-rate's recorded loss rate is higher than the current bit-rate's throughput. Measuring the loss rate of each supported bit-rate would be in-efficient because sending packets at lower bit-rates could waste transmission time, and because successive unicast losses are time-consuming for bit-rates that do not work. SampleRate addresses this problem by only sampling at bit-rates whose lossless throughput is better than the current bit-rate's throughput. SampleRate also stops probing at a bit-rate if it experiences several successive losses. This thesis presents measurements from indoor and outdoor wireless networks that demonstrate that SampleRate performs as well or better than other bit-rate selection algorithms. SampleRate performs better than other algorithms on links where all bit-rates suffer from significant loss.

In [8], the authors propose a practical rate adaptation algorithm, Smart Sender, which utilizes both statistics and the received signal strength indicator (RSSI) of ACK packets to determine the transmission rate that maximizes the throughput. They implement the algorithm in commercial WLAN products and carry out extensive experiments for performance evaluation. The results demonstrate that using throughput computations, count of ACK packets and RSSI of ACKs greatly improves system throughput and responsiveness under various wireless environments.

Zhang *et al.* focussed on practical constraints in rate adaptation and solved them [9]. Most work relies only on frame losses to infer channel quality, but performs poorly if frame losses are mainly caused by interference. In their work, they conducted a systematic measurement-based study to confirm that in general SNR is a good prediction tool for channel quality, and identify two key challenges for this to be used in practice:

1. The SNR measures in hardware are often uncalibrated and so the thresholds are hardware dependent.

2. The direct prediction from SNR to frame delivery ratio is often over optimistic in interference conditions.

Based on these observations, they present a novel practical SNR- Guided Rate Adaptation scheme which solves the practical constraints not addressed in other works.

Another common technique is the one proposed by Qiao *et al.*, where they use tables of payload length and rate to perform the rate adaptation [10]. In their work, they present a generic method to analyze the goodput performance of an 802.11a system under the distributed coordination function (DCF) and express the expected effective goodput as a closed-form function of the data payload length, the frame retry count, the wireless channel condition, and the selected data transmission rate. Then, based on the theoretical analysis, they propose a novel MPDU (MAC protocol data unit)-based link adaptation scheme for the 802.11a systems.

It is a simple table-driven approach and the basic idea is to preestablish a best PHY mode table by applying the dynamic programming technique. The best PHY mode table is indexed by the system status triplet that consists of the data payload length, the wireless channel condition, and the frame retry count. At runtime, a wireless station determines the most appropriate PHY mode for the next transmission attempt by a simple table lookup, using the most up-to-date system status as the index.

Zhou *et al.*, in [11], use correlation techniques for ascertaining the appropriate rate. Existing schemes either assume perfect channel information, or conduct rate adaptation in a black box way, hence can not achieve desirable performance. They propose a novel scheme called correlation based rate adaptation to address the rate adjustment problem. Unlike other schemes, this splits rate into more atomic components and adjusts them according to the correlation between rate adaptation actions and transmission results. They use IEEE 802.11n as the context for design, where transmission mode has been expanded to spatial dimension in addition to the usual modulation and convolution coding mechanisms. Performance evaluation shows that proposed scheme can conduct rate adaptation in a more logical way and significantly outperform the comparison scheme.

Won and Kim, in their work, propose a rate adaptation technique which involves overhearing and determining rates of other users' packets for evaluating the optimal rate (as opposed to estimating the channel condition for the adaptation) [12]. Various rate adaptation schemes that select optimal transmission rate according to the receivers' channel condition have been proposed. In their paper, they propose a novel rate adaptation scheme that performs well without control overhead. The key idea of their proposed scheme is that if a station successfully overhears a downlink transmission whose data rate is higher than its current rate, then it requests the AP to increase the data rate to overheard frame's transmission rate. Thus they adapt rate without measuring any channel statistics.

In WLANs, a packet may be lost due to fading/shadowing or as a result of collisions. Rate adaptation techniques often misinterpret packet loss due to collision as decrease in SNR, thus degrading the performance. One of the key challenges in designing a rate adaptation scheme for IEEE 802.11 WLANs is to differentiate bit errors from link-layer collisions. Many rate adaptation schemes adopt the RTS/CTS mechanism to prevent collision losses from triggering unnecessary rate decrease. However, the RTS/CTS handshake incurs significant overhead and is rarely activated in today's infrastructure WLANs.

In [13], the authors propose a new rate adaptation scheme that mitigates the collision effect on the operation of rate adaptation. In contrast to the previous approaches adopting fixed rate-increasing and decreasing thresholds, their scheme varies threshold values based on the measured network status. Using the "retry" information in 802.11 MAC headers as feedback, they enable the transmitter to estimate current network state. The proposed rate adaptation scheme does not require additional probing overhead incurred by RTS/CTS exchanges and can be easily deployed without changes in firmware. They demonstrate the effectiveness of our solution by comparing with existing approaches through extensive simulations.

Rate adaptation is one of the basic functionalities in today's WLANs. Although it is primarily designed to cope with the variability of wireless channels and achieve higher system spectral efficiency, its design needs consideration of cross-layer dependencies, in particular the link-layer collisions. Most practical rate adaptations focus on the time-varying characteristics of wireless channels, ignoring the impact of collisions. As a result, they may lose their effectiveness due to unnecessary rate downshift wrongly triggered by the collisions. Some proposed rate adaptations use RTS/CTS to suppress the collision effect by differentiating collisions from channel errors, but the RTS/CTS handshake, however, incurs significant overhead and is rarely activated in infrastructure WLANs. In [14], authors propose a unique collision-aware rate adaptation scheme, called Probabilistic-Based Rate Adaptation. The key ideas include

1. Probabilistic-based adaptive usage of RTS/CTS, which is in direct contrast to trial based RTS Probing and window-based adaptive usage of RTS/CTS.

2. Threshold-based rate adjustment, which allows a station to make more appropriate rate adjustment decisions, thanks to its accurate estimation of the channel-errors.

Simulation results show that this scheme clearly outperforms all other testing schemes, particularly in random topology networks with fading wireless channels.

In [15], the authors introduce a new approach for optimizing the operation of rate adaptations by adjusting the rate-increasing and decreasing parameters based on link-layer measurement, thus designing an algorithm to be collision aware. To construct the algorithm, they study the impact of rate-increasing and decreasing thresholds on performance and show that dynamic adjustment of thresholds is an effective way to mitigate the collision effect in multi-user environments. Their method does not require additional probing overhead incurred by RTS/CTS exchanges and may be practically deployed without change in firmware. They demonstrate the effectiveness of our solution, comparing with existing approaches through extensive simulations.

Ref. [16] is also an example of rate adaptation considering collisions. Here, instead of dealing with individual collisions, the algorithm estimates the current traffic and uses these estimates for adaptations. In this work, the authors conduct a systematic evaluation on the effectiveness of various existing rate adaptation algorithms and related proposals for loss differentiations, with multiple stations transmitting background traffic in the network. They observe that existing RTS-based loss differentiation schemes do not perform well in all background traffic scenarios.

In addition, they realize that RTS-based loss differentiation schemes can mislead the rate adaptation algorithms to persist on using similar data rate combinations regardless of background traffic level, thus result in performance penalty in certain scenarios. The fundamental challenge is that a good rate adaptation algorithm must dynamically adjust the rate selection decision objectives with respect to different background traffic levels. So they design a new Background traffic aware rate adaptation algorithm (BEWARE) that addresses the above challenge. BEWARE uses a mathematical model to calculate on-the-fly the expected packet transmission time based on current wireless channel and background traffic conditions.

Varzakas, in [17] and [18], makes an assumption that the transmission rate can take the theoretically optimal value at any instant and optimize the parameters of CDMA and orthogonal frequency division multiplexing (OFDM) communication systems respectively.

A hybrid direct-sequence/slow frequency hopping code-division multiple-access system operating in Rayleigh fading is described and its spectral efficiency is estimated in terms of the theoretically achievable average channel capacity (in the sense of information theory) per user in Ref [17]. The analysis covers the operation over a broadcast cellular time-varying link and leads to a simple, novel closed-form expression for the optimal number of simultaneously active users per cell based on the maximization of the achieved spectral efficiency.

The spectral efficiency of an OFDM cellular system operating in a Rayleigh fading environment is described and estimated in terms of the theoretically achievable average channel capacity (in the Shannon sense) per user in [18]. The analysis covers the operation over a downlink cellular time-varying link and leads to a simple novel closed-form expression for the optimal number of individual OFDM subcarriers, based on the maximization of the achieved spectral efficiency.

Lin *et al.* analyze the effect of link adaptation on the performance of HiperLAN 2 in [19]. HiperLAN type 2 is a wireless broadband access network standard, which operates in the 5 GHz band. A key feature of the physical layer of HiperLAN/2 is link adaptation, i.e., the dynamic selection of one out of various physical layer modes with different coding and modulation schemes. In this paper, the system performance of link adaptation for packet data services within the H/2 concept is studied. The simulation results show that a high user throughput can be reached in the investigated environments.

2.2 Various Power Adaptation Techniques in Literature

The various power adaptation techniques are as follows.

Kalaf and Rubin realize focus on multi hop networks and state that high power can save hops in multi hop routing and use that information to indirectly save the power (by reducing the total number of hops in the transmission) by adapting it [20].

Paul *et al.*, in their work, study the effect of forward error correction and automatic repeat requests on power used and propose to adapt them in order to minimize total power used [21]. Low power consumption is a key design metric for portable wireless network devices where battery energy is a limited resource. The resultant energy efficient design problem can be addressed at various levels of system design, and indeed much research has been done for hardware power optimization and power management within a wireless device. However, with the increasing trend towards thin client type wireless devices that rely more and more on network based services, a high fraction of power consumption is being accounted for by the transport of packet data over wireless links. This offers an opportunity to optimize for low power in higher layer network protocols responsible for data communication among multiple wireless devices.

Consider the data link protocols that transport bits across the wireless link. While traditionally designed around the conventional metrics of throughput and latency, a proper design offers many opportunities for optimizing the metric most relevant to battery operated devices: the amount of battery energy consumed per useful user level bit transmitted across the wireless link. This includes energy spent in the physical radio transmission process, as well as in computation such as signal processing and error coding.

Their work describes how energy efficiency in the wireless data link can be enhanced via adaptive frame length control in concert with adaptive error control based on hybrid forward error correction and automatic repeat request. Key to their approach is a high degree of adaptivity. The length and error coding of the atomic data unit (frame) going over the air, and the retransmission protocol are (a) selected for each application stream based on quality of service (QoS) requirements, and (b) continually adapted as a function of varying radio channel conditions due to fading and other impairments.

A distributed power control mechanism is described in [22] as another approach for saving the power in WLANs. In their paper, distributed power control is proposed as a means to improve the energy efficiency of routing algorithms in ad hoc networks. Each node in the network estimates the power necessary to reach its own neighbors, and this power estimate is used both for tuning the transmit power (thereby reducing interference and energy consumption) and as the link cost for minimum energy routing. With reference to classic routing algorithms, such as Dijkstra and Link State, as well as more recently proposed ad hoc routing schemes, such as AODV, they demonstrate by extensive simulations that in many cases of interest their scheme provides substantial transmit energy savings while introducing limited degradation in terms of throughput and delay.

2.3 Joint Rate and Power Adaptation Techniques

The following works are concerned with joint adaptations.

Ref. [23] is a paper concerned with power control for CDMA systems. The benefits of adaptive joint power control and rate allocation for uplink transmission in a wideband CDMA cellular system are investigated. Closed-loop power control, to adaptively adjust the transmit power, has the effect of maintaining a target signal-to-interference ratio and BER performance. On the other hand, rate adaptation requires less transmit power, although the BER performance may be poorer.

The authors differentiate the power update interval from the data rate update interval, analyze and evaluate the performance of two joint rate/power adaptation algorithms in a fading environment: optimal spreading factor-power control and greedy rate packing-power control. Numerical results show that latter scheme exhibits superior throughput performance compared with other three adaptation schemes. Closed Loop Power Control alone exhibits throughput and BER performances comparable to those of the former scheme, but consumes a significantly higher amount of transmit power. Rate adaptation only is not efficient in enhancing throughput, but its power consumption is minimal.

Li *et al.* choose rate to minimize the number of hops and hence power in a multi-hop network [24], thus adapting rate to minimize power. Multiple physical layer rates are supported in IEEE 802.11-based wireless networks, where links can adopt joint transmission power control and rate adaptation to achieve energy efficiency. This paper studies the selfish rate adaptation behavior under throughput requirement.

A round-based non-cooperative game is proposed assuming there is only one link which can adjust its transmission strategy in each unit time. It is shown that there is an optimal transmission strategy for a link, and a greedy algorithm is presented to select a near-optimal transmission strategy. It is observed that scheduling order affects the feasibility and the total power consumption. To alleviate the influence of scheduling order, pricing function is introduced, which motivates selfish links to share the channel fairly and efficiently. Simulation results show the proposed approach leads to not only more feasible solutions, but also power efficiency.

Wang *et al.* select the rate for minimizing power by formulating it as an optimization problem [25]. In their paper, they study the problem of using the rate adaptation technique to achieve energy efficiency in an IEEE 802.11-based multihop network. Specifically, they formulate it as an optimization problem, i.e., minimizing the total transmission power over transmission data rates, subject to the traffic requirements of all the nodes in a multihop network. They can show that this problem is actually a well-known multiple-choice knapsack problem, which is proven to be an NP-hard problem.

Therefore, instead of finding an optimal solution they seek a suboptimal solution. The key technique to attack this problem is distributed cooperative rate adaptation. Here, they promote node cooperation due to our observation that the inequality in noncooperative channel contention among nodes caused by hidden terminal phenomenon in a multi hop network tends to result in energy inefficiency. Under this design philosophy, they propose the new scheme and prove that it converges.

Zhao *et al.* select the rate to minimize retransmissions and hence the power used [26]. In their work, they investigate the joint effect of MAC and physical layers on power efficiency in IEEE 802.11a WLAN. Specifically, they study the link adaptation for a power efficient transmission by selecting a proper transmission mode and power level with the aid of our derived power efficiency model.

This study addresses the fundamental impact of the MAC protocol on the power efficiency of IEEE 802.11a WLANs. Some implications for system design are also discussed. In particular, they show that the non-radio-transmission power plays an important role in the power optimization of IEEE 802.11a WLAN.

Kim and Huh in their work allow either power or rate adaptation based on channel conditions, hence allowing either throughput maximization or power minimization [27]. Link Adaptation techniques, such as rate adaptation and power control, aim at reliable data transmission through maintaining link quality. In order to do that, they measure the performance of WLAN in real environments that produce unexpected interference from neighbor access points or electronic devices.

In this paper, they propose a strategy for the link adaptation technique in WLAN MAC. The new strategy provides two decisions to estimate the link condition and to manage both the transmission rate and power. Finally, they show reliable transmission through the throughput measurement.

Chapter 3

The RPPA System

3.1 Introduction to RPPA

The bandwidth and power used by the WLAN devices have to be conserved effectively. Rate and power adaptation are suggested in literature to diminish the negative impact of time varying wireless channels on the utilization of the two resources. Many adaptation algorithms have been reported to either maximize the throughput or minimize the power consumed by the WLAN devices. Algorithms are also developed for the joint adaptations of rate and power to allow a trade-off between the conservation of the two resources in the WLAN devices. Theoretically, rate and power can be varied continuously and selecting one defines the other for an optimally performing system. However, as opposed to other literature, the proposed RPPA algorithm recognizes that practical systems allow only a finite number of transmission rates (The IEEE 802.11a/g allows selection of rate from a set of 8 distinct values) and therefore power minimization is possible even after the selection of the rate that maximizes the throughput. Thus, the RPPA algorithm proposed in this chapter, distinguishes theory and practice and takes advantage of the limitations of practical systems effectively to conserve both the resources, as opposed to the other algorithms that allow only trade-offs.

3.2 Principle

The wireless channel condition keeps varying with time due to (fast and slow) fading and shadowing effects. This causes the SNR of the received packet to change with time. Each rate of transmission (supported in IEEE 802.11a/g) requires a minimum SNR at the receiver to ensure an acceptable BER. If it is lesser than the required SNR for a given rate, then using that rate would result in more than acceptable errors and hence the rate of transmission has to be switched to a lower one. However, maintaining SNR above the threshold level is unnecessary. In an ideal scenario, as SNR varies continuously, the rate has to be varied continuously in order to maximize the throughput. But only discrete rates are allowed to be used by the transmitter in any practical system. The IEEE 802.11 standard allows these discrete rates of transmissions – 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. Since the rates are discrete, there are only discrete threshold SNR values for these rates. Therefore, even after selecting the rate (to maximize the throughput), the transmission power can be minimized so long as the SNR is above the required threshold for the selected rate. Hence, in practical systems, it is possible to minimize power, to some extent, even after throughput maximization. This is the principle behind the proposed RPPA algorithm.

3.3 RPPA Algorithm Details

RPPA involves two stages of adaptation: the rate selection, which is followed by the optimal power choice. During any transmission period, the instantaneous received power, and hence the received SNR, is determined by the transmit power, the path loss, shadowing and fading components. The primary objective of the algorithm is to determine the maximum rate that can be transmitted at any instant of time, so as to maximize the throughput. Hence, for any given loss, it first needs to determine the maximum SNR (the SNR of the received packet when transmission takes place at maximum power) that can be received. This SNR would be greater than the minimum threshold SNR required for some of the rates. The algorithm has to then select the maximum rate possible of those in the list.

Once a rate is selected, the minimum required SNR at the receiver is known. Hence the transmitter power can be minimized so that the received SNR is nearly the threshold required for the chosen rate and no more. But since the channel is continuously varying, it is always possible that the loss can increase in the next transmission. The transmitter power computed by the above procedure must be increased by some percentage so as to accommodate the possible change. An increase of 1.8% was used to counter the effect of the channel's Doppler spread in this chapter. As this value may be different for practical implementations, it is important to realize that this does not have a direct impact on the power saved (though intuitively it may seem that an increase in its value should have a negative influence on the power saved!!!), the reasons being as follows. Once a confidence interval is chosen for the algorithm, the threshold SNR values of the different modes have to be increased based on the magnitude of the selected confidence interval. But, since the threshold SNRs of all the modes are translated by similar values, the gap between the thresholds of the consecutive modes remains almost the same (as before translation). As the power saved by the proposed RPPA algorithm is dependent only on the gaps between the threshold SNRs of the consecutive modes (and not on their values), the power saved is quite independent of the magnitude of the confidence intervals. However, since the confidence intervals are defined as percentages, they will be slightly different for each of the threshold SNRs and so will result in some variation in the power saved for the different channel conditions (but it will not have a direct negative impact!!!).

The receiver at any instant knows the SNR of the packet received and also the required SNR. Thus it can compute the decrease in transmission power which allows the transmission at the chosen rate. The receiver can then send the request for the decrease in power along with the request for the new rate. (Note that the receiver need not know the details of path loss at all. It can just send the decrease in power required and the transmitter can decrease transmit power accordingly.)

In practical cases, the power is varied in discrete steps. So the new power is computed by the transmitter and then the lowest power greater than (or equal to) the new computed transmission power is selected for transmission.

3.4 Algorithm

The adaptation algorithm is therefore as follows:

- *Initialize Threshold SNR table* $SNR_{Th_i} \forall i$, *where higher index value represents higher rate.*

- *For each packet in receiver , determine the received SNR value* SNR_{Rx}.

- *To compute the highest rate possible,*

$$\max_{SNR_{Th_i} > SNR_{Rx}} i$$

- *Calculate* $SNR_{diff} = SNR_{Th_i} - SNR_{Rx}$ *and send the difference to transmitter.*

- *The new transmission power at transmitter* $P_{T_{New}} = P_T - SNR_{diff}$, *where* P_T *is the old transmission power.*

Chapter 4

Simulations of Unoptimized RPPA System

This chapter discusses the simulations performed and the performance gain obtained with the implementation of an unoptimized RPPA system. The RPPA system is entirely characterized by the list of power levels allowed for the system. In an unoptimized system, it is assumed that the power levels allowed for transmission are uniformly distributed. This chapter is divided into sections based on the different steps followed. The first section deals with the experiment for determining the threshold SNR for the eight modes of IEEE 802.11a/g standard. The description of the algorithm with which the proposed algorithm is compared and the metric that is used for the comparison follows in the next section. The third section explains the choice of different design parameters that are of practical significance to the implementation of the proposed algorithm and the final section gives the results. For ease of representations, the different modes of IEEE 802.11 are labeled in this chapter as shown in Table 4.1. Also, SNR_{Rx} is used to denote the received SNR when the transmission is done at maximum power allowed by the system.

4.1 Determination of the Threshold SNRs

The minimum SNR requirement criteria for any rate is assumed to be the SNR at which the resulting BER would be 10^{-5} (for a transmission at that rate) and that SNR is defined as the threshold SNR for the rate in consideration. This implies that a mode can be used so long as SNR_{Rx} is greater than the threshold SNR for that mode. BER vs SNR curves are plotted, using simulations (hard decoding assumed), to determine the threshold values for the different modes allowed in IEEE 802.11 and is shown in Fig. 4.1. It also has the reference BER value of 10^{-5} marked in order to facilitate the determination of the threshold SNR values.

As can be seen from Fig. 4.1, Mode 1 needs higher SNR for reaching the threshold BER as compared to Mode 2, even though the former mode involves transmissions at lower rate. Hence, whenever SNR_{Rx} reaches the threshold SNR for Mode 1, it satisfies the minimum SNR criteria for Mode 2 and so the adaptation

Table 4.1: Label for different Rates of IEEE 802.11

Rate	**Mode Label**
BPSK Rate 1/2	Mode 0
BPSK Rate 3/4	Mode 1
QPSK Rate 1/2	Mode 2
QPSK Rate 3/4	Mode 3
QAM16 Rate 1/2	Mode 4
QAM16 Rate 3/4	Mode 5
QAM64 Rate 2/3	Mode 6
QAM64 Rate 3/4	Mode 7

algorithm can switch to the latter mode (as it allows a higher rate of transmission). Thus Mode 1 is not used at all in the adaptations. The threshold SNRs for the different modes is obtained from the figure and is shown in Table 4.2.

4.2 Rate Maximization Algorithm

This subsection defines the algorithm to be compared with RPPA. The comparison is performed between the proposed algorithm and an algorithm that would maximize the rate without adapting the power. The latter algorithm is called the Rate Maximization (RM) algorithm. Both these algorithms result in similar throughput (since they both choose the maximum of all the rates that satisfy the SNR

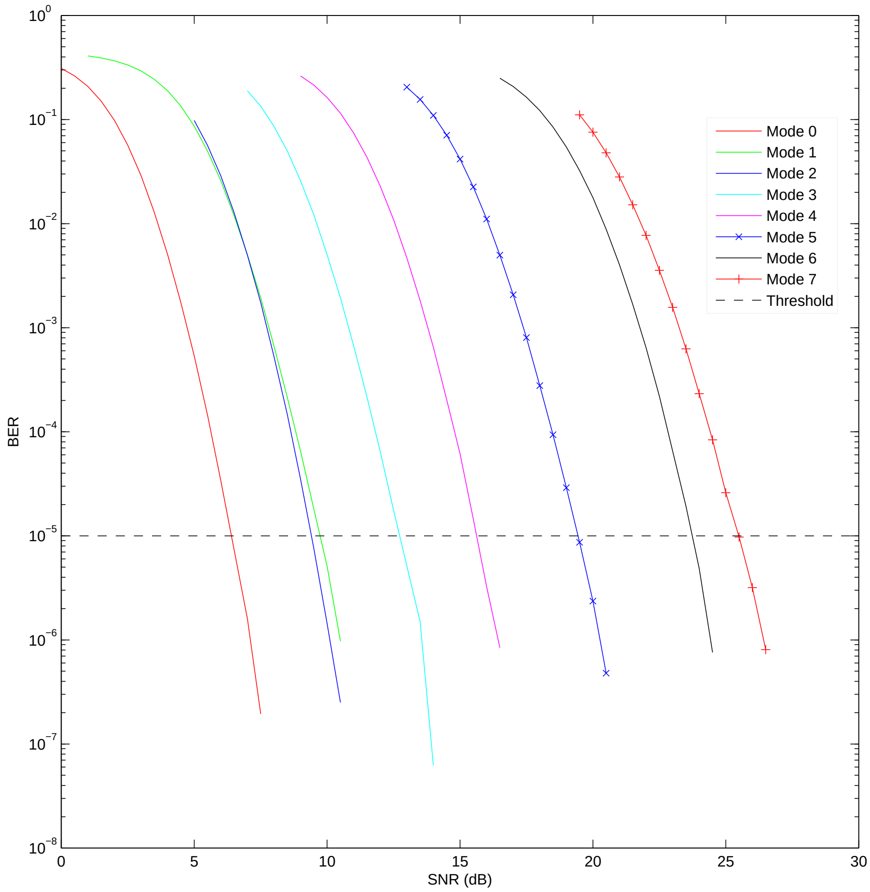

Figure 4.1: BER vs SNR for different rates of IEEE 802.11

constraint) but the proposed algorithm also saves as much power as possible while the other algorithm always transmits at maximum power. Hence the comparison metric is chosen to be the power saved by RPPA, for the same throughput delivery as the RM algorithm.

Table 4.2: Minimum SNR Thresholds for different Rates

Mode	**SNR(dB)**
Mode 0	6
Mode 2	9
Mode 3	13.5
Mode 4	16
Mode 5	19
Mode 6	23.5
Mode 7	26

4.3 Design Parameters

The next step is to determine the different parameters on which the power saved would be dependent on. Clearly, one of the parameters is the number of power levels (or the number of bits required to represent the power chosen, which is log to the base 2 of the total number of levels). As the number of steps increases, the saving in power should increase, till it reaches saturation. The implicit assumption here is that the power levels are uniformly distributed, thus making the system an unoptimized one. Optimization of the RPPA system follows in the following chapter.

The second parameter varied in the simulations is the minimum power (P_{min}) to be used by the system. The maximum power level allowed by the system,

P_{max}, is not considered as a design parameter since it's value is often dictated by other constraints. P_{min} can be designed to be the minimum power level of any transmit mode (which is the minimum power at which the mode would still be used by RPPA algorithm). The definition of minimum power of transmit mode needs further clarification, as is given below. To understand the meaning of minimum power level of a mode, consider a mobile device that is moving towards the access point (AP). As it moves nearer, the transmit power can be reduced depending on its distance from AP. But at a certain distance, the mobile device would realize that transmission at a higher rate is possible if it transmits at P_{max}. Thus, just before the mobile device reaches that distance, it would be transmitting at minimum power for that mode. After it reaches that distance, the mode will no longer be used (as the mobile device moves closer and closer). Thus each mode will have a minimum transmit power level. Thus the minimum power level for any mode is determined by the difference between its own threshold SNR and that of the next higher mode.

This is chosen as a parameter for the following reason. The minimum power levels for the different modes are different. Selecting one of them as P_{min} has the following effect. Some of the modes will have minimum power levels greater than P_{min} and they will be using only part of the power levels in the system (They will ignore the power levels that are lesser than their minimum power levels). On the other hand, the modes that have minimum power levels lesser than P_{min} will have to use P_{min} even if they can use lower powers for transmission, thus using higher than necessary power. That is because P_{min} is the lowest level that the system allows for transmission.

Table 4.3: Minimum Power allowed for different Rates

Mode	**Power(dBm)**
Mode 0	17
Mode 2	15.5
Mode 3	17.5
Mode 4	17
Mode 5	15.5
Mode 6	17.5
Mode 7	15

4.4 Simulation and Results

The simulations are performed for different values of the chosen parameters. The maximum transmit power is assumed to be $20dBm$ and noise power is assumed to be $-96dBm$ for simulation purposes. The maximum transmit power level and noise power level values are taken from [28]. For the maximum power assumed, the minimum power levels for different modes are obtained as shown in Table 4.3.

As can be seen, the minimum power levels are repetitive in some cases. Hence, in plots of results, the minimum power levels are labeled as given in Table 4.4.

Table 4.4: Label for Minimum Powers in figures

Label	**Power(dBm)**
$MinPw$ 1	15
$MinPw$ 2	15.5
$MinPw$ 3	17
$MinPw$ 4	17.5

The results for different number of steps and different minimum power levels are plotted. Figure 4.2 shows the percentage increase in power used, from the proposed algorithm to the rate maximizing algorithm, for the same throughput (The average power used by the RM system is always $20dBm$).

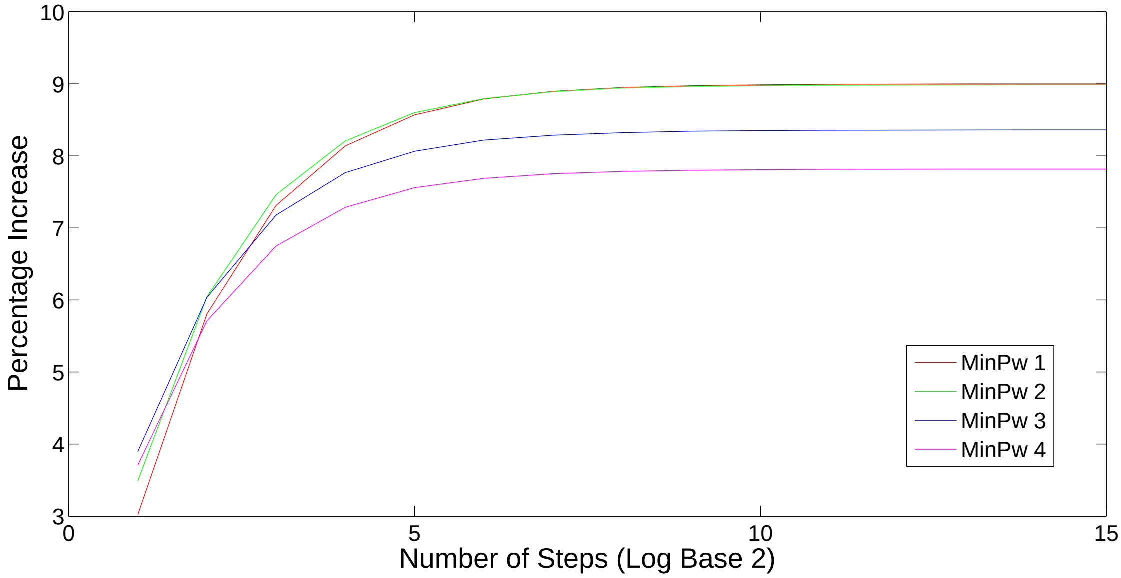

Figure 4.2: Percentage increase in power from RPPA system to RM system vs No. of power levels (Log base 2)

Chapter 5

Optimization Algorithm for the RPPA System

5.1 Problem Statement

The RPPA system is entirely characterized by the list of power levels allowed for the system as the list of allowed rates in predefined in the IEEE 802.11 standard. In the earlier chapter, the power levels were assumed to be uniformly distributed between the selected P_{min} and the maximum power allowed. In this chapter, the list of power levels to be selected is optimized. From the description of the algorithm, it is clear that the system always delivers the maximum throughput possible. Thus the power saved by the algorithm is the parameter to be optimized. Therefore the optimization problem is to determine the list of power levels that result in maximal savings in power. It is a constrained optimization problem, as the maximum and minimum power levels allowed are dictated by other factors. The number of power levels used (N) is a design parameter and is decided beforehand. Thus the optimization problem is defined as - "`to choose` N `power levels that maximizes the power saved, given the maximum and minimum power levels allowed as constraints`".

5.2 Problem Formulation

Given the list of power levels ($P_i, i = 1, .., N$) such that $P_k < P_{k+1}$, the problem is to compute the average power (P_{avg}) used. Then the optimization problem can be written as,

$$\min_{P_{min} \leq \{P_i, i=1,..,N\} \leq P_{max}} P_{avg}. \tag{5.1}$$

To compute P_{avg}, it must be realized that the power used by the algorithm at any instant may be dependent on many factors, but the time average power at any point is dependent only on the path loss and hence only on the distance (of the point) from the AP. Therefore, P_{avg} can be expressed as,

$$P_{avg} = \int_0^{R_{max}} P(r) f_R(r) dr, \tag{5.2}$$

where $P(r)$ is the power used at a distance r, R_{max} is the distance beyond which a mobile device cannot communicate with the AP (which depends on the choice of

P_{max}) and $f_R(r)$ is the probability density function (pdf) of the nodes that access the AP. If R_{max}, $P(r)$ and $f_R(r)$ are computed in terms of the power list selected, then the problem is completely formulated.

5.3 The Probability Density Function ($f_R(r)$)

The probability of finding a node at a distance r is proportional to the area of a strip at a distance r and of width dr. The area of the strip at distance r is given by,

$$A(r) = 2\pi r dr. \tag{5.3}$$

Therefore the probability of finding a node at a distance r, $Prob(r)$, can be written as,

$$Prob(r) = \frac{2\pi r}{\int_0^{R_{max}} 2\pi r dr} dr. \tag{5.4}$$

Also, $Prob(r)$ can be written in terms of pdf as follows.

$$Prob(r) = f_R(r)dr. \tag{5.5}$$

Therefore, from Eqs.(5.4) and (5.5),

$$f_R(r) = \frac{2r}{R_{max}^2}. \tag{5.6}$$

The pdf has been found in terms of R_{max} here. So, if R_{max} is computed in terms of power list selected, then the pdf can also be found in terms of the power list by using Eq.(5.6).

5.4 Power at a Distance r ($P(r)$)

To intuitively understand how $P(r)$ can be defined, consider the following arguments. As a mobile device moves away from the AP, the rate used for transmission has to be decreased in steps thus giving rise to the division of the given region into different bands corresponding to different rates. And within a single rate band, as the mobile device moves from the band's inner circle towards its outer boundary, the transmitter power used has to be increased in steps. A pictorial representation of the variation of modes (for IEEE 802.11) and power levels within modes, on an average, with distance from AP is shown in Fig. 5.1. The modes (Mode i, i$= 0, 1, .., 7$) in the figure corresponds to different rate such that Mode 0 uses the lowest rate and Mode 7 the highest rate. Note that Mode 1 is not used by mobile devices, as had been explained earlier.

From the figure and the argument, it is evident that any power level is used in a number of discrete bands, which can be defined by their inner and outer radii.

$$P(r) = \begin{cases} P_i \ ; & R_{min_{i,j}} \leq r \leq R_{max_{i,j}} \ \forall i \epsilon [1..N] \ \forall j \epsilon [0..(M-1)] \\ 0 \ ; & otherwise \end{cases} \tag{5.7}$$

Clearly, $R_{max_{i,j}}$ and $R_{min_{i,j}}$ are the outer and inner radii of the band using power P_i and rate of Mode j, in a system having a total of M modes (again, Mode 0

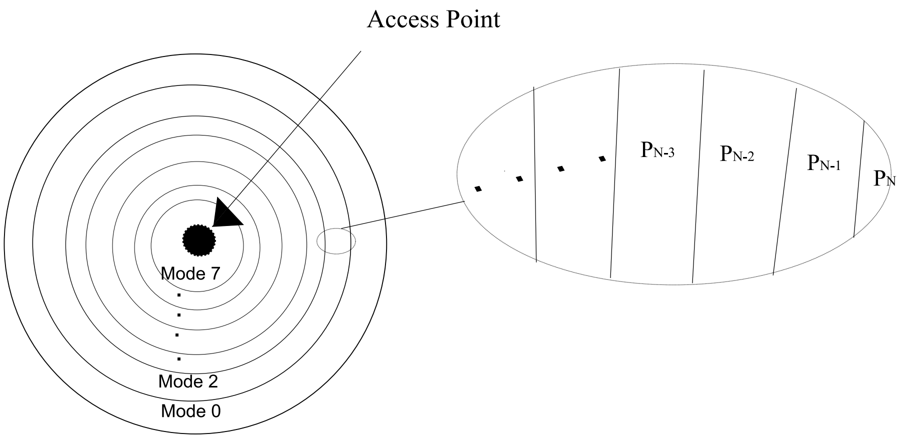

Figure 5.1: Variation of modes and power levels, on an average, from AP

referring to the lowest rate mode). The set $[a..b]$ is used to indicate the set of all integers in the range $[a, b]$.

5.5 Average Power (P_{avg})

Here the average power is evaluated in terms of the various radii. In Eq.(5.6), the pdf had been evaluated in terms of R_{max}. Clearly, the mobile device at the farthest distance (R_{max}) from AP is going to be using the lowest rate and highest possible power. Thus,

$$R_{max} = R_{max_{N,0}}. \tag{5.8}$$

Hence, substituting Eqs.(5.6),(5.7) and (5.8) in Eq.(5.2), we get,

$$P_{avg} = \sum_{i=1}^{N} \sum_{j=0}^{M-1} \int_{R_{min_{i,j}}}^{R_{max_{i,j}}} P_i \frac{2r}{R^2_{max_{N,0}}} dr. \tag{5.9}$$

Solving Eq.(5.10), the average power used by the algorithm is obtained in terms of the inner and outer radii as well as the given power levels.

$$P_{avg} = \sum_{i=1}^{N} \sum_{j=0}^{M-1} \frac{P_i}{R^2_{max_{N,0}}} \left[R^2_{max_{i,j}} - R^2_{min_{i,j}} \right]. \tag{5.10}$$

Having determined P_{avg} in terms of power level list and inner/outer radii, solving for the inner and outer radii as a function of the given power levels will completely describe the average power in terms of the power levels.

5.6 Inner & Outer Radii

The inner radii of one band acts as the outer radii of the previous band. Hence it suffices to determine all the outer radii in terms of power levels and the inner radii would automatically be determined. Thus,

$$R_{min_{i,j}} = \begin{cases} R_{max_{i-1,j}} \ ; & \forall i \epsilon [2..N] \ \forall j \epsilon [0..(M-1)] \\ 0 \ ; & otherwise \end{cases} . \tag{5.11}$$

The maximum radii of different power levels in different modes is computed in two steps. In the first step, the maximum radii of the different modes is computed under the temporary assumption that the different modes exist separately and that there is no switch between the modes. In the second step, the assumption is revoked and the effect of co-existence of all the modes, on the computed radii values, is determined. The temporary assumption is made only to split the computation of the radii into two fairly straight forward steps.

When the modes are considered individually, the maximum radii for i^{th} power level in j^{th} mode is given by,

$$R_{max_{i,j}} = d_0 10^{\frac{P_i - P_{R_j}}{10n}}, \tag{5.12}$$

where n and d_0 are channel based constants and P_{R_j} is the minimum threshold received power for the j^{th} mode, to be computed from the threshold SNR values and noise power. Equation (5.12) has been obtained by using the well known path loss equation [2] to compute the distance at which each transmitted power level, P_i, would reach down to the threshold received power value of each of the modes, P_{R_j}.

The above equation assumes that the modes exist independently. To determine the radii values when the modes can switch between one another, it has to be realized that a lower mode (lower rate) is to be given lesser importance than the next higher mode. Hence, once the distance reaches the point when the higher mode can be used, the lower mode is no longer used. This has the following impact on the radii computation.

$$R_{max_{i,j}} = \max\{R_{max_{i,j}}, R_{max_{N,j+1}}\}. \tag{5.13}$$

The above equation can be interpreted as follows. Whenever a band of a mode j lies within any band (and thus within the outermost band) of mode $j+1$, the former band is dissolved indirectly by equating both its inner and outer boundary to the same value $R_{max_{N,j+1}}$.

5.7 Optimization

It can be observed, from the equations derived in this section, that the optimization cannot be solved by using just mathematical tools. A brute force approach was used for solving the optimization problem. The range $[P_{min}, P_{max}]$ was divided into a set $[P_{min}, P_{min} + \triangle P, P_{min} + 2\triangle P, ..., P_{max}]$ by selecting an appropriate value for $\triangle P$, where $\triangle P$ is a step size parameter. Then the value of P_{avg} was computed for all combinations of N power levels (for different values of N), using Eqs.(5.12),(5.13),(5.11) and (5.10) in that order. Finally the optimal combination of N power levels was determined by comparing the obtained results. The one condition that had to be followed while selecting the power levels was that one of the power levels always had to be P_{max} (as that determines the range up to which every mode is used and hence has to be a constant for all combinations of power levels in consideration).

5.8 The Optimization Algorithm

The complete optimization procedure for the RPPA system is given as an algorithm here.

1. *Initialization*

    - *Determine the threshold SNRs for the different modes, based on the standard in consideration.*
    - *Compute the threshold received power levels for the different modes* $\{P_{R_j}, j\epsilon[0..(M-1)]\}$*, based on threshold SNRs and noise power.*
    - *Estimate the values of* P_{max} *and* P_{min} *that can be used for the system design.*
    - *Decide on the number of power levels* N*.*
    - *Choose a value for* $\triangle P$*.*
    - *Calculate the set* $[P_{min}, P_{min}+\triangle P, P_{min}+2\triangle P, ..., P_{max}]$*.*

2. *Looping*

    - *Select the first/next combination of* $N-1$ *power levels (*N^{th} *power level is always* P_{max}*) to obtain the set* $\{P_i, i\epsilon[1..N]\}$*.*
    - *Compute* $R_{max_{i,j}} = d_0 10^{\frac{P_i - P_{R_j}}{10n}} \forall i\epsilon[1..N]\ \forall j\epsilon[0..(M-1)]$*.*
    - *Compute* $R_{max_{i,j}} = \max\{R_{max_{i,j}}, R_{max_{N,j+1}}\}\ \forall i\epsilon[1..N], j\epsilon[0..(M-2)]$*.*
    - *Initialize* $R_{min_{i,j}} = 0\ \ \forall i, j$*.*
    - *Compute* $R_{min_{i,j}} = R_{max_{i-1,j}}, i\epsilon[2..N],\ j\epsilon[0..(M-1)]$*.*
    - *Compute* $P_{avg} = \sum_{i=1}^{N}\sum_{j=0}^{M-1} \frac{P_i}{R^2_{max_{N,0}}}\left[R^2_{max_{i,j}} - R^2_{min_{i,j}}\right]$*.*

- *Maintain the power level list having the minimum* P_{avg} *and compare it with the currently computed average power to check if the list has to change in the current loop.*

3. *Optimal power levels determined.*

4. *Exit.*

Chapter 6

Optimization and Numerical Simulations of the Optimized RPPA System

This chapter explains the results of using the optimization algorithm discussed in the last chapter to optimize the RPPA algorithm for IEEE 802.11. The simulations performed using the optimized system and the results obtained are also elaborated. It is divided into sections based on the different steps followed. The first section explains the results of optimization of the RPPA system. The next and final section presents the results of the numerical simulations.

6.1 Optimization of the System for IEEE 802.11

The optimization algorithm involves two stages - the initialization, which is followed by looping for determining the optimal power level values. The threshold SNR values are initialized using Table 4.2. For the assumed noise power of $-96dBm$, the threshold received power level values are computed for different modes. The value of maximum transmit power level P_{max} is, as before, decided to be $20dBm$. The minimum power level P_{min} is defined to be $15dBm$, as it is the minimum value in the Table 4.3 and none of the modes are used below that value. Such a choice of P_{min} allows the optimization algorithm to consider all possible combinations of power levels.

Finally, the value of $\triangle P$ is chosen to be 0.1 and the RPPA system is optimized for different number of power levels allowed, N, varying it exponentially from 2 to 16. The optimal power level values obtained are as shown in Fig. 6.1. As can be seen from the figure, the values are not distributed uniformly for any N. An uniform distribution of power levels would result in the design of a sub-optimal system.

6.2 Simulation and Results

The simulations are performed for different values of N $(2, 4, 8\ and\ 16)$ and the power used by the optimized RPPA system, in each case, is compared to that of an RM system. The results obtained are plotted in Fig. 6.2. Figure 6.2 shows the percentage increase in power used by the rate maximizing algorithm, as compared to the proposed algorithm, for the same throughput, plotted against the different

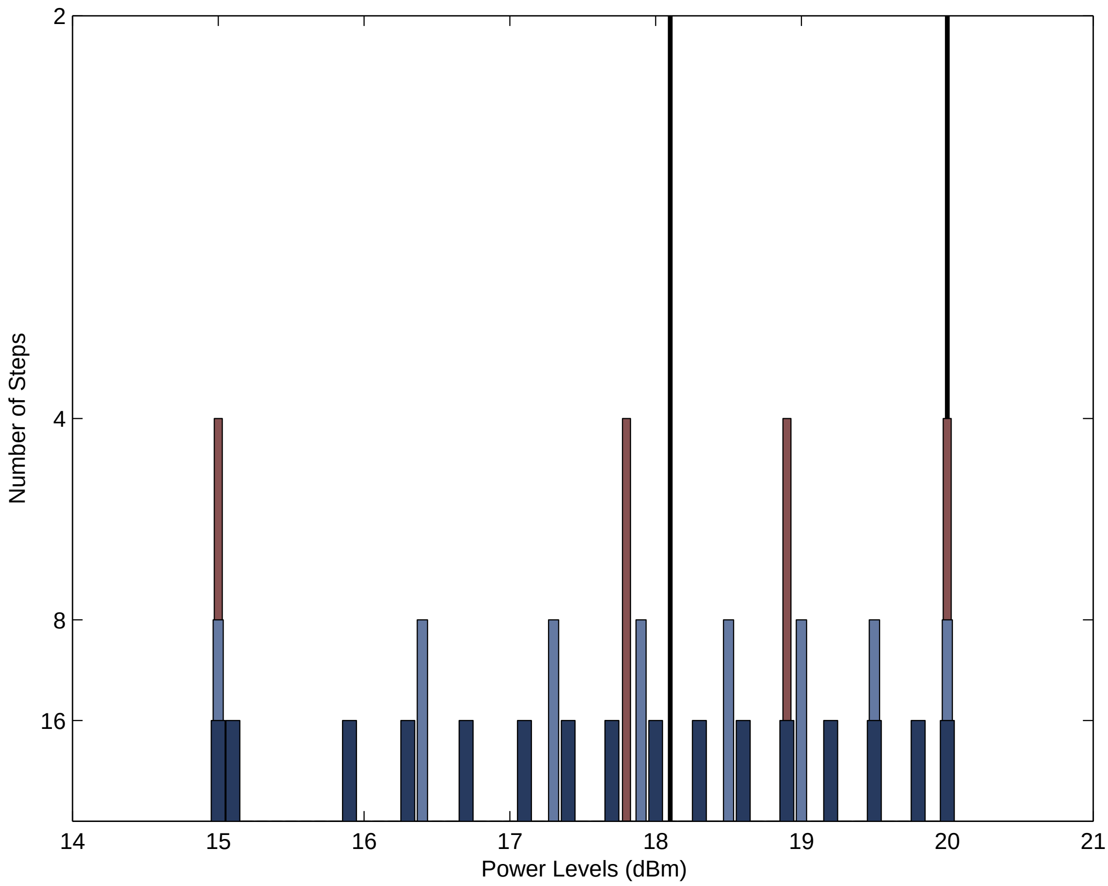

Figure 6.1: Optimum Power Level Values for different number of steps (2,4,8 & 16)

values of N used in its design. The power used by the RM system is always P_{max}, as it does not involve conservation of power.

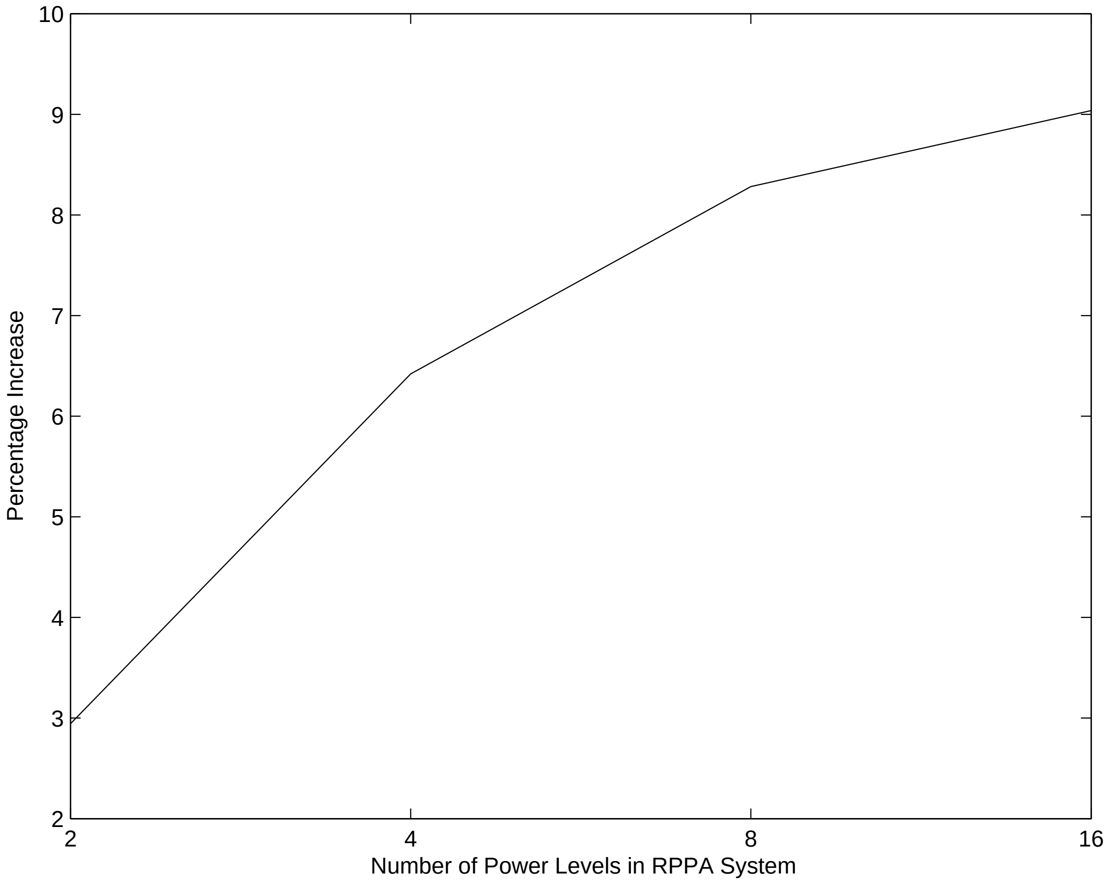

Figure 6.2: Percentage increase in power from an Optimized RPPA system to RM system vs No. of power levels

Chapter 7

Discussions of the Results

This chapter discusses the results obtained in chapters 3 and 5. It uses the results to compare the unoptimized and optimized RPPA systems.

7.1 Discussion on the Effect of Minimum Power P_{min} for the Unoptimized RPPA System

For larger number of power levels, the power saved tends to be higher for a lower minimum power level value(P_{min}). But for lower numbers, a higher minimum power level value seems to offer better savings in power used.

This phenomenon may be explained by the following arguments. At lower number of levels, the higher minimum power levels offer a wider choice of levels for all the modes of IEEE 802.11, but the lower minimum power level choice results in most levels not being used by many modes. That is because the levels which are greater than the minimum power level of a given mode will not be used by that mode. This explain why power saved is more for higher values of P_{min} at lower number of levels.

However the advantage offered by subdivision keeps decreasing with number of levels. So, beyond a certain number of power levels, the advantage offered by further subdivision at higher power levels becomes lesser as compared to allowing the P_{min} value to decrease, thus allowing some of the modes to select lesser power levels. Hence it follows that at higher number of power levels, lower values of minimum powers should be chosen and at lower number of levels, higher minimum powers should be the choice.

Anomalies- Consider the following statements which cannot be explained by the reasoning above.

1. Even at lower number of levels, the choice of $MinPw$ 3 saves much more power than $MinPw$ 4, even though the latter is larger.

2. At saturation, $MinPw$ 1 and $MinPw$ 2 seem to perform similarly, even though the above arguments suggest the former should save more at higher number of power levels.

Explanation for Anomalies- Even though the reasoning given above explains the effect of minimum power level choice on power saved to some extent, it is not complete and so these anomalies exist. We just need to take one more parameter into consideration to explain these behaviors, i.e. the modes for which the $MinPw$ are minimum powers of.

$MinPw$ 3 is the minimum power level for the lowest mode. So its selection as the minimum power level offers an advantage to the lowest mode and disadvantage to some of the higher modes. The lower rate modes are the ones that will be used when the mobile is at farther distances. Since the probability of a mobile being at any distance increases with the value of the distance, the power saving will be greater due to lower modes. Therefore, since the advantage affects the lowest mode while the disadvantage affects some of the higher modes, the average savings is much more for $MinPw$ 3 as compared to $MinPw$ 4. Similarly, $MinPw$ 1 is linked only to the highest mode and thus choosing it over $MinPw$ 2 is not offering any advantage.

From all the above arguments, we can conclude that when designing systems with lower number of power levels, we must use $MinPw$ 3, but at higher number of levels $MinPw$ 1 or $MinPw$ 2 will be more advantageous and will result in more power saving.

7.2 Discussion on the Effect of Other Parameters for the Unoptimized RPPA System

The term 'other parameters' refers to the parameters which are not the design parameters and so cannot be selected during the implementation of RPPA systems. These parameters are P_{max}, whose value is dictated by other constrains, and noise power, which is also not selectable. This sections describes the effect of these parameters on power saved by the RPPA system.

As had been explained in Chapter 3, the power saved in a RPPA system is dependent only on the average difference between the threshold SNRs of the different modes allowed by IEEE 802.11 and these differences are determined only by the rates allowed in the standard. Since any change in P_{max} or noise power results in translation in the values of SNRs, it does not affect the difference and hence does not evoke a change in power saved by the RPPA system. Thus the power saved by the unoptimized RPPA system is not dependent on the values of P_{max} or noise power.

7.3 Discussion on Results of Optimization

From the results of optimization, it can be observed that the power levels are not uniformly distributed for the optimal system. They are, in general, loosely packed at lower power values and tend to become closely packed towards the higher values. The reason for this phenomenon may be attributed to the following. The probability of finding a mobile device at a distance from AP increases with the distance. Since higher power level values are used at larger radii, using more number of higher power levels (and less number of lower ones, given the total allowed number of power levels N) offers an advantage to a larger fraction of the mobile nodes. That in turn results in a greater saving of power. Therefore, when the power levels are loosely packed at lower power level values (and closely packed as the power level values tend to their maximum), the system has more number of higher power level values thus resulting in better savings in power. Hence the optimal system observes the phenomenon in consideration.

7.4 Discussion on Simulations comparing RM and RPPA Algorithms

As can be seen from Figs. 4.2, **??**, 6.2 and **??**, the proposed algorithm can save up to 9% power for maximum throughput delivery. It can be noted from the graphs that the power saved increases with the value of the number of power levels N. This can be attributed to the fact that the algorithm always has to select the lowest power level greater than the computed power and hence the decrease in power saved is directly determined by the average gap between any two power levels. Since the gap between any two levels decreases with the number of steps, an increase in the value of N results in further saving of power.

Fortunately, the graphs seem to saturate as N increases, indicating that a finite choice of N should result in a near-optimal power saving. This is because the reduction in gap obtained by adding some extra power levels to the system decrease with the number of power levels. Therefore the saving in power keeps decreasing with each increase in number of power levels, resulting in saturation in power conserved beyond a point. A value of 16 for optimized and a value of 32 for the unoptimized system seems to be the elegant choices for the number of steps, as the graphs seem to reach saturation at that value of N and any exponential increase in the number of power levels will result only in marginal decrease in power used by the RPPA system.

7.5 Comparison between Optimized and Unoptimized RPPA Systems

Clearly, the advantage of the optimized system is that it requires only half the number of power levels as the unoptimized one for optimal power saving. However it should be noted that the power level values are not uniformly distributed in the optimal system and that may pose a problem in practical implementations. That is because practical transmitters can transmit power levels only with some error margin and since the levels are not uniformly distributed in the optimized RPPA system, they will be closely packed in some range of power values and so this system may have very less tolerance for error, as opposed to the unoptimized RPPA system.

7.6 Discussion on Commercial Deployment of RPPA Algorithm

The proposed algorithm saves 9% power under simulated conditions. It is important to realize that real world deployment does not affect this value to a great extent. This is because WLANs are used in indoor environments and so are affected mainly by slow fading (as opposed to cellular mobile environment). Thus power adaptation, just as rate adaptation, allows a good saving in resources. The main bottleneck of the algorithm is that it requires the ACK packets to have additional information not supported in legacy IEEE 802.11 standard.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

A new algorithm named RPPA having focus on both rate and power adaptation is proposed in this work. The objective of the algorithm is to save power while maximizing the rate of transmission. The algorithm makes use of the fact that there are only discrete rates allowed by practical standards and realizes that power can be saved even while operating at maximum throughput. It is designed and optimized for IEEE 802.11a/g in this work. Simulations are performed to compare the unoptimized and optimized system with a rate maximization algorithm and the power saved is found for different number of power levels allowed in the RPPA system. It is found that the proposed algorithm can save up to 9% power while operating at maximum throughput, which is a significant saving as far as mobile devices are concerned.

From the simulation results it is found that the number of power levels need not be greater than 16 for optimized and 32 for the unoptimized RPPA system, as the graphs reach saturation beyond that point. For the unoptimized RPPA system, it is also determined that $MinPw$ 1 or $MinPw$ 2 should be used as the minimum power levels. The advantages and disadvantages of optimizing the RPPA system are also discussed. Thus, this work proposes an algorithm that effectively utilizes the constraints of practical systems and achieves a significant saving in power even while operating at maximum throughput.

8.2 Future Work

8.2.1 Practical Rate Adaptation

Rate adaptation involves two steps - first the channel prediction which is then followed by an optimal rate choice. The SNR of the received packet dictates the maximum rate that channel allows for a lossless transmission (where lossless is defined by a maximum allowed bit error rate BER). Thus the receiver has to determine the SNR of the received packet and then has to transmit it back to the sender in order to allow the sender to select an optimal rate. However, the current standard for WLANs IEEE 802.11 does not allow the receiver to piggyback this information along with the ACK packet. Therefore practical rate adaptation techniques to be used with the current standard cannot rely on information from the receiver. So they involve measuring signal statistics at the sender end and using that information for predicting the rate. The statistics generally used are as follows.

1. Signal strength/SNR measurement of ACK packets - to estimate the SNR of receiving packet and select rate based on the estimated value.

2. Count of successful ACKs received - to determine whether current rate is supported by the channel and so test with next higher rate (either periodically or based on some rule).

3. Throughput of the different rates used in the near past - to select the rate which has had highest throughput in the near past.

Clearly, the three measurement are rough estimates of the channel condition and are prone to errors. The signal strength/SNR at sender end may not be the same as the measurements at the receiver end. The count of ACKs is a good indication of success of current rate, but it does not indicate when the next higher rate will be supported by the channel. Even for the throughput case, the comparison can be done only with throughput of the rates used in near past and hence cannot assure that a rate not used in near past is suboptimal as compared to the rate selected. So many research works try different combinations of the the above three statistics and use the combination for their decision making regarding the rate. ARF, AARF and ONOE are some algorithms based on count of ACKs. The algorithm proposed in [6] uses signal strength measurements for selecting the rate. SampleRate and SmartSender use hybrid combinations of these techniques.

8.2.2 Design of Practical RPPA Systems

While the above methods can estimate the next rate, they do not specify the optimal power level to to selected for the transmission. One method could be to use the RSSI value of the received packet at the sender end. But, as mentioned in the previous section, SNR at sender end may not be the same as that in the receiving end. So, similar to practical rate adaptation techniques, the method can also measure other statistics for decreasing the error in the estimation of the optimal power level value. The future work for this work will involve determining the optimal combination of the above statistics for allowing RPPA to be used in practice.

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