Joint Rate and Power Adaptation for Wireless Local Area Networks in Nakagami Multipath Fading Channels

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Summary

This thesis aims to propose a fast joint rate and power adaptation algorithm for wireless local area networks (WLANs) in Nakagami fading channels. Furthermore, we develop analytical methods to evaluate the goodput and energy efficiency of Institute of Electrical and Electronics Engineers (IEEE) 802.11a WLAN from both the medium access control (MAC) layer and physical (PHY) layer perspectives.

The main challenge for power and rate adaptation in WLAN lies in fact that energy efficiency and goodput enhancement are indeed two contradictory goals. To achieve higher goodput, it is necessary to operate in a higher level of modulation and have fewer redundant bits in coding, thereby requiring higher transmitted power to maintain the bit error rate (BER) performance. How the IEEE 802.11a/g WLAN selects a suitable modulation and coding scheme (MCS) and decides appropriate transmitted power to optimize the performance tradeoff between energy efficiency and goodput becomes a difficult but important task.

We propose a fast channel-driven rate and power adaptation (CDRPA) algorithm for WLANs. For different objectives, we compare several joint rate and power adaptation schemes to optimize the performance tradeoff between energy efficiency and goodput. The power-first CDRPA scheme first selects the transmit power to improve energy efficiency and then the data rate to enhance goodput. The rate-first CDRPA scheme first selects the data rate to enhance the goodput and then the transmit power to improve the energy efficiency. Then, we extend the CDRPA algorithm to the multi-user case and improve it by a weighted moving-average approach to predict the channel condition. From numerical results, we find that the rate-first CDRPA scheme can provide best goodput performance, while maintaining comparable energy efficiency as the power-first CDRPA scheme. Here, we suggest that the rate-first CDRPA scheme is an appropriate rate and power adaptation for WLANs that can optimize the performance tradeoff between goodput enhancement and energy saving.

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CHAPTER 1

Introduction

The Institute of Electrical and Electronics Engineers (IEEE) 802.11a/g wireless local area network (WLAN) is becoming an important standard for wireless data networks because of its higher transmission rates compared to the first generation IEEE 802.11b WLAN. Therefore, we take the IEEE 802.11a WLAN as an example to evaluate the performance of proposed algorithm in this thesis. The IEEE 802.11a WLAN adopts orthogonal frequency division multiplexing (OFDM) and other advanced transmission techniques to achieve data rates ranged from 6 Mbps to 54 Mbps [1]. The essential issue for WLANs is the throughput [1] enhancement by rate adaptation. Additionally, one important issue for WLANs is how to improve energy efficiency to extend the usage time of the limited battery energy.

The objectives of this thesis are two folds. First, we are motivated to develop a fast joint rate and power adaptation algorithm for WLANs. The adaptation algorithm dynamically adjusts transmit power and rate according to the signal quality in a Nakagami fading channel, called channel-driven joint rate and power adaptation (CDRPA) algorithm. For different objectives, we compare several joint rate and power adaptation schemes. From the numerical results, we will suggest an appropriate joint rate and power adaptation for WLANs.

The second objective of this thesis is to develop a physical (PHY)/medium

[1] Hereafter throughput, the term goodput will be used to mean the successfully delivered data payload without the overhead at the receiver.

access control (MAC) cross-layer analytical method to evaluate goodput and energy efficiency of the joint rate and power adaptation algorithm for WLANs in Nakagami fading channels. We want to incorporate the impacts of both MAC layer and PHY layer under a generalized channel model into the goodput and energy efficiency computation in the joint rate and power adaptive wireless system.

1.1 Problem and Solution

In recent years, wireless local area networks (WLANs) become very popular. One important issue for WLANs is how to improve energy efficiency to extend the usage time of the limited battery energy. The current IEEE 802.11h defines a report mechanism for power control in the WLAN [2]. The other essential issue for WLANs is the throughput enhancement. Current IEEE 802.11a/g WLAN standard specify eight modulation and coding schemes (MCS), which can be used for dynamically changing transmission parameters for improving throughput. Thus, an interesting problem arises, how to simultaneously enhance the throughput and energy efficiency performance for the IEEE 802.11 WLAN by dynamically adapting the MCS and transmitted power.

The main challenge for joint power and rate adaptation in WLANs lies in the fact that energy efficiency and throughput enhancement are indeed two contradictory goals. To achieve higher throughput, it is necessary to operate in a higher level of modulation and have fewer redundant bits in coding, thereby requiring higher transmitted power to maintain the bit error rate (BER) performance. Thus, although the IEEE 802.11a/g WLAN has eight modulation and coding schemes, how to select a suitable MCS and decides appropriate transmitted power to optimize the performance tradeoff between energy efficiency and throughput becomes a difficult but important task.

1.1.1 Goodput and Energy Efficiency Analysis

Qiao et al. derived an analytical method to compute the goodput and energy efficiency by taking the MAC parameters into consideration. However, the channel model used in [3] is the additive white Gaussian noise (AWGN) channel. In this thesis, we improve the analytical method of [3] to incorporate the generalized Nakagami fading channel [4]. Thus, the goodput and energy efficiency performance of the IEEE 802.11a WLAN can be evaluated for different fading environments.

1.1.2 Joint Rate and Power Adaptation

The challenge for power and rate adaptation in WLAN lies in fact that energy efficiency and goodput enhance are indeed two contradictory goal. How to develop an effective joint rate and power adaptation scheme is an important issue. The scheme proposed in [3] is aiming to maximize the energy efficiency, and too complicated to implement because it requires a dynamic programming technique to determine the transmission parameters on each transmission. In this thesis, we develops a fast joint rate and power adaptation algorithm in the generalized Nakagami fading channel. It is named as the channel-driven joint rate and power adaptation (CDRPA) algorithm which can adjusts data rate and transmit power level according to the signal quality. For different objectives, we propose several schemes based on the CDRPA algorithm. From our numerical results, we will suggest an appropriate joint rate and power adaptation for WLANs.

1.2 Thesis Outline

The rest of this thesis is organized as follows. Chapter 2 introduces the backgrounds for the IEEE 802.11 MAC protocol and the IEEE 802.11a physical layer parameters as well as the radio channel characteristics. In Chapter 3, we describe the channel-driven joint rate and power adaptation (CDRPA) algorithm. In Chapter 4, we extended the proposed CDRPA algorithm in Chapter 3 to the multi-user case with RTS/CTS. At last, Chapter 5 gives the concluding remarks and suggestions for future works.

CHAPTER 2

Background

In this chapter, we will investigate the background for the IEEE 802.11a as well as the Nakagami fading channel model in this thesis. We list the document as follows.

2.1 IEEE 802.11a Physical Layer

In this thesis, we take the IEEE 802.11a/g WLAN as an example of rate and power adaptive systems to evaluate the performance of the proposed CDRPA algorithm. The IEEE 802.11a/g physical (PHY) layer provides eight different data rates ranged from 6 to 54 Mbps. Tables 2.1 and 2.2 show the related rate-dependent parameters in the IEEE 802.11a PHY layer and the maximum transmitted power levels in various frequency bands [1, 5].

2.2 IEEE 802.11 MAC Protocol

In the IEEE 802.11 [6], the distributed coordination function (DCF) is a fundamental mechanism to access the wireless medium. All the WLAN devices share the common medium by the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. In standard, there are two kinds of mechanism for DCF mode which are the two-way and four-way handshaking as follows.

Table 2.1: Eight modulation and coding schemes for the associated data rates in the IEEE 802.11a/g WLAN.

Mode m	Data Rate	Modulation	Coding rate	BpS(m)*
1	6 Mbps	BPSK	1/2	3
2	9 Mbps	BPSK	3/4	4.5
3	12 Mbps	QPSK	1/2	6
4	18 Mbps	QPSK	3/4	9
5	24 Mbps	16-QAM	1/2	12
6	36 Mbps	16-QAM	3/4	18
7	48 Mbps	64-QAM	2/3	24
8	54 Mbps	64-QAM	3/4	27

* Bytes per OFDM Symbol

2.2.1 Two-way Handshake Mechanism

Figure 2.1 shows possible scenarios of frame transmission based on the CSMA/CA MAC protocol in the basic mode.

(a) Successful frame transmission: Following the CSMA/CA MAC protocol, the transmitter successfully sends out a data frame after waiting the duration of a dis-

Table 2.2: Transmitted power levels for the IEEE 802.11a/g WLAN.

Frequency Band	Maximum Transmitted Power with 6 dBi Antenna Gain
5.150-5.250 GHz	40 mW (16 dBm)
5.250-5.350 GHz	200 mW (23 dBm)
5.725-5.825 GHz	800 mW (29 dBm)

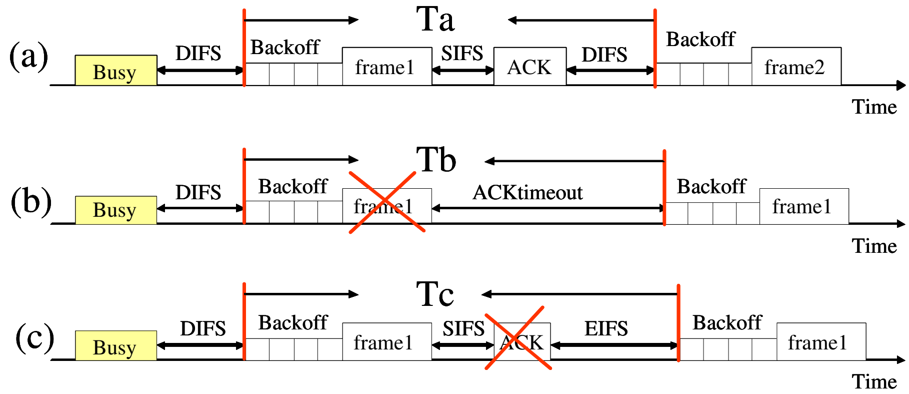


Figure 2.1: Possible scenarios of frame transmission according to the CSMA/CA MAC protocol in the basic mode: (a) successful frame transmission; (b) erroneous data frame transmission; (c) erroneous ACK frame transmission.

tributed inter-frame space (DIFS) and a random backoff. Further waiting a short inter-frame space (SIFS) duration, the transmitter successfully receives an acknowledgment (ACK) control frame from the receiver.

(b) Erroneous data frame transmission: If the transmitter sends out a data frame 1 and does not receive the ACK frame within a duration of ACKtimeout, the transmitter presumes that the data frame reception is in error. Then, the transmitter retransmit the data frame 1.

(c) Erroneous ACK frame transmission: If the transmitter receives a corrupted ACK frame, the transmitter will wait an extended inter-frame space (EIFS) duration and retransmit data frame 1, where EIFS is longer than DIFS and SIFS.

2.2.2 Four-way Handshake Mechanism

For optional, the DCF defines the four-way handshaking mechanism, which requires that the transmitter and receiver exchange RTS (Request-To-Send) and CTS (Clear-To-Send) control frames prior to the data frame transmission. In the RTS/CTS handshaking mechanism, there are five possible scenarios for the frame transmission, as shown in Fig. 2.2:

(1) Successful frame transmission: The transmitter sends a RTS control frame to contend the medium after waiting the duration of a distributed inter-frame space (DIFS) and a random backoff. The transmitter successfully sends a data frame after receiving the CTS frame and waiting a short inter-frame space (SIFS) duration. Then waiting a SIFS duration, the transmitter successfully receives an acknowledgment (ACK) control frame from the receiver.

(2) Erroneous frame transmission: If the transmitter does not receive any CTS frame in an CTStimeout duration, the transmitter presumes that the transmission failure of RTS is due to the channel effect or packet collisions. On the other hand, if the transmitter successfully send a RTS frame, it means that the medium is reserved by the RTS frame of transmitter. So, if the following frame handshaking (i.e. CTS, data, ACK) is failed, the transmission failure surely is due to the channel effect.

2.2.3 Generalized Nakagami Fading Channel Model

In this thesis, we consider a generalized Nakagami fading channel [4]. The probability density function (pdf) of the transmitted signal in the Nakagami fading channel is given by

$$p(\alpha) = \frac{2m^m \alpha^{2m-1}}{\Omega^m \Gamma(m)} \exp(-\frac{m\alpha^2}{\Omega}), \tag{2.1}$$

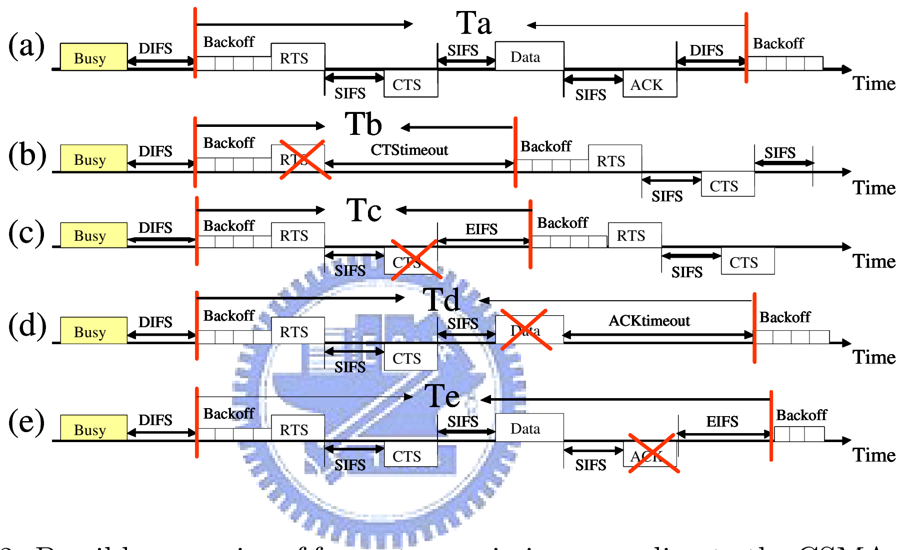


Figure 2.2: Possible scenarios of frame transmission according to the CSMA/CA MAC protocol in the RTS/CTS mode, i.e. (a) successful frame transmission. (b) erroneous RTS frame transmission. (c) erroneous CTS frame transmission. (d) erroneous data frame transmission. (e) erroneous ACK frame transmission.

Table 2.3: Channel states for the IEEE 802.11a/g WLAN in the Nakagami fading channel with $m = 1$ and the corresponding data rates.

channel state	s_1	s_2	s_3	s_4
E_b/N_0 range	$[0, 16.471)$	$[16.471, 25.984)$	$[25.984, 63.807)$	$[63.807, \infty)$
$DataRate(Mbps)$	12	24	48	54

where α, m, and Ω are the fading amplitude, the Nakagami fading parameter, and the local mean power, respectively. The Nakagami channel model becomes the Rayleigh fading channel as $m = 1$, whereas it becomes the non-fading AWGN channel as $m \to \infty$. Thus, the Nakagami fading channel is general enough to characterize most of the multipath fading conditions.

2.2.4 Transition Probability Matrix

In [7], a wireless fading channel can be divided into multiple channel states (s_j) with the required E_b/N_0 threshold (η_j) for data rate j. Note that s_j is equivalent to the event when $E_b/N_0 \in [\eta_{j-1}, \eta_j)$. In [7], it was shown that only four PHY modes are necessary for the IEEE 802.11 WLAN in the Nakagami fading channel with $m = 1$. Table 2.3 shows the four channel states for the IEEE 802.11 WLAN in such a channel and the corresponding E_b/N_0 ranges and the data rates. Let the transition probability (p_{jk}) represent the probability that the channel state changes from the state s_j to s_k, and x_i be the E_b/N_0 at the i-th transmission. Then, p_{jk} can be expressed as:

$$\begin{aligned} p_{jk} &= P(x_{i+1} \in (\eta_{k-1}, \eta_k) | x_i \in (\eta_{j-1}, \eta_j)) \\ &= \frac{\int_{\eta_{k-1}}^{\eta_k} \int_{\eta_{j-1}}^{\eta_j} p(\alpha_i, \alpha_{i+1}) d\alpha_i d\alpha_{i+1}}{\int_0^{\infty} \int_{\eta_{j-1}}^{\eta_j} p(\alpha_i, \alpha_{i+1}) d\alpha_i d\alpha_{i+1}}. \end{aligned} \tag{2.2}$$

The joint *pdf* $p(\alpha_i, \alpha_{i+1})$ is required to compute p_{jk}. In a Nakagami fading channel, $p(\alpha_{t-\tau}, \alpha_t)$ can be computed by

$$p(\alpha_{t-\tau}, \alpha_t) = \frac{4(\alpha_{t-\tau}\alpha_t)^m}{(1-\rho)\Gamma(m)\rho^{(m-1)/2}}(\frac{m}{\Omega})^{m+1}$$

$$\cdot I_{m-1}(\frac{2m\sqrt{\rho}\alpha_{t-\tau}\alpha_t}{(1-\rho)\Omega})\exp(-\frac{m(\alpha_{t-\tau}^2+\alpha_t^2)}{(1-\rho)\Omega}), \tag{2.3}$$

where α_t is the channel fades at time instants t, $I_{m-1}(\cdot)$ is the $(m-1)$-th order modified Bessel function of the first kind, $\Gamma(m)$ is the Gamma function, ρ is the channel correlation coefficient, m is the Nakagami shape factor, and $E[\alpha_{t-\tau}^2] = E[\alpha_t^2] = \Omega$ is the average power. From [4] ρ can be evaluated by

$$\rho = \frac{J_0(2\pi f_d\tau) + K\cos(2\pi f_d\tau\cos\theta_0)}{2+2K}, \tag{2.4}$$

where K is the ratio of the specular power to the scattering power, θ_0 is the angle of arrival phase. From [8], the relation between K and m can be computed by

$$K = \frac{\sqrt{m^2-m}}{m-\sqrt{m^2-m}}. \tag{2.5}$$

In (2.5), τ can be used to represent the duration between two channel estimations. We will apply the transition probability in (2.5) to calculate the goodput and energy efficiency for the CSMA WLAN in the Nakagami fading channels, which will be discussed in the next chapter.

2.3 Literature Survey

In the literature on the subject of the IEEE 802.11 WLANs, the rate adaptation and power control mechanism are mainly discussed to improve either throughput or energy efficiency individually.

First, let's discussed the related works for rate adaptation in the WLANs from the perspective of throughput enhancement. One well-known rate adaptation scheme is the auto rate fallback (ARF) algorithm [9]. The basic idea of ARF is to count the successful and missing ACK frames. After the transmitter does not correctly receive two consecutive ACK frames, it lowers the data rate in the next retransmission. When receiving ten ACK frames successfully, the transmitter increases its data rate. A rate adaptation scheme based on the long-term and short-term of statistics of successful and failed transmitted frames was proposed in [10]. Because counting the number of ACK frames requires a lot of time, the ARF algorithm or the statistics-based rate adaptation scheme may not react fast enough to follow the fluctuation of the wireless channel. To expedite the rate adaptation process, many studies focused on providing fast rate adaptation algorithms without counting the number of received ACK frames [7, 11–15]. In [11], the transmission rate for the WLAN was suggested to adjust according to the received signal strength of the received frames. Furthermore, the authors in [12] proposed a Receiver-Based AutoRate (RBAR) algorithm. For each data transmission, an RTS/CTS handshaking mechanism can be invoked for the channel access. After the reception of RTS control frame, the receiver responds with the channel information for data rate selection by CTS frame. However, it needs to define the new frame formate of CTS frame. In [13], it was suggested to select the proper modulation and coding scheme (m) based on the payload length (l), the received signal quality of the ACK frame (s), and the retry count (n). Through completely searching all the (m, l, s, n) and picking the one with the highest goodput, the proposed scheme in [13] results in the "optimum" goodput performance. Although possessing the best goodput performance, the complexity of searching all the combination of (m, l, s, n) cannot be ignored. To reduce the complexity of the rate adaptation scheme in [13], the authors in [7, 14] suggested a reduced mode rate adaptation scheme for the IEEE 802.11a WLAN by removing some unnecessary physical modes in Nakagami fading channels. It was shown that the reduced mode channel-driven rate adaptation (CDRA) scheme in [7, 14] can deliver comparable goodput performance as the optimal complete search rate adaptation scheme in [13].

Now let's discuss the related works of power and rate adaptation for WLANs from the energy efficiency perspective. The authors in [16] and [17] proposed to turn off unnecessary functions and specify the criteria for entering into the sleeping mode. In [18] a simple power control scheme for the IEEE 802.11a/h WLAN was proposed by estimating the path-loss according to the difference between the received signal power level and transmitted power level of the Request-to-Send (RTS) frame. Then, the path loss information will be inserted in the Clear-to-Send (CTS) frame and feedback to the transmitter. In [3], Qiao et al. proposed the minimum-energy transmission strategy, called MiSer algorithm, which maximizes the successfully received bits per unit of consumed energy by completely searching all the combinations of the transmitted power level and the MCS in the AWGN channel. The MiSer algorithm can be viewed as the optimum energy efficiency algorithm. Likewise, Qiao et al. propose another joint rate and power adaptation scheme for the PCF mode of the WLANs [19].

To our knowledge, a framework adapting power and rate jointly considering both the energy efficiency and goodput performances is not seen too many in the literature. In this thesis, we will discuss both the energy efficiency and goodput performances in some joint power and rate adaptation schemes. We will also propose a proper procedure of joint power and rate selection to acquire the trade-off between energy efficiency and goodput performances.

CHAPTER 3

Joint Rate and Power Adaptation Mechanism (Basic Mode)

Rate adaptation and power control are two essential techniques for throughput enhancement and energy saving, respectively. However, it is challenging to improve the throughput and save power simultaneously since they are two fundamentally contradictory goals. High throughput requires higher modulation levels and less protection of coding, thereby leading to higher transmit power to maintain the minimum bit error rate performance. In this chapter, we discuss how to jointly adapt the transmit power and rates to improve the performance tradeoff between the two contradictory goals of throughput enhancement and energy saving for wireless local area networks (WLANs). We propose a fast channel-driven joint rate and power adaptation (CDRPA) algorithm to adjust transmit rates and power according to the signal quality in a Nakagami fading channel. For different objectives, we compare several joint rate and power adaptation schemes. The power-first CDRPA scheme first selects the transmit power to improve energy efficiency and then the data rate to enhance goodput. The rate-first CDRPA scheme first selects the data rate to enhance the goodput and then the transmit power to improve the energy efficiency. We also develop analytical methods to compute the goodput and energy efficiency of the WLAN in the generalized Nakagami fading channel. From the numerical results, we find that the power-first CDRPA scheme is most energy efficient, but has about 40 % lower goodput than the rate-first CDRPA scheme. The rate-first CDRPA scheme can provide best goodput performance, while maintaining comparable energy efficiency as the power-first CDRPA scheme.

3.1 Analysis

3.1.1 Goodput

The goodput is defined as the number of successfully delivered *information* bits per second. Denote $E[P_D]$ the average delivered information bits, $E[t_T]$ the average transmission time for a data frame. Then, the goodput is written as

$$\mathcal{G}(l,s,m,c) = \frac{E[P_D](l,s,m,c)}{E[t_T](l,s,m,c)}, \tag{3.1}$$

where (l,s,m,c) represent the data payload, the received E_b/N_0, the transmission PHY mode, and the number of transmission attempts, respectively. Because $E[P_D]$ include the average successfully delivered information bits at the first transmission attempt and that at the retransmission, it is followed that

$$\begin{aligned} E[P_D](l,s,m,c) = P_S(l,s,m)\cdot l + [1 - P_S(l,s,m)] \\ \cdot \{\sum_{k=1}^{N} p_{jk}\cdot E[P_D](l,r,m(r),c+1)\}, \end{aligned} \tag{3.2}$$

where $P_S(l,s,m)$ is the successful probability of frame transmission; N is the total number of channel states; p_{jk} is the transition probability of channel states defined in (2.2). According to the two-way handshaking procedure, the receiver sends an ACK after successfully a data frame. Therefore, the successful probability of frame transmission $P_{SFT}(l,s,m)$ can be calculated as

$$P_S(l,s,m) = [1 - P_{e,data}(l,s,m)]\cdot[1 - P_{e,ack}(s)], \tag{3.3}$$

where $P_{e,data}(l,s,m)$ and $P_{e,ack}(s)$ are the error probability of the data frame and ACK frame, respectively. In [7], the analytical expression for $P_{e,data}(l,s,m)$ and $P_{e,ack}(s)$ were derived.

From Fig. 2.1, frame transmission based on the legacy CSMA MAC protocol has three possible scenarios. Figure 2.1(a)(b)(c) show the durations of successful frame transmission (T_a), erroneous data frame transmission (T_b), and erroneous ACK frame transmission (T_c), respectively. Specifically, T_a, T_b, and T_c are equal to

$$\begin{cases} T_a = \overline{T_{bkoff}}(c) + T_{data}(l,m) + T_{SIFS} + T_{ACK} + T_{DIFS}, \\ T_b = \overline{T_{bkoff}}(c) + T_{data}(l,m) + T_{ACKTimeout}, \\ T_c = \overline{T_{bkoff}}(c) + T_{data}(l,m) + T_{SIFS} + T_{ACK} + T_{EIFS}. \end{cases} \tag{3.4}$$

Therefore, the average transmission time $E[t_T]$ can be expressed as

$$\begin{aligned} &E[t_T](l,s,m,c) = \\ &P_S(l,s,m) \cdot T_a + P_{e,data}(l,s,m) \cdot T_b + (1 - P_{e,data}(l,s,m)) \cdot P_{e,ack}(s) \cdot T_c \\ &+ (1 - P_S(l,s,m)) \cdot \{\sum_{k=1}^{N} p_{jk} \cdot E[t_T](l,r,m(r),c+1)\}. \end{aligned} \tag{3.5}$$

Recall that $BpS(m)$ is the bytes-per-symbol for the PHY mode m as listed in Table 2.1. Then, T_{EIFS}, $T_{ACKtimeout}$, T_{DIFS}, T_{data}, and T_{ACK} can be computed as [6]

$$T_{EIFS} = T_{SIFS} + T_{ACK} + T_{DIFS} + T_{preamble} + T_{PLCPhdr}, \tag{3.6}$$

$$T_{ACKtimeout} = 2 \times T_{SIFS} + T_{ACK} + 2 \times T_{slot}, \tag{3.7}$$

$$T_{DIFS} = T_{SIFS} + 2 \times T_{slot}, \tag{3.8}$$

$$\begin{aligned} T_{data}(l,m) &= T_{preamble} + T_{signal} + T_{sym} \cdot \left\lceil \frac{\text{MAChdr} + \text{FCS} + (T_{Service} + T_{Tailbit})/8 + l}{BpS(m)} \right\rceil \\ &= 20\mu s + T_{sym} \cdot \left\lceil \frac{30.75 + l}{BpS(m)} \right\rceil, \end{aligned} \tag{3.9}$$

and

$$T_{ACK} = T_{preamble} + T_{signal} + T_{sym} \cdot \left\lceil \frac{\text{MAChdr\_ACK} + (T_{Service} + T_{Tailbit})/8}{BpS(1)} \right\rceil$$

$$= 20\mu s + T_{sym} \cdot \left\lceil \frac{16.75}{BpS(1)} \right\rceil, \tag{3.10}$$

where MAChdr = 24 bytes, FCS = 4 bytes, and MAChdr_ACK = 14 bytes. Denote CW_{min} and CW_{max} the minimum and maximum contention window sizes. We can express the average backoff time as

$$\overline{T_{bkoff}}(c) = \frac{\min[2^c \cdot (CW_{min} + 1) - 1, CW_{max}]}{2} \cdot T_{slot}. \tag{3.11}$$

3.1.2 Energy Efficiency

The energy efficiency ζ is defined as the ratio of the average delivered information bits $E[P_D]$ to the total energy consumption for a data frame transmission $E[\varepsilon_T]$, that is,

$$\zeta(l, s, m, c) = \frac{E[P_D](l, s, m, c)}{E[\varepsilon_T](l, s, m, c)}. \tag{3.12}$$

By the same reasoning to evaluate $E[t_T]$ in (4.6), there are three possible energy consumption of frame transmission based on the legacy CSMA MAC protocol. Denote $P_{t\_mode}(p_t)$ and P_{r_mode} the power consumption for a terminal operating in the transmitting and receiving modes, respectively. Let P_{rec}, P_{pa}, and P_{com} be the power consumption of the receiver front end, power amplifier, and the shared components in both receive and transmit circuits. P_{r_mode} and $P_{t\_mode}(p_t)$ can be expressed as

$$\begin{cases} P_{r\_mode} = P_{com} + P_{rec}, \\ P_{t\_mode}(p_t) = P_{com} + P_{pa} = P_{com} + \dfrac{p_t}{\eta(p_t)}, \end{cases} \tag{3.13}$$

where η and p_t are the power conversion efficiency of the power amplifier and the transmit power level, respectively. Similarly, the total energy consumption for a data frame transmission $E[\varepsilon_T]$ can be recursively calculated as

$$
\begin{aligned}
& E[\varepsilon_T](l,s,m,c) = \\
& \overline{\varepsilon_{bkoff}}(c) + P_S(l,s,m)\cdot[\varepsilon_{data}(l,m,p_t)+\varepsilon_{SIFS}+\varepsilon_{ACK}+\varepsilon_{DIFS}] \\
& + P_{e,data}(l,s,m)\cdot[\varepsilon_{data}(l,m,p_t)+\varepsilon_{ACKtimeout}] \\
& + (1-P_{e,data}(l,s,m))\cdot P_{e,ack}(s)\cdot[\varepsilon_{data}(l,m,p_t)+\varepsilon_{SIFS}+\varepsilon_{ACK}+\varepsilon_{EIFS}] \\
& + (1-P_S(l,s,m))\cdot\{\sum_{k=1}^{N} p_{jk}\cdot E[\varepsilon_T](l,r,m(r),c+1)\}. \qquad (3.14)
\end{aligned}
$$

where $\overline{\varepsilon_{bkoff}}(c)$, $\varepsilon_{data}(l,m,p_t)$, ε_{SIFS}, ε_{ACK}, and ε_{DIFS} are the energy consumption of the average backoff time, data frame transmission, waiting SIFS time, ACK frame transmission, and waiting DIFS time, respectively. $\overline{\varepsilon_{bkoff}}(c)$, $\varepsilon_{data}(l,m,p_t)$, ε_{SIFS}, ε_{ACK}, and ε_{DIFS} are equal to

$$\overline{\varepsilon_{bkoff}}(c) = \overline{T_{bkoff}}(c)\cdot P_{r\_mode}, \qquad (3.15)$$

$$\varepsilon_{data}(l,m,p_t) = T_{data}(l,m)\cdot P_{t\_mode}(p_t), \qquad (3.16)$$

$$\varepsilon_{SIFS} = T_{SIFS}\cdot P_{r\_mode}, \qquad (3.17)$$

$$\varepsilon_{ACK} = T_{ACK}\cdot P_{r\_mode}, \qquad (3.18)$$

and

$$\varepsilon_{DIFS} = T_{DIFS}\cdot P_{r\_mode}. \qquad (3.19)$$

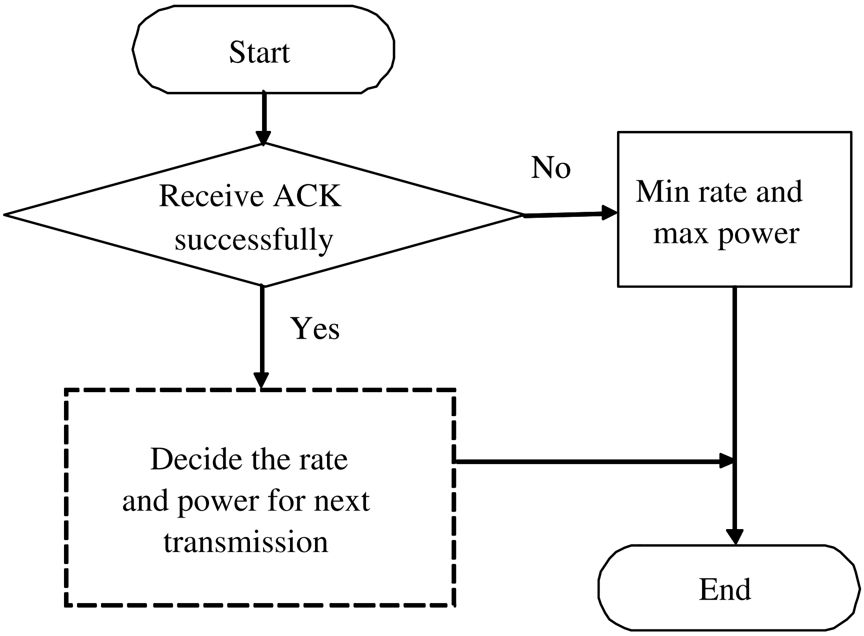


Figure 3.1: The flow chart of the CDRPA algorithm.

3.2 Channel-Driven Rate and Power Adaptation (CDRPA) Algorithm

In this section, we detail the proposed channel-driven rate and power adaptation (CDRPA) algorithm. Then, we propose several schemes based on the CDRPA algorithm to achieve different performance objectives.

3.2.1 Principle

The fundamental idea of CDRPA algorithm is to adjust the transmit rate and power according to the received E_b/N_0 of ACK frame in the previous frame transmission. Figure 3.1 shows the flow chart of CDRPA algorithm, which is elaborated as follows:

1. First, the transmitter sends the data frame with lowest rate and largest power and

Table 3.1: The required E_b/N_0 of the eight data rates in Nakagami fading channel with m=1, assuming transmit power is 30 dBm.

Data Rate (Mbps)	6	9	12	18
E_b/N_0	13.962	56.398	$\underline{13.962}$	56.398
Data Rate (Mbps)	**24**	**36**	**48**	**54**
E_b/N_0	$\underline{16.471}$	45.757	$\underline{25.984}$	$\underline{63.807}$

waits for the ACK frame.

2. If the transmitter successfully receives ACK frame, it adjusts the transmit rate and power for the next frame, according to the received E_b/N_0 of ACK frame. Otherwise, go back to step 1.

3. The transmit rate and power selection depends on the user's performance objective.

Next, we will discuss the selections of transmit rate and power in the CDRPA algorithm.

- **Transmit Rate Selection**: The CDRPA selects the transmit rate with lowest energy consumption or highest goodput according to the concept of physical mode reduction. The reduced mode concept in IEEE 802.11 WLAN picks off some inefficient data rates for the rate adaptation schemes to reduce the complexity while keeping the goodput performance. For example, in Table 4.1, we can observe that the required E_b/N_0 for 24 Mbps data rate is smaller than that for 18 Mbps. The phenomenon also happens for the transmit rate of 12 and 48 Mbps. Therefore, the reduced physical mode still has similar goodput performance compared to the full mode.

- **Transmit Power Selection**: The CDRPA decides the transmit power according to the available link margin obtained by the ACK frame in the previous transmission. The available link margin L_{margin} is defined as

$$L_{margin} = E_b/N_{0_{rx}} - E_b/N_{0_{req}}, \tag{3.20}$$

where $E_b/N_{0_{rx}}$ is the received E_b/N_0 of ACK frame; $E_b/N_{0_{req}}$ is the required E_b/N_0 threshold of the lowest data rate. From (4.11), the available link margin represents how much power can be reduced without dropping the frame. Moreover, since the ACK control frame is transmitted by the maximum power level. The transmitter can adjust the transmit power by for the next transmission as

$$p_t = \lceil p_{t_{max}} - L_{margin} \rceil, \tag{3.21}$$

where $p_{t_{max}}$ is the maximum transmit power level. Therefore, the transmitter can use low transmit power to send the frame, and it avoids the frame dropping due to insufficient transmit power.

Next, we will detail two schemes based on the CDRPA algorithm, i.e. "power-first", and "rate-first" CDRPA schemes to achieve different performance objectives.

3.2.2 Power-First CDRPA Scheme

The objective of power-first CDRPA scheme is to select transmit rate and power with the maximal energy efficiency for frame transmissions. Figure 3.2 shows the flow chart of power-first CDRPA scheme, which is described as follows:

1. After successfully receiving ACK frame, the power-first CDRPA scheme first determines the suitable transmit power level for every feasible data rate according to the received E_b/N_0 of the previous ACK frame by (4.11) and (4.12).

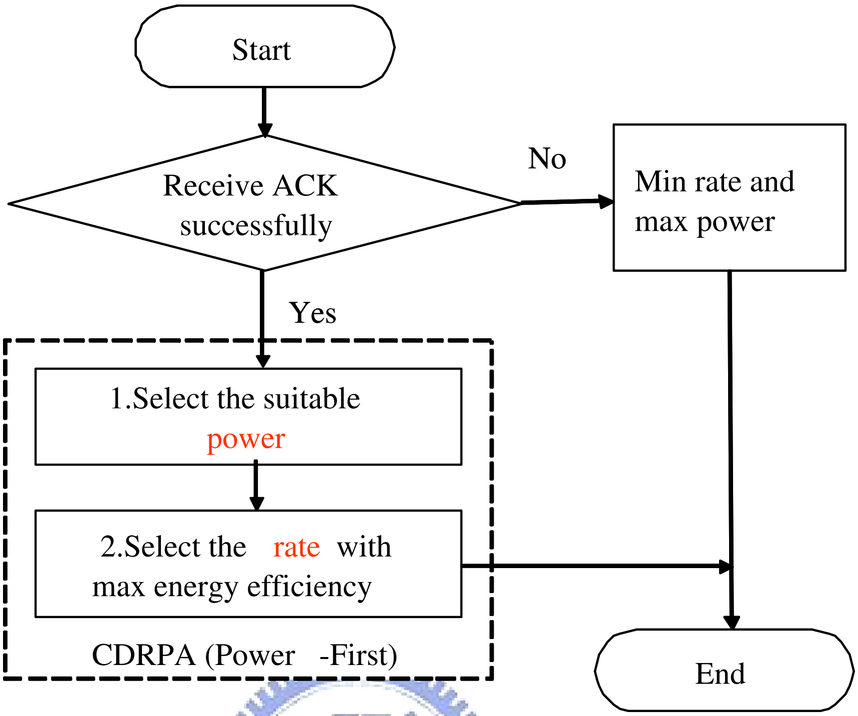


Figure 3.2: The flow chart of the power-first CDRPA scheme.

2. Then, from (4.7), it calculates the energy consumption for every feasible of rates and powers determined in step 1.

3. At last, the power-first CDRPA scheme selects the transmit rate with the maximal energy efficiency for the next frame transmission.

For example, assuming the maximal transmit power p_{tmax}=30 dBm and the received E_b/N_0 of the previous ACK frame is 18 dB. In step 1, the power-first CDRPA scheme chooses to transmit frame with two possible transmit rates and powers: 12 Mpbs/26 dBm and 24 Mbps/29 dBm. Then, the scheme calculates the energy efficiency of the two selected transmit rate and power by (4.7). At last, the step 3 in the scheme finds that the transmit rate and power with 24 Mbps/29 dBm has the lowest energy consumption. Therefore, the power-first CDRPA scheme of CDRPA algorithm has the lower energy consumption in frame transmission.

3.2.3 Rate-First CDRPA Scheme

In contrast to the power-first CDRPA scheme, the rate-first CDRPA scheme aims to maximize the goodput performance for the frame transmissions. Figure 3.3 shows the flow chart of rate-first CDRPA scheme, which is detailed as follows:

1. Based on the reduced mode table, the rate-first CDRPA scheme first selects the transmit rate whose required E_b/N_0 threshold is close and lower than the received E_b/N_0 of the ACK frame in the previous transmission.

2. Then, from (4.12), it calculates the transmit power level according to the available link margin.

As described above, we can expect the goodput performance of the rate-first CDRPA scheme and the CDRA algorithm [14] are the same due to the same selected rate. However, the energy consumption of the rate-first CDRPA scheme is smaller than that of the CDRA algorithm due to the additional power adaptation mechanism.

3.3 Numerical Results

In this section, we compare the energy efficiency and goodput performances of the two proposed schemes in CDRPA algorithm, the CDRA algorithm [14], and the complete searching method in [3]. Note that the transmit power in CDRA algorithm is fixed; while the complete searching method maximize the energy efficiency with the optimum transmit rate and power. The parameters in the numerical results are summarized in Table 4.2.

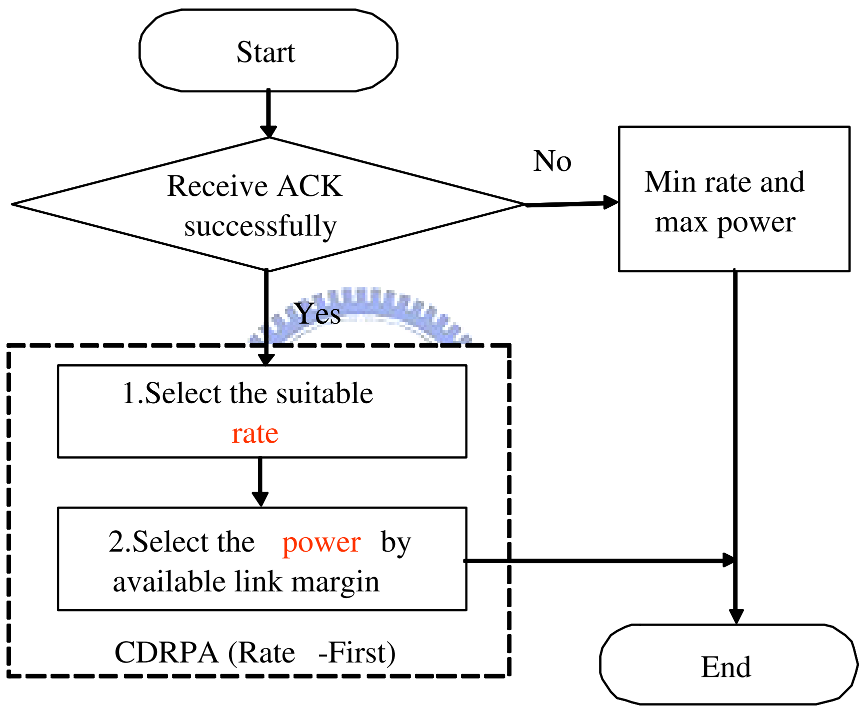


Figure 3.3: The flow chart of the rate-first CDRPA scheme.

Table 3.2: System parameters used in numerical results.

Parameters	Value
packet payload	1500 bytes
ACK	112 bits
PLCP preamble duration	16 μ s
PLCP signal field duration	4 μ s
OFDM symbol time	4 μ s
Slot time	9 μ s
SIFS	16 μ s
DIFS	34 μ s
CW_{min}	15
CW_{max}	1023
P_{tmax}	30 dBm

3.3.1 Goodput Performance

Figure 3.4 shows the goodput of different algorithms in Nakagami fading channel with $m = 1$. As shown in the figure, both the rate-first CDRPA scheme and CDRA algorithms can provide the highest goodput compared to the other two algorithms. The CDRA and rate-first CDRPA scheme choose high transmit rate to maximize the goodput performance; while the others reduce the transmit power to improve the energy efficiency. For example, as $E_b/N_0 = 30$ dB, the goodput performance of rate-first CDRPA scheme and CDRA algorithm is larger than the others by 67 %. We also validates the analytical result of rate-first CDRPA scheme using the IEEE 802.11a simulator. We can observe that the analytical result is close to the simulation.

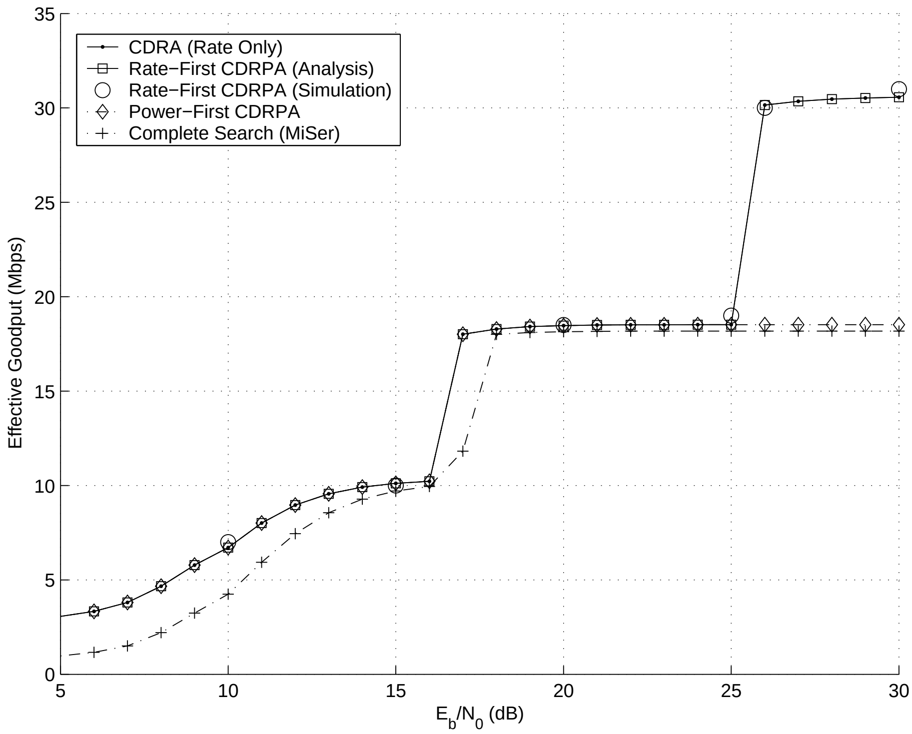


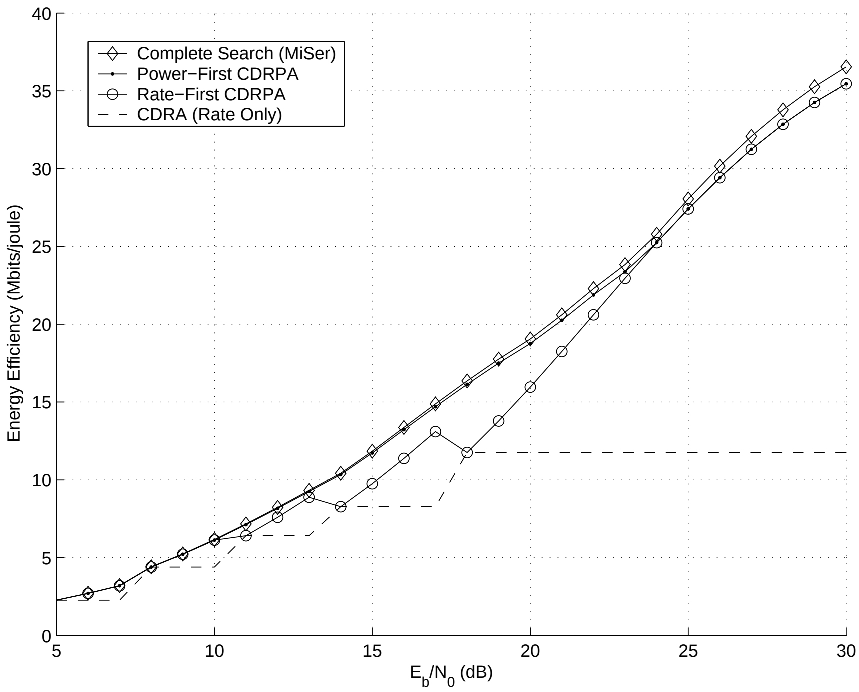
Figure 3.4: The goodput of different algorithms in the Nakagami fading channel with $m = 1$.

3.3.2 Energy Efficiency Performance

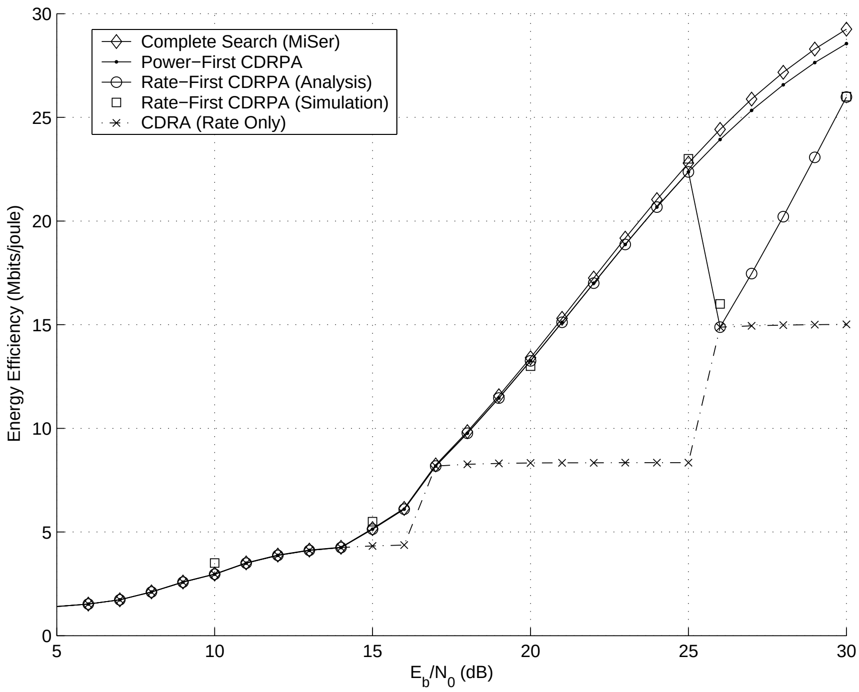
Figure 3.5 shows the energy efficiency of different algorithms in AWGN channel and Nakagami fading channel with m=1, respectively. As shown in the figure 3.5, the energy efficiency performance for all the algorithms in AWGN channel is better than that in Nakagami fading channel. Because the signal strength in AWGN channel does not vary with time, the channel information obtained from the previous ACK frame directly reflect the channel state in the current transmission. However, in Nakagami fading channel, the channel state information may be incorrect and lead to the frame retransmission due to the signal strength variation. As a result, the energy efficiency in Nakagami channel decreases due to the unnecessary frame transmissions.

Another interesting phenomenon is that the energy efficiency of the rate-first CDRPA scheme experiences a sudden drop at the E_b/N_0 whose values equal to the required E_b/N_0 of a transmit rate. Note that the rate-first CDRPA scheme increases the transmit rate instead of reducing the transmit power as the channel is good. Therefore, the energy efficiency of the rate-first CDRPA scheme experiences a sudden drop due to the use of high transmit power.

At last, comparing Figs. 3.4 and 3.5, the rate-first CDRPA scheme can provide best goodput performance, while maintaining comparable energy efficiency. Although the power-first CDRPA scheme has the maximum energy efficient, it loses 40 % goodput performance compared to the rate-first CDRPA scheme, especially in high E_b/N_0. Therefore, the rate-first CDRPA scheme may be a good choice for the joint rate and power adaptation considering both the energy efficiency and goodput performance.



(a)



(b)

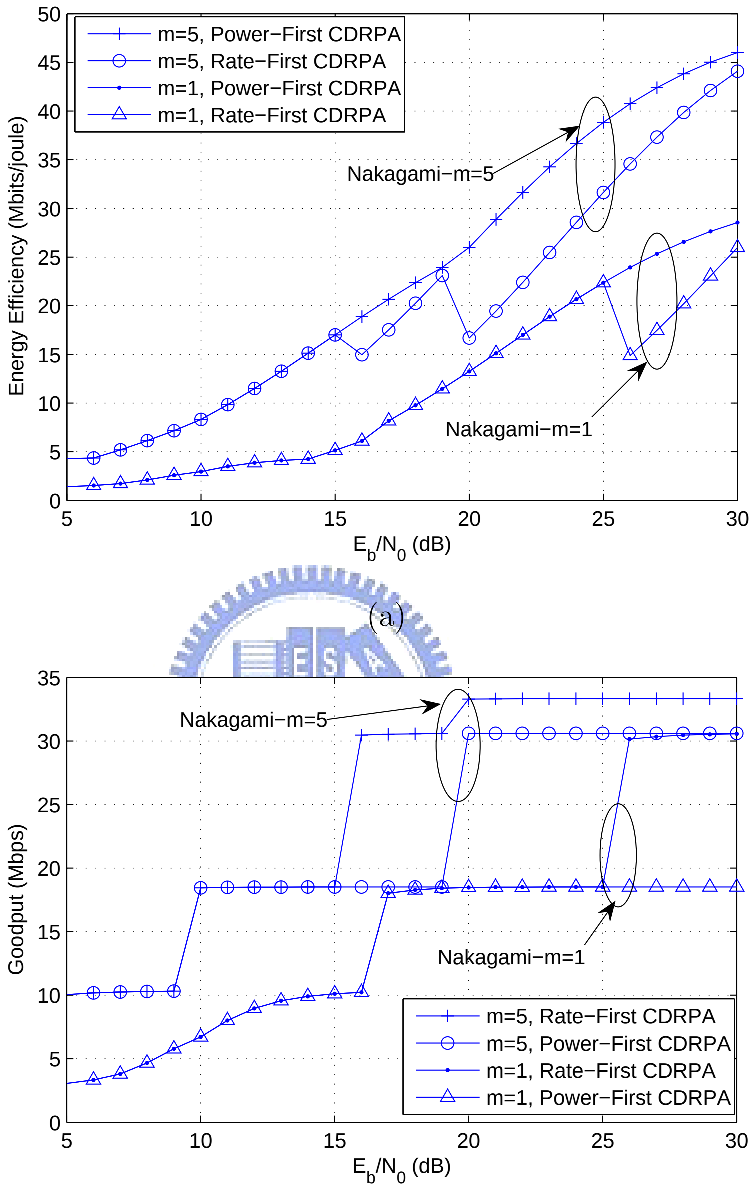
Figure 3.5: The energy efficiency performance in AWGN channel and in Nakagami fading channel with m=1, respectively.

3.3.3 Impacts of Nakagami Shape Factor on Energy Efficiency

In Fig. 3.6(a) and 3.6(b), we investigate the impacts of Nakagami factor on both the energy efficiency and goodput performances of the power-first and rate-first CDRPA schemes. The channel with small Nakagami factor m indicates the large signal variation and leads frame retransmissions due to the high frame outage probability. Therefore, both the energy efficiency and goodput performances with small Nakagami factor m is smaller than that with large m.

3.4 Conclusions

In this chapter, we have presented a fast channel-driven rate and power adaptation (CDRPA) algorithm for WLANs in Nakagami fading channels. The CDRPA algorithm adjusts the rate and power for data transmission according to the signal quality. We also develop analytical methods to compute the goodput and energy efficiency of the WLAN in Nakagami channels. Our numerical results demonstrate that the suggested rate-first CDRPA scheme can provide best goodput performance, while maintaining comparable energy efficiency.



(b)

Figure 3.6: The impacts of Nakagami shape factor on the energy efficiency and goodput.

CHAPTER 4

Joint Rate and Power Adaptation Schemes (RTS/CTS Mode)

In this chapter, we extend the proposed channel-driven rate and power adaptation (CDRPA) algorithm to the multi-user case with RTS/CTS. First, we develop a physical (PHY)/medium access control (MAC) cross-layer analytical method to evaluate goodput and energy efficiency of CDRPA algorithm incorporating the radio channel characteristics and the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. Then, to investigate the tradeoffs between energy efficiency and goodput enhancement, we propose and compare two rate and power adaptation schemes: the power-first CDRPA scheme and the rate-first CDRPA scheme. The power-first CDRPA scheme first selects the transmission power aiming to enhance energy efficiency and then the data rate to improve goodput. On the contrary, the rate-first CDRPA scheme first selects data rate aiming to boost goodput and then the transmission power to save power consumption. Numerical results show that the rate-first scheme can achieve better goodput, which maintaining comparable energy efficiency as the power-first scheme. In addition, we further suggest a weighted moving-average approach to predict the channel condition, which can help improve the energy efficiency of the rate-first CDRPA scheme. Numerical results show that this moving-average based approach can indeed improve the energy efficiency of rate-first CDRPA scheme.

4.1 Analysis

4.1.1 Goodput

The goodput is defined as the number of successfully delivered *information* bits per second. Denote $E[P_D]$ the average delivered information bits, $E[t_T]$ the average transmission time for a data frame. Then, the goodput is written as

$$\mathcal{G}(l,s,m,c,n) = \frac{E[P_D](l,s,m,c,n)}{E[t_T](l,s,m,c,n)}, \tag{4.1}$$

where (l,s,m,c,n) represent the data payload, the received E_b/N_0, the transmission PHY mode, the number of transmission attempts, and the number of contending users, respectively. Because $E[P_D]$ include the average successfully delivered information bits at the first transmission attempt and that at the retransmission, it is followed that

$$\begin{aligned} E[P_D](l,s,m,c,n) &= P_S(l,s,m,n)\cdot l + [1-P_S(l,s,m,n)] \\ &\cdot \{\sum_{k=1}^{N} p_{jk}\cdot E[P_D](l,r,m(r),c+1,n)\}, \end{aligned} \tag{4.2}$$

where $P_S(l,s,m,n)$ is the successful probability of frame transmission; N is the total number of channel states; p_{jk} is the transition probability of channel states defined in (2.2). According to the four-way handshaking RTS/CTS procedures, a data frame is successfully delivered, as long as all the frames in the sequence of "RTS-CTS-DATA-ACK" are successfully received. Therefore, the successful probability of frame transmission $P_S(l,s,m,n)$ can be calculated as

$$P_S(l,s,m,n) = [1-P_{f,RTS}(n,s)]\cdot[1-P_{e,CTS}(s)]\cdot[1-P_{e,data}(l,s,m)]\cdot[1-P_{e,ACK}(s)], \tag{4.3}$$

where $P_{f,RTS}(n,s)$ is the failure probability of RTS with considering the impacts of MAC-layer access contention and PHY-layer reception error. In addition, $P_{e,CTS}(s)$,

$P_{e,data}(l,s,m)$, and $P_{e,ACK}(s)$ are the frame error probability for CTS, data, and ACK frames, respectively. Referring to [20] and [21,22], we can calculate these transmission failure and frame error probabilities (i.e. $P_{f,RTS}(n,s)$, $P_{e,CTS}(s)$, $P_{e,data}(l,s,m)$, and $P_{e,ACK}(s)$).

Now, we calculate the average transmission time for a data frame. From Fig. 2.1, frame transmission based on the legacy CSMA MAC protocol has five possible scenarios according to the RTS/CTS four-way handshaking mechanism. Let $\overline{T_{bkoff}}(c)$ be the average backoff window size for the c-th transmission attempt and $T_{data}(l,m)$ be the transmission time for a data frame with payload size l using PHY mode m. Referring the figure 2.1, the duration of successful frame transmission T_a is equal

$$T_a = \overline{T_{bkoff}}(c) + T_{RTS} + T_{SIFS} \times 3 + T_{CTS} + T_{data}(l,m) + T_{ACK} + T_{DIFS}. \tag{4.4}$$

Similarly, the duration of erroneous CTS, data, and ACK frame transmissions are equal to

$$\begin{cases} T_b = \overline{T_{bkoff}}(c) + T_{RTS} + T_{CTStimeout}, \\ T_c = \overline{T_{bkoff}}(c) + T_{RTS} + T_{SIFS} + T_{CTS} + T_{EIFS}, \\ T_d = \overline{T_{bkoff}}(c) + T_{RTS} + T_{SIFS} \times 2 + T_{CTS} + T_{data}(l,m) + T_{ACKtimeout}, \\ T_e = \overline{T_{bkoff}}(c) + T_{RTS} + T_{SIFS} \times 3 + T_{CTS} + T_{data}(l,m) + T_{ACK} + T_{EIFS}, \end{cases} \tag{4.5}$$

where T_{SIFS}, T_{DIFS}, and T_{EIFS} stand for the durations of a short inter-frame space (IFS), a distributed IFS, and a extended IFS, respectively. T_{RTS}, T_{CTS}, and T_{ACK} are the transmission durations of RTS, CTS, and ACK control frames. $T_{CTStimeout}$ and $T_{ACKtimeout}$ represent the durations of a CTS timeout and an ACK timeout. According to IEEE 802.11a WLAN standard [6], the values of $T_{data}(l,m)$, $\overline{T_{bkoff}}(c)$, $T_{CTStimeout}$, and $T_{ACKtimeout}$ can be specified as in [23]. Then, the average transmission time $E[t_T]$ can be expressed as

$$E[t_T](l,s,m,c,n) =$$

$$P_S(l,s,m,n)\cdot T_a + P_{f,RTS}(n,s)\cdot T_b + (1-P_{f,RTS}(n,s))\cdot P_{e,CTS}(s)\cdot T_c$$

$$+ (1-P_{f,RTS}(n,s))\cdot(1-P_{e,CTS}(s))\cdot P_{e,data}(l,s,m)\cdot T_d$$

$$+ (1-P_{f,RTS}(n,s))\cdot(1-P_{e,CTS}(s))\cdot(1-P_{e,data}(l,s,m))\cdot P_{e,ack}(s)\cdot T_e$$

$$+ (1-P_S(l,s,m))\cdot\{\sum_{k=1}^{N} p_{jk}\cdot E[t_T](l,r,m(r),c+1,n)\}. \tag{4.6}$$

4.1.2 Energy Efficiency

The energy efficiency ζ is defined as the ratio of the average delivered information bits $E[P_D]$ to the total energy consumption for a data frame transmission $E[\varepsilon_T]$, that is,

$$\zeta(l,s,m,c,n) = \frac{E[P_D](l,s,m,c,n)}{E[\varepsilon_T](l,s,m,c,n)}. \tag{4.7}$$

By the same reasoning to evaluate $E[t_T]$ in (4.6), $E[\varepsilon_T]$ can be expressed as

$$E[\varepsilon_T](l,s,m,c,n) =$$

$$P_S(l,s,m,n)\cdot[(T_{SIFS}\times 2 + T_{ACK} + T_{DIFS})\cdot P_{r\_mode} + T_{data}(l,m)\cdot P_{t\_mode}(p_t)]$$

$$+ P_{f,RTS}(n,s)\cdot[(T_{SIFS} + T_{slot}\times 2)\cdot P_{r\_mode}]$$

$$+ (1-P_{f,RTS}(n,s))\cdot P_{e,CTS}(s)\cdot[T_{EIFS}\cdot P_{r\_mode}]$$

$$+ (1-P_{f,RTS}(n,s))\cdot(1-P_{e,CTS}(s))\cdot P_{e,data}(l,s,m)\cdot[(T_{SIFS} + T_{ACKtimeout})\cdot P_{r\_mode}$$

$$+ T_{data}(l,m)\cdot P_{t\_mode}(p_t)]$$

$$+ (1-P_{f,RTS}(n,s))\cdot(1-P_{e,CTS}(s))\cdot(1-P_{e,data}(l,s,m))\cdot P_{e,ack}(s)$$

$$\cdot[T_{SIFS}\times 2 + T_{ACK} + T_{EIFS})\cdot P_{r\_mode} + T_{data}(l,m)\cdot P_{t\_mode}(p_t)]$$

$$+ (1 - P_S(l,s,m)) \cdot \{\sum_{k=1}^{N} p_{jk} \cdot E[\varepsilon_T](l,r,m(r),c+1,n)\} + \varepsilon_o, \tag{4.8}$$

where $\varepsilon_o = (\overline{T_{bkoff}}(c) + T_{SIFS} + T_{CTS}) \cdot P_{r\_mode} + T_{RTS} \cdot P_{t\_mode}(p_{tmax})$ represents the common part of energy consumption for the successful and erroneous frame transmission. In (4.8), $P_{t\_mode}(p_t)$ and P_{r_mode} are the power consumption for a terminal operating in the transmitting and receiving modes, respectively. Clearly, the power consumption in transmitting mode $P_{t\_mode}(p_t)$ strongly depends on the frame transmission power p_t as in [3].

4.2 Channel-Driven Rate and Power Adaptation (CDRPA) with RTS/CTS

4.2.1 Principle

The fundamental idea of CDRPA algorithm is to adjust the transmission rate and power according to the received signal quality (E_b/N_0) of CTS frame in the current frame transmission. In CDRPA algorithm, all control frame (RTS, CTS, and ACK frames) are transmitted at minimal rate with maximal power (p_{tmax}) for reliability. Therefore, the E_b/N_0 value of received control frame can be used to represent the channel condition at a given noise power spectra density N_0. Figure 4.1 shows the flow chart of rate-first CDRPA algorithm with moving averaged channel quality prediction, which is elaborated as follows:

1. Estimate the received E_b/N_0 of current CTS frame, and let it be x_1. Let x_2 be the received E_b/N_0 of previous control frame (ACK or CTS). If the ACKtimeout of the previous ACK frame occurs, x_2 is the R_bN_0 of the previous CTS frame. Otherwise, the erroneous ACK frame received, x_2 is the E_b/N_0 of the previous erroneous ACK frame.

Table 4.1: Required E_b/N_0 for eight transmission PHY modes in Nakagami fading channel with m=1, assuming transmit power is 30 dBm.

Data Rate (Mbps)	6	9	12	18
E_b/N_0	13.962	56.398	13.962	56.398

Data Rate (Mbps)	24	36	48	54
E_b/N_0	16.471	45.757	25.984	63.807

2. Check whether ACK frame of previous data frame transmission is successfully received. If so, the channel condition is quantified by the channel quality index (CHQ), and let

$$CHQ = x_1 \ (the\ E_b/N_0\ value\ of\ received\ CTS). \tag{4.9}$$

Otherwise, CDRPA algorithm will predict the channel condition by applying a weighted moving averaged (MA) approach, as discussed in Section 4.2-B.

3. According to the predicted channel quality, CDRPA algorithm jointly adjusts transmission rate and power based on the selection criteria described in Section 4.2-C. For different objectives, we propose two schemes based on the CDRPA algorithm: the power-first CDRPA scheme and the rate-first CDRPA scheme.

4.2.2 Weighted Moving Averaged Prediction for Channel Quality

If the ACK frame of previous transmission is not successfully received (i.e. ACK timeout or ACK error), CDRPA algorithm will predict the channel condition in a conservative fashion. Let the E_b/N_0 of current CTS frame be x_1 and the E_b/N_0

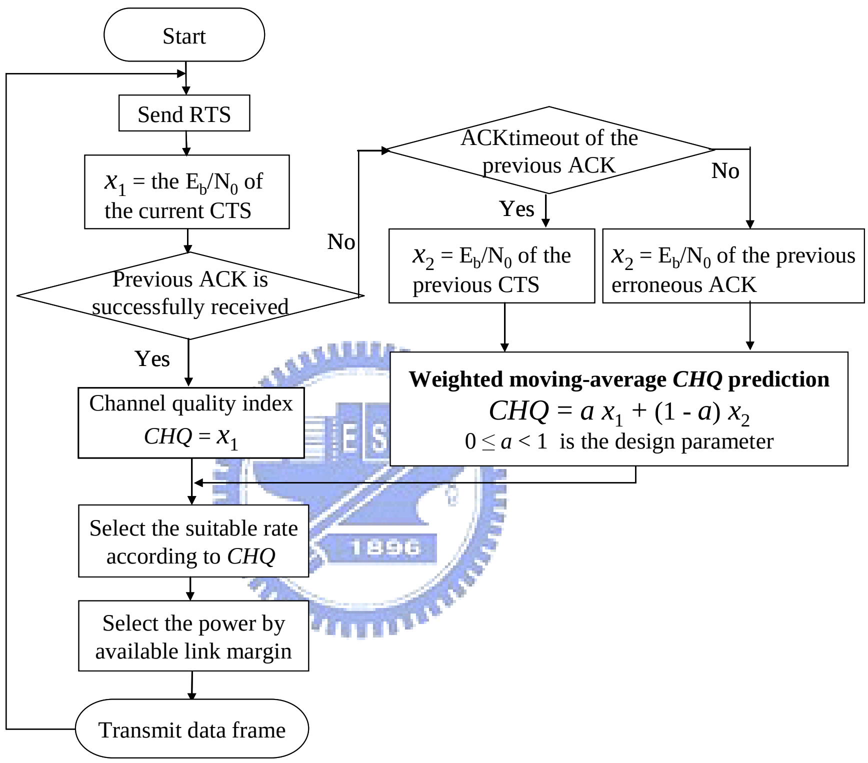


Figure 4.1: The flow chart of the rate-first CDRPA algorithm with RTS/CTS mechanism and moving averaged channel quality prediction.

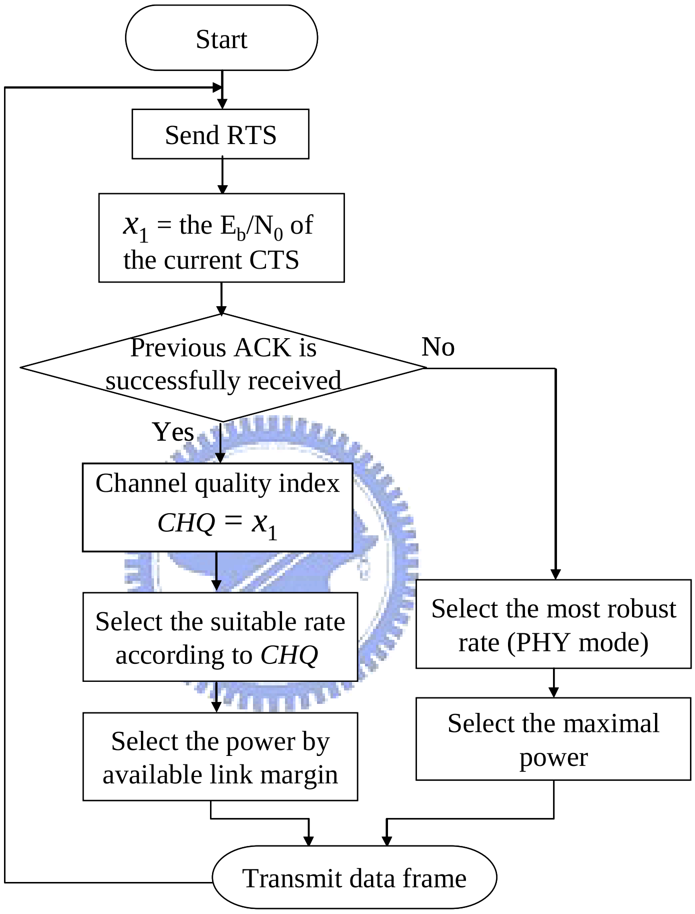


Figure 4.2: The flow chart of the conservative rate-first CDRPA algorithm with the RTS/CTS mechanism.

of previous erroneous control frame be x_2. Therefore, we suggest that the channel quality index is replaced by

$$CHQ = a \cdot x_1 + (1 - a) \cdot x_2, \tag{4.10}$$

where $0 \leq a < 1$ is the design parameter. By (4.10), the channel quality is actually underestimated. However, the data frame can be transmitted more reliably with lower rate/higher power, thereby reducing the number of retransmission and then saving total power consumption for a data frame.

In addition, we also propose a conservative CDRPA algorithm without moving averaged channel quality prediction, as shown in Fig. 4.2. If the previous ACK frame is not successful, the CDRPA algorithm sends the data frame with the most robust PHY mode and maximal power to ensure the successful data frame transmission.

4.2.3 Rate and Power Selection Criteria

- **Reduced-Mode Rate Selection**: Referring to [7], we can neglect some inefficient transmission PHY modes in the rate selection process. Consider an example in a Nakagami fading channel with $m = 1$. From Table 4.1, it is obvious that the required E_b/N_0 for 24 Mbps is much less than that for 18 Mbps, at given PER=10 %. This phenomenon implies that the PHY mode with 18 Mbps is inefficient. Following such a reasoning, we will just use the transmission PHY modes with 12, 24, 48, and 54 Mbps, while in a Nakagami fading channel with $m = 1$.

- **Link-Margin Power Selection**: The transmission power for a data frame is determined according to the predicted link margin. Suppose that the required E_b/N_0 for the selected PHY mode is x_{req}. Then, the available link margin L_{margin} for a given PHY mode can be defined as

$$L_{margin} = CHQ - x_{req}. \tag{4.11}$$

Then, the transmission power p_t for data frame will be determined by

$$p_t = \lceil p_{t_{max}} - L_{margin} \rceil, \tag{4.12}$$

where $p_{t_{max}}$ is the maximal transmission power level.

Based to the principles of CDRPA algorithm discussed above, we further propose two adaptation schemes as follows.

4.2.4 Power-First CDRPA Scheme

The goal of power-first CDRPA scheme is to adjust the rate and power to enhance energy efficiency, as described in the following.

1. According to the predicted channel quality index (CHQ), find all the feasible data rates from a reduced mode table like Table 4.1.
2. By (4.11) and (4.12), determine the power level and calculate the energy efficiency for each feasible data rate.
3. Select the rate-power combination with the maximal energy efficiency for current data transmission.

For example, assume that the predicted channel quality index is CHQ=26 dB and the maximal transmission power level $p_{t_{max}} = 30$ dBm. Form Table 4.1, we can transmit the data frame at the rate of 12 Mbps, 24 Mbps or 48 Mbps. By (4.11) and (4.12), the available link margin for 48 Mbps is $26 - 25.984 = 0.016$ dB and the transmission power leverl is $\lceil 30 - 0.016 \rceil = 30$ dBm. In the same manner, the transmission power levels are determined as 21 dBm for 24 Mbps and 18 dBm for 12 Mbps. After computation, we can obtain that the rate-power combination of (24 Mbps, 21 dBm) can achieve maximal energy efficiency.

4.2.5 Rate-First CDRPA Scheme

In the power-first CDRPA scheme, goodput performance may be sacrificed to improve energy efficiency. On the contrary, therefore, the goal of rate-first CDRPA scheme is to adjust the transmission rate and power to boost goodput performance, as detailed in the following.

1. According to the predicted channel quality index (CHQ), find the maximal feasible transmission rate from Table 4.1.

2. By (4.11) and (4.12), determine the transmission power for the data transmission.

For example, assume that the predicted channel quality index is CHQ=26 dB and the transmission power $p_{t_{max}} = 30$ dBm. From Table 4.1, rate-first CDRPA scheme first determines the data rate of 48 Mbps. By (4.11) and (4.12), the available link margin is $26 - 25.984 = 0.016$ dB and then the transmission power level is $\lceil 30 - 0.016 \rceil = 30$ dBm.

The power-first CDRPA scheme first selects the transmission power aiming to enhance energy efficiency and then the data rate to improve goodput. On the contrary, the rate-first CDRPA scheme first selects data rate aiming to boost goodput and then the transmission power to save power consumption. Therefore, it is expected that the rate-first CDRPA scheme can boost the goodput performance at the cost of power consumption. In numerical results, we will discuss such a tradeoff between energy efficiency and goodput in more detailed.

4.3 Numerical Results

In this section, we first compare the performances of the power-first and rate-first CDRPA schemes and the complete searching scheme, MiSer [3]. Then, we investigate the effect of weighted moving-average CHQ prediction method for rate-first CDRPA scheme. In addition, we compare the computation cost between power-first and complete search schemes. The parameters in numerical results are summarized in Table 4.2. Consider the average power of fading amplitude $E[\alpha_t^2] = \Omega = 1$ with doppler spread $f_d = 20$ Hz, i.e. the walking speed at 1 m/sec.

Table 4.2: System parameters used in numerical results.

Parameters	Value
packet payload	1500 bytes
RTS	160 bits
CTS	112 bits
ACK	112 bits
Slot time	9 μ s
SIFS	16 μ s
DIFS	34 μ s
EIFS	118 μ s
$p_{t_{max}}$	30 dBm

4.3.1 Comparison of Goodput and Energy Efficiency

Figure 4.3 shows the goodput and energy efficiency against the number of contention users in Nakagami fading channel with $m = 1$. Here, the conservative CDRPA algorithm adopts the most robust rate and maximal power (i.e., 12 Mbps and 30 dBm) for data frame retransmission once the previous frame transmission is not success. In addition, the power-first CDRPA scheme keeps up the approximate goodput with the complete search scheme. Figure 4.3(a) shows that the rate-first CDRPA scheme can achieve higher goodput performance than the power-first CDRPA scheme. In this example, the rate-first CDRPA scheme has about 80% higher goodput than the power-first CDRPA scheme. However, we can observe in Fig. 4.3(b) that the power-first CDRPA scheme has better energy efficiency performance than the rate-first CDRPA scheme. We can find the rate-first CDRPA scheme has about 11.5% lower energy efficiency than the power-first CDRPA scheme. Therefore, we suggest the rate-first CDRPA scheme can be a good choice for the rate and power adaptation to improve the performance tradeoff between and goodput performance.

Figure 4.4 shows the goodput and energy efficiency in Nakagami fading channel with $m = 5$. To compare Fig. 4.3 and 4.4, there are similarly behaviors for goodput and energy efficiency. The rate-first CDRPA scheme has the better goodput, while maintaining comparable energy efficiency as the power-first CDRPA scheme. Another interesting phenomenon, we can observe the performance with smaller Nakagami factor m is smaller than that with larger m. The value of Nakagami factor m is increasing as the more LOS component in the fading channel. The smaller Nakagami factor m indicates the severer fades in the channel and leads frame retransmissions due to the high frame outage probability with lower data rate and higher transmission power.

4.3.2 The Effects of Moving-Average Channel Quality Prediction

If adopting the most robust rate and maximal power to retransmit data frame, the scheme is not efficient for the performance of goodput and energy efficiency. As the frame transmission is failure, we further suggest a weighted moving-average CHQ prediction scheme to conservatively predict the channel condition. In this approach, we adopt more robust rate and power to reduce the number of retransmission and save the total energy consumption.

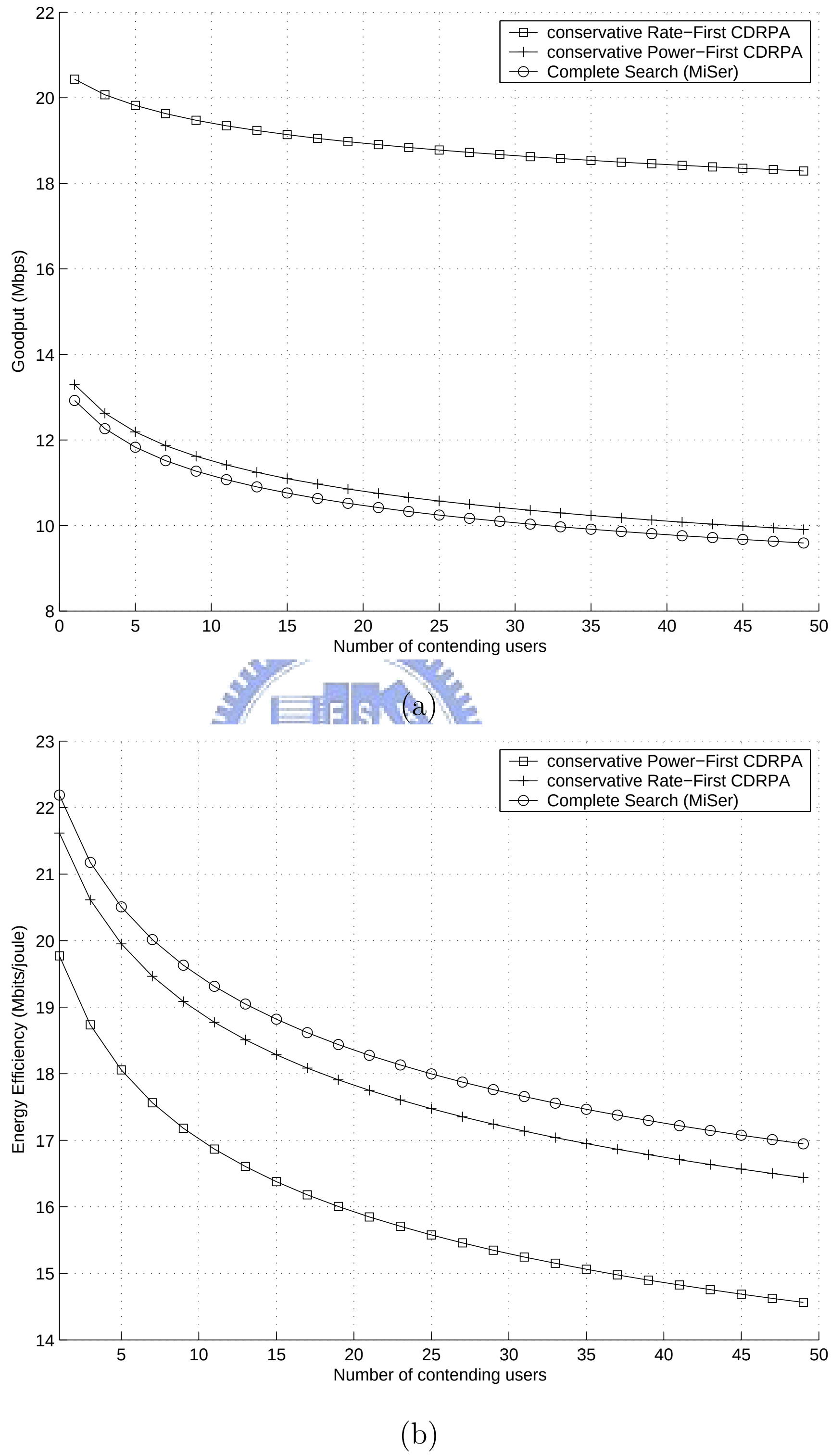
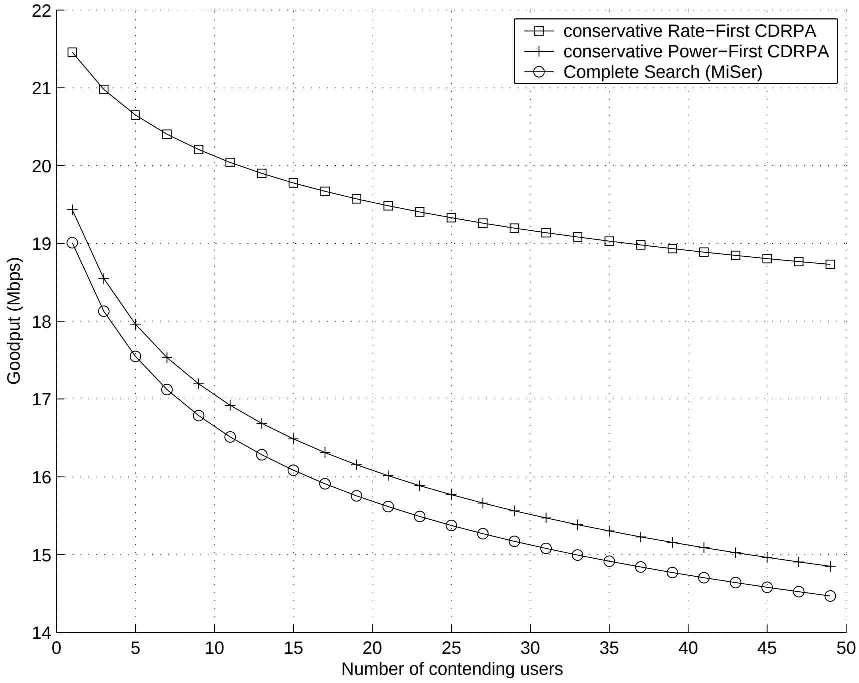
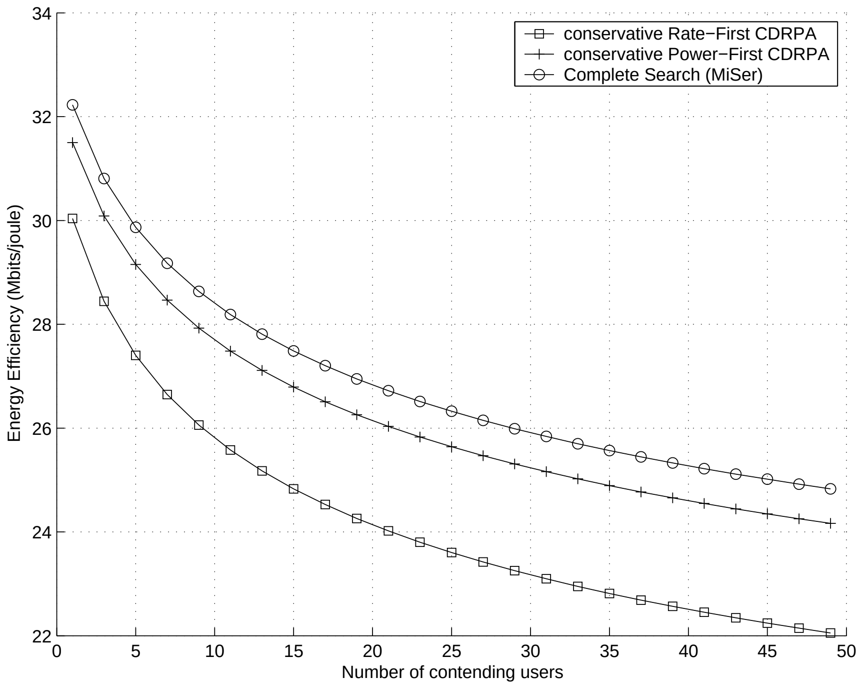


Figure 4.3: The goodput and energy efficiency performances against the number of contending users in Nakagami fading channel with $m = 1$. Here, the conservative CDRPA algorithm adopts the most robust rate and maximal power for data frame retransmission once the previous frame transmission is failed.



(a)



(b)

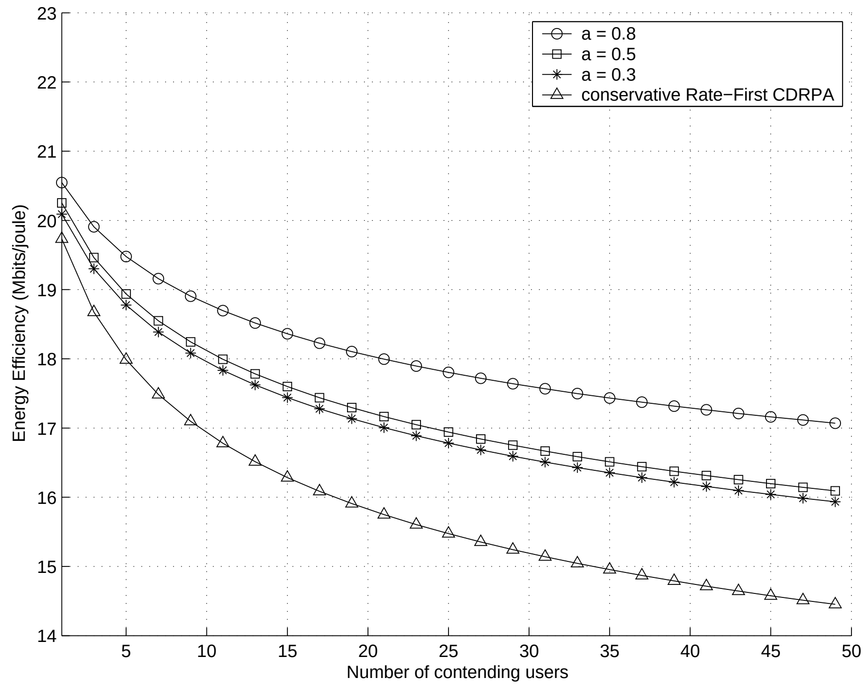
Figure 4.4: The goodput and energy efficiency performances versus the number of contending users in Nakagami fading channel with $m = 5$. Here, the conservation CDRPA algorithm adopts the most robust rate and maximal power for data frame retransmission once the previous frame transmission is failed.

Figure 4.5(a) shows the energy efficiency versus the number of contention users if the current received E_b/N_0 is 30dB. The moving-average CHQ prediction approach can significantly improve energy efficiency for rate-first CDRPA scheme. As the weighting factor mainly is based on the current channel information ($a = 0.8, 1 - a = 0.2$) at the $E_b/N_0 = 30$ dB, the rate-first CDRPA scheme with moving-average CHQ prediction approach can have about 24% higher energy efficiency than the conservative rate-first CDRPA scheme. For Fig. 4.5(b), given $E_b/N_0 = 15$ dB, the improvement of the rate-first CDRPA scheme is about the 51% highrt than the conservative rate-first CDRPA scheme. We note that the values of design parameter a depends on the radio environment, e.g. channel quality, Nakagami factor. The optimal design for a is beyond the scope of this thesis.

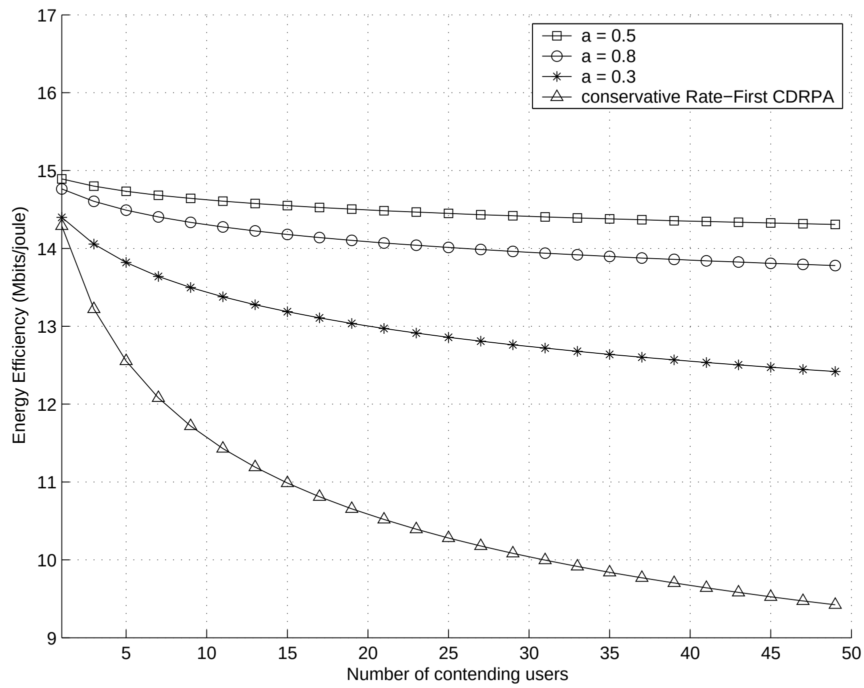
Similarly, Fig. 4.6(a) shows the goodput versus the number of contending users if the current received E_b/N_0 is 30dB. The moving-average CHQ prediction approach can improve a few goodput for the conservative rate-first CDRPA scheme. As the weighting factor a is 0.5 at the $E_b/N_0 = 30$ dB, the rate-first CDRPA scheme with moving-average CHQ prediction approach has just about 1.6% higher goodput than which with minimal rate and maximal power. For Fig. 4.5(b), given $E_b/N_0 = 15$ dB, the goodput of rate-first CDRPA scheme is comparable as the conservative rate-first CDRPA scheme. Thus, we suggest the moving-average channel quality prediction method to improve the energy efficiency of the rate-first CDRPA algorithm.

4.3.3 Computation Cost

Table 4.3 compares the total number of rate-power candidates in the complete search method and that in the power-first CDRPA scheme. Here, we consider eight transmit rates in IEEE 802.11a WLAN and fifteen power levels for data frame from 16 dBm to 30 dBm. In the complete search method, it needs to calculate the energy efficiency

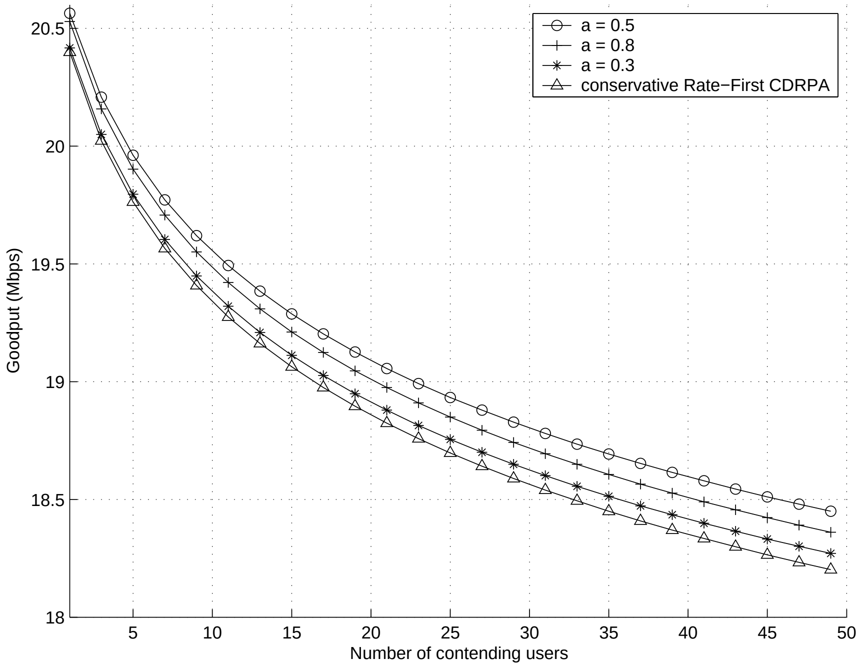


(a)

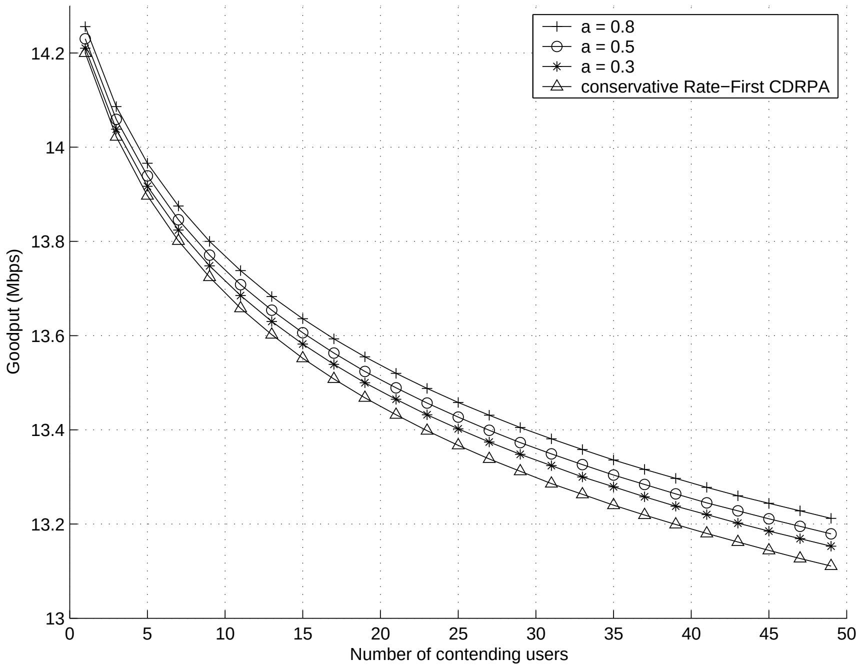


(b)

Figure 4.5: The energy efficiency of rate-first CDRPA scheme (a) At the current received $E_b/N_0 = 30dB$. (b) At the current received $E_b/N_0 = 15dB$. ($0 \leq a < 1$ is the design parameter).



(a)



(b)

Figure 4.6: The goodput of rate-first CDRPA scheme (a) At the current received $E_b/N_0 = 30dB$. (b) At the current received $E_b/N_0 = 15dB$. ($0 \leq a < 1$ is the design parameter).

Table 4.3: Computation cost comparison.

Number of rate-power candidates	Complete Search	CDRPA	Complexity Reduction
AWGN (m=∞)	8×15	7	94.16 %
Rician (m=5)	8×15	5	95.83 %
Rayleigh (m=1)	8×15	4	96.67 %

for all the possible rate-power combinations. That is, there are 8×15 candidates. On the other hand, the power-first CDRPA scheme first selects the transmission power according to the available link margin. Then, it compares the energy consumption of each data rate and the selected transmission power. The total number of rate-power candidates in the power-first CDRPA scheme is the same as the size of the reduced physical modes. As a result, the computation costs of CDRPA algorithm in AWGN and Rayleigh fading channel are reduced by 94 % and 97 % compared to the complete search method, respectively.

4.4 Conclusions

In this chapter, we have proposed a fast channel-driven rate and power adaptation (CDRPA) algorithm for WLANs in Nakagami fading channels. We also develop a PHY/MAC cross-layer analytical method to evaluate goodput and energy efficiency for the CSMA/CA MAC protocol with RTS/CTS in Nakagami fading channels. To investigate the tradeoffs between energy efficiency and goodput enhancement, we propose and compare two rate and power adaptation schemes: the power-first CDRPA scheme and the rate-first CDRPA scheme. In addition, we further suggest a weighted moving-average channel quality prediction method to improve the energy efficiency of the rate-first CDRPA algorithm. From the numerical results, the rate-first CDRPA scheme can significantly improve more goodput performance than the power-first CDRPA scheme, while maintaining comparable energy efficiency as the power-first CDRPA scheme.

CHAPTER 5

Conclusions and Future Research Suggestions

The objective of this thesis is to propose a fast joint rate and power adaptation algorithm for WLANs in a more realistic channel model. We also develop a cross-layer analytical model to compute the goodput and energy efficiency performance of WLANs for the CSMA/CA MAC protocol with RTS/CTS in Nakagami fading channels.

5.1 Summary of Contributions

In Chapter 3 of this thesis, we have proposed a fast joint rate and power adaptation algorithm, called channel-driven rate and power adaptation (CDRPA) algorithm, in the Nakagami fading channel. The power-first CDRPA scheme first selects the transmitted power to improve energy efficiency and then decides the MCS for an appropriate data rate. The rate-first CDRPA scheme first chooses the MCS and the data rate to maximize the goodput and then determines the transmitted power to achieve energy efficiency. Analytical models of computing the goodput and energy efficiency for the IEEE 802.11 WLAN in the Nakagami fading channel are also developed. From the numerical results, we demonstrate that the power-first CDRPA scheme can approach the energy efficiency performance of the optimal MiSer algorithm proposed in [3] with less computation cost by taking advantage of channel information. However, the power-first CDRPA algorithm has about 40 % lower goodput than the rate-first CDRPA scheme. The rate-first CDRPA scheme can provide better goodput performance than the MiSer and power-first CDRPA scheme, while maintaining comparable energy efficiency as the power-first CDRPA scheme.

Further, in Chapter 4, we extend the CDRPA algorithm to the multiple user case with RTS/CTS. We develop a physical (PHY)/medium access control (MAC) cross-layer analytical method to evaluate goodput and energy efficiency of CDRPA algorithm, which incorporates the impacts of radio channel characteristics and the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol. On the top of CDRPA algorithm, this thesis proposes and compares two adaptation schemes: the power-first and the rate-first CDRPA schemes. The power-first CDRPA scheme first selects the transmission power and then the data rate aiming to improve energy efficiency. In this scheme, goodput performance may be traded for energy efficiency because of selecting a lower data rate with less transmission power. By contrast, therefore, the rate-first CDRPA scheme first selects the data rate and then the transmission power aiming to boost goodput performance. Numerical results show that the performance of the power-first CDRPA scheme approaches to that of a dynamic-programming based adaptation approach, while avoid complicated computations for transmission rate and power selection. It is also shown that the rate-first CDRPA scheme can achieve better goodput, which maintaining comparable energy efficiency as the power-first CDRPA scheme. We further suggest a weighted moving-average approach to conservatively predict the channel quality, if previous frame transmission failure occurs. Numerical results show that this moving-average prediction can indeed improve the energy efficiency of rate-first CDRPA scheme.

5.2 Suggestions for Future Research

For the future research, we provide the following suggestions to extend our work:

- For high mobility users, the channel coherent time is short. Thus, the accurary of the channel prediction method in such a channel is needed for further investigation.
- Nakagami fading parameter is related to the number of PHY modes. Nevertheless, how to obtain the Nakagami fading parameter is unsolved yet.
- The optimal weighting factors for the moving-average channel quality prediction method is an open issue.
- In this thesis, we design the CDRPA algorithm and analyze the performance of WLANs in disregard of the impact on the fragmentation for the frame transmission. It is important to further take the effect of the frame fragmentation into the algorithm design.

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