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

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***Abstract*— In this paper, we propose a fast joint rate and power adaptation algorithm for wireless local area networks (WLAN). The proposed algorithm adjusts the rate and power for frame transmission according to the channel state observed at the physical layer, and is named as channel-driven rate and power adaptation (CDRPA) algorithm. The CDRPA algorithm first chooses lowest transmit power under different transmission rate modes according to the previous received ACK frame. Then, the station calculates the required energy consumption among the selected rate and power combination. At last, the proposed algorithm selects the rate and power combination with minimum energy consumption for the next frame transmission. Comparing to the optimal solution for joint rate and power adaptation proposed in [1], the CDRPA algorithm reduces the algorithm's computation complexity and approaches to the optimal solution under the Nakagami fading channel.**

## I. Introduction

At present, the wireless local area network (WLAN) is becoming a popular technology for wireless communication. As the devices in WLAN mostly are powered by the battery, one of the important issues is how to extend the lifetime of device under the limited energy. There are many related works for the energy saving issue. Depending on the operation mode of a station, the related works for the energy saving issue can be categorized as follows. Several policies [2], [3] have been proposed to force a WLAN device to enter the sleeping mode adaptively at appropriate moments to save battery energy.

In [4], [5], [6] the authors provide the algorithms respectively to apply Transmit Power Control (TPC) in the transmit mode of WLAN systems based on the IEEE 802.11h [7], which allows a WLAN device to use the minimum required power level to transmit. In this paper we focus on the transmit mode to save energy. However, the wireless environment varies with time. Data rate also be an important parameter which need to be adjusted depending on the channel situation to increase the transmission reliability. There are many rate adaptation algorithms be proposed [8], [9], [10], [11]. Because the rate adaptation can enhance the transmission reliability, the power adaptation can save battery energy. Hence, in [1] and [12] the authors consider the joint rate and power adaptation for WLAN.

This paper focus on the transmit mode to provide the joint rate and power adaptation algorithm, and it includes two major contributions. First, we improve the analytical model of [1] to incorporate the generalized Nakagami fading channel. Thus, the energy efficiency performance of the IEEE 802.11a WLAN can be evaluated for different fading environments. Secondly, we propose a channel-driven rate and power adaptation (CDRPA) algorithm which can switch the PHY mode and power level according to the available channel state information. The CDRPA algorithm reduces the algorithm's computation complexity due to the number for the calculations of energy consumption in rate and power selection is reduced. We will show that the energy efficiency performance of the proposed scheme approaches to that of the optimum scheme in [1].

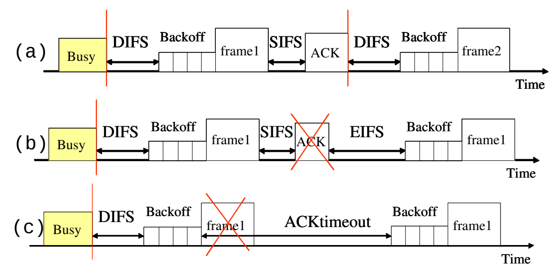


Fig. 1. DCF of MAC protocol, i.e. (a)Successful frame transmission. (b)Frame retransmission due to ACK reception error. (c)Frame retransmission due to data frame reception error.

## II. System overview

### A. IEEE 802.11 MAC

In the IEEE 802.11 MAC layer [15], the distributed coordination function (DCF) is the fundamental mechanism to access the wireless medium. All the stations share the medium by using carrier sense multiple access with collision avoidance (CSMA/CA). Considering the basic DCF access scheme, there are three possible scenario for a frame transmission, as shown in Fig. 1:

(1) Successful frame transmission, Fig. 1(a):
Following the CSMA/CA procedure, the transmitter transmits a frame after waiting a random backoff duration and a distributed inter-frame space (DIFS) duration. The receiver sends an acknowledgment (ACK) control frame to acknowledge the frame successful reception, after receiving the frame and waiting a short inter-frame space (SIFS) duration.

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(2) Frame retransmission due to ACK reception error, Fig. 1(b):
When the transmitter receives a corrupted ACK frame, the transmitter will wait an extended inter-frame space (EIFS) duration and retransmit the frame. The EIFS is much larger than any of the other intervals.

(3) Frame retransmission due to data frame reception error, Fig. 1(c):
When waiting for a ACKtimeout duration without any ACK frame received, the station can know the data frame reception error. The station will retransmit the frame again.

### B. Generalized Fading Channels

In this paper, we consider the Nakagami fading channel model to approach the generalized fading channels. For the model, the probability density function (pdf) of the signal amplitude is given by

$$p_\alpha(x) = \frac{2m^m 2^{2m-1}}{\Omega^m \Gamma(m)} exp(-\frac{mx^2}{\Omega}), \quad (1)$$

where $\alpha$, $m$, and $\Omega$ are the fading amplitude, the Nakagami shape factor, and the average fading power. As $m = 1$, the Nakagami channel model becomes the Rayleigh fading channel, while as $m \to \infty$, the Nakagami-$m$ fading channel becomes the non-fading AWGN channel.

## III. Developments of Algorithm

### A. Channel-Driven Rate and Power Adaptation (CDRPA) algorithm

In this subsection, we detail the channel-driven rate and power adaptation (CDRPA) algorithm, as shown in Fig. 2. The CDRPA chooses the proper PHY mode and transmit power according to the $E_b/N_0$ of previously received ACK frame. The steps are shown as follows:

(1) At first, the transmitter transmits the frame with initial rate and power.
(2) Then, the transmitter waits for the ACK frame. If the transmitter successfully receives ACK frame , it adjusts rate and power by CDRPA for next transmission. If not, the transmitter transmits again with initial rate and power.
(3) If the transmitter successfully receives ACK frame, the CDRPA obtains the suitable set of transmission rate and power from the rate/power threshold table according to the $E_b/N_0$ from the received ACK frame.
(4) From the set of obtained rate and power, the CDRPA selects the one with the minimum energy consumption for next frame transmission.

In the following subsections, we will detail the "rate/power threshold table" and "the minimum energy selection" in the CDRPA algorithm.

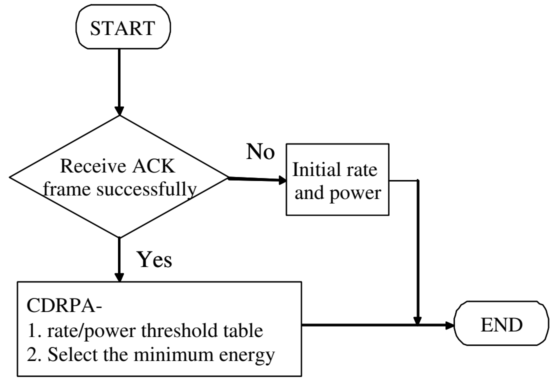


Fig. 2. The flow chart of CDRPA algorithm.

TABLE I
The required $E_b/N_0$ of the eight data rates.

| Data Rate (Mbps) | 6 | 9 | 12 | 18 |
|---|---|---|---|---|
| $E_b/N_0$ | 11.05 | 15.16 | 10.85 | 15.26 |
| Data Rate (Mbps) | 24 | 36 | 48 | 54 |
| $E_b/N_0$ | 13.18 | 18.27 | 19.15 | 21.90 |

### B. Rate/Power Threshold Table

Table I lists the required $E_b/N_0$ of the eight data rates in the Rayleigh fading channel with delay spread 100 nsec assuming the 10 % PER and 30 dBm transmit power [11]. We observe that when data rate is 24 Mbps, the required $E_b/N_0$ is smaller than that of 9 and 18 Mbps. The same situation happens to the data rate with 6 and 12 Mbps. Therefore, we can neglect the PHY modes of 6, 9, 18 Mbps and still have the similar performance of the IEEE 802.11a. We call this scheme as the reduced mode rate adaptation.

Then, we extend the rate/power threshold table based on the reduced mode. Due to the ACK control frame is transmitted with fixed maximum power, the channel quality can be obtained from the $E_b/N_0$ of received ACK frame. If the $E_b/N_0$ of received ACK frame is much more larger than the reduced mode threshold, we maybe can use the lower transmit power to save energy. We show the relation between $E_b/N_0$ and transmission energy $(T/2)$ as following:

$$\begin{aligned} \sigma_z^2 &= N_0/T_s = \frac{N_0}{T_s}\frac{E_c}{RE_b} = \frac{N_0}{T_s}\frac{T/2}{N_{BPSC}RE_b} \\ &= \frac{T/2}{T_s(E_b/N_0)RN_{BPSC}}, \end{aligned} \quad (2)$$

where $\sigma_z^2$, $T_s$ and $T$ are the noise power, the sampling period and the symbol duration. We assume that $E_c$ is the energy of a coded bit, and can be expressed as $E_c = (T/2)/N_{BPSC} = RE_b$, where $N_{BPSC}$ and $R$ are the coded bits per subcarrier and coding rate. Assume the noise power is fixed, the $E_b/N_0$ increase 1 dB, when the transmit power increases 1 dBm. Therefore, as $E_b/N_0$ decrease 1 dB, the required $E_b/N_0$ will increase 1 dB. Then, we can get the rate/power threshold table extended from the rate threshold table in the reduced mode, like Fig. 3(a).

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(a) rate/power threshold table

| PHY mode | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Rate/Power threshold (dB) with Pt = 30dBm | 10.85 | 13.18 | 18.27 | 19.15 | 21.90 |
| Rate/Power threshold (dB) with Pt = 29dBm | 11.85 | 14.18 | 19.27 | 20.15 | 22.90 |
| Rate/Power threshold (dB) with Pt = 28dBm | 12.85 | 15.18 | 20.27 | 21.15 | 23.90 |
| Rate/Power threshold (dB) with Pt = 27dBm | 13.85 | 16.18 | 21.27 | 22.15 | 24.90 |
| Rate/Power threshold (dB) with Pt = 26dBm | 14.85 | 17.18 | 22.27 | 23.15 | 25.90 |

(b) select the minimum energy

| Energy (m joule) |
|---|
| 0.2222 |
| 0.1577 |
| 0.1670 |
| 0.1990 |
| 0.3981 |

Fig. 3. A simple example for (a) rate/power threshold table (b) select the minimum energy.

### C. Minimum energy selection

We take a simple example for the "the minimum energy selection" of CDRPA, as shown in Fig. 3(a). The rate/power selection is according to the previously received ACK frame. Assume the $E_b/N_0$ of the received ACK frame is 22 dB we can obtain the five rate/power combinations according to the rate/power threshold. Then, we compare their energy consumptions and select the minimum one. Therefore, as shown in Fig. 3(b) the selected rate and power are 48 Mbps and 28 dBm, respectively.

## IV. Mathematical Model

In this section, we detail the procedure of the analytical model. Due to the wireless channel is variant with time. First, we divide the channel state by Table I and calculate the transition probability matrix of the channel states. Then, we can calculate the energy efficiency by the transition probability matrix.

### A. Transition Probability Matrix

Denote the transition probability $p_{jk}$ as the probability that transmits from the channel state $s_j$ to $s_k$. Let $x_i$ be the $E_b/N_0$ of the i-th packet, then, $p_{jk}$ can be expressed as:

$$p_{jk} = P(x_{i+1} \in (\eta_{k-1}, \eta_k) | x_i \in (\eta_{j-1}, \eta_j)) = \frac{P(x_{i+1} \in (\eta_{k-1}, \eta_k), x_i \in (\eta_{j-1}, \eta_j))}{P(x_i \in (\eta_{j-1}, \eta_j))}. \quad (3)$$

We need to know the joint pdf $p(x_i, x_{i+1})$ to compute $P(x_{i+1} \in (\eta_{k-1}, \eta_k), x_i \in (\eta_{j-1}, \eta_j))$. In the Nakagami fading channel, the joint pdf $p(x_{t-\tau}, x_t)$ [11] is given by

$$p(x_{t-\tau}, x_t) = \frac{4(x_{t-\tau}x_t)^m}{(1-\rho)\Omega(m)\rho^{(m-1)/2}}(\frac{m}{\Omega})^{m+1} \cdot I_{m-1}(\frac{2m\sqrt{\rho}x_{t-\tau}x_t}{(1-\rho)\Omega}) exp(-\frac{m(x_{t-\tau}^2 + x_t^2)}{(1-\rho)\Omega}), \quad (4)$$

where $x_t$, $I_{m-1}(\cdot)$, $\Gamma(m)$, $\rho$, and $m$ are the $E_b/N_0$ at time instants $t$, the $(m-1)^{th}$-order modified Bessel function of the first kind, the Gamma function, the channel correlation coefficient, and the Nakagami shape factor, respectively.

Therefore, $P(x_{i+1} \in (\eta_{k-1}, \eta_k), x_i \in (\eta_{j-1}, \eta_j))$ and $P(x_i \in (\eta_{j-1}, \eta_j))$ can be expressed as

$$P(x_{i+1} \in (\eta_{k-1}, \eta_k), x_i \in (\eta_{j-1}, \eta_j)) = \int_{\eta_{k-1}}^{\eta_k} \int_{\eta_{j-1}}^{\eta_j} p(x_i, x_{i+1}) dx_i dx_{i+1} \quad (5)$$

and

$$P(x_i \in (\eta_{j-1}, \eta_j)) = \int_0^{\infty} \int_{\eta_{j-1}}^{\eta_j} p(x_i, x_{i+1}) dx_i dx_{i+1}. \quad (6)$$

Next, we can apply the transition probability into calculating the energy efficiency.

### B. Energy efficiency computation

In this paper, we define that the energy efficiency ($\zeta$) is the ratio of the expected delivered data payload ($P_D$) to the expected total energy consumption ($E[\varepsilon_T]$) represented as follows:

$$\zeta(l, s, m, n) = \frac{E[P_D](l, s, m, n)}{E[\varepsilon_T](l, s, m, n)}, \quad (7)$$

where $P_D$ and $\varepsilon_T$ are the delivered data payload and the transmission energy respectively. The average delivered data payload with payload length ($l$), channel state ($s$), PHY mode ($m$) and frame retry count ($n$) is

$$E[P_D](l, s, m, n) = P_{SFT}(l, s, m) \cdot l + [1 - P_{SFT}(l, s, m)] \cdot \{\sum_{k=1}^{N} p_{jk} \cdot E[P_D](l, r, m(r), n+1)\}, \quad (8)$$

where $N$, $r$, $p_{jk}$ are the number of channel state, the SNR value for the next transmission, and the transition probability from channel state $j$ to $k$ [11]. The $P_{SFT}$ is the success probability of frame transmission, i.e.:

$$P_{SFT}(l, s, m) = [1 - P_{e,data}(l, s, m)] \cdot [1 - P_{e,ack}(s)], \quad (9)$$

where $P_{e,data}(l, s, m)$ and $P_{e,ack}(s)$ are the error probability of data and ACK frame, respectively. The average energy consumption of a frame transmission, $E[\varepsilon_T]$ can be expressed as:

$$E[\varepsilon_T](l, s, m, n) = \{T_{SC}(l, m, n) + P_{SFT}(l, s, m) \cdot T_{DIFS} + [1 - P_{SFT}(l, s, m)] \cdot \overline{D_{wait}(n+1)}\} \cdot P_t(l, s, m) + [1 - P_{SFT}(l, s, m)] \cdot \{\sum_{k=1}^{N} p_{jk} \cdot E[\varepsilon_T](l, r, m(r), n+1)\}, \quad (10)$$

where $P_t$ is the transmit power. $T_{SC}(l, m, n)$ and $\overline{D_{wait}}(n)$ are the duration of the $n$-th success connection and the average waiting time before the $n$-th transmission attempt, as follows:

$$T_{SC}(l, m, n) = \overline{T_{bkoff}}(n) + T_{data}(l, m) + T_{SIFS} + T_{ACK}, \quad (11)$$

$$\overline{D_{wait}}(n) = \frac{P_{e,data(l, s_{n-1}, m_{n-1})}}{1 - P_{SFT}(l, s_{n-1}, m_{n-1})} \cdot T_{ACKtimeout} + \frac{[1 - P_{e,data(l, s_{n-1}, m_{n-1})}] \cdot P_{e,ack}(s_{n-1})}{1 - P_{SFT}(l, s_{n-1}, m_{n-1})} \cdot T_{EIFS}, \quad (12)$$

where

$$T_{data}(l,m) = T_{PREAMBLE} + T_{SIGNAL} + T_{SYM} \cdot \lceil \frac{28 + (16+6)/8 + l}{BpS(m)} \rceil = 20\mu s + T_{SYM} \cdot \lceil \frac{30.75 + l}{BpS(m)} \rceil, \quad (13)$$

$$T_{ACK} = T_{PREAMBLE} + T_{SIGNAL} + T_{SYM} \cdot \lceil \frac{14 + (16+6)/8}{BpS(1)} \rceil = 20\mu s + T_{SYM} \cdot \lceil \frac{16.75}{BpS(1)} \rceil. \quad (14)$$

$$\overline{T_{bkoff}}(n) = \frac{min[2^{n-1} \cdot (CW_{min}+1) - 1, CW_{max}]}{2} \cdot T_{slot}, \quad (15)$$

where $T_{PREAMBLE}$, $T_{SIGNAL}$, and $T_{SYM}$ are the PLCP preamble duration, PLCP signal field duration, and OFDM symbol interval. The $BpS(m)$, the bytes-per-symbol information for PHY mode m, is listed in Table III. $CW_{min}$, $CW_{max}$ are the minimum and maximum contention window respectively. The $T_{slot}$, $T_{SIFS}$, $T_{DIFS}$, $T_{EIFS}$, and $T_{ACKtimeout}$ are the duration of a slot, SIFS, DIFS, EIFS, and ACKtimeout respectively. So, we can get the energy efficiency performance of our CDRPA scheme by (7), (8), (10).

## V. Numerical results

In this paper, we consider the IEEE 802.11a [13] as an example in evaluating the performance. The related physical parameters in the IEEE 802.11a are shown in the Table II and Table III.

TABLE II
Transmit Power Levels for North America Operation.

| Frequency Band | Maximum Transmit 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) |

TABLE III
Eight PHY Rate-dependent parameters.

| 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

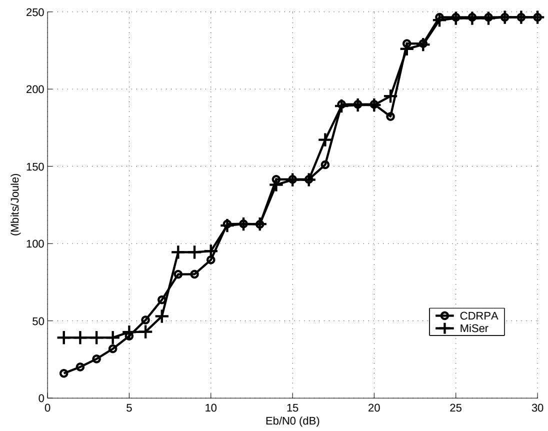


Fig. 4. The energy efficiency under the AWGN channel.

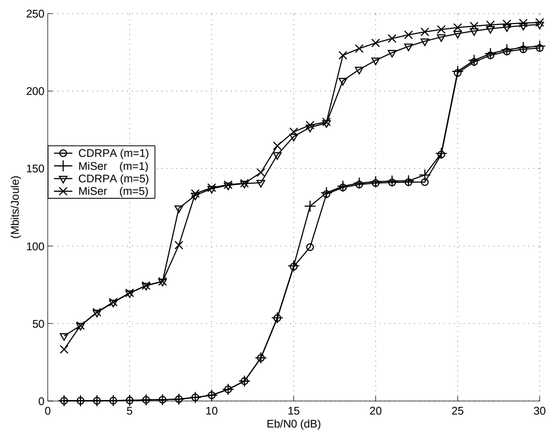


Fig. 5. Under the Nakagami fading channels with parameter m.

### A. Under the AWGN channel

Figure 4 compares the energy efficiency of MiSer and CDRPA algorithm in the AWGN channel. We can find that the energy efficiency performance of CDRPA algorithm is close to the MiSer. However, the MiSer has to calculate the energy efficiency of all the combination of rates and powers, and select the one pair with the maximum energy efficiency. However, CDRPA is based on the $E_b/N_0$ of ACK frame and select the appropriate rate and power to calculate their energy consumption with calculating the order of rate and still maintain the performance.

### B. Under the Nakagami fading channel

In Fig. 5, we compare the energy efficiency under the Nakagami fading channel with different Nakagami shape factor m. As m equals to 1, it is equivalent to the Rayleigh fading channel. Since the Rayleigh fading channel has larger power variation than other fading channels under the same of average signal power, it needs to adopt the more robust modulation and higher power to achieve the required PER. Therefore, the performance for the Rayleigh channel is worse than the Nakagami fading channel with large m.

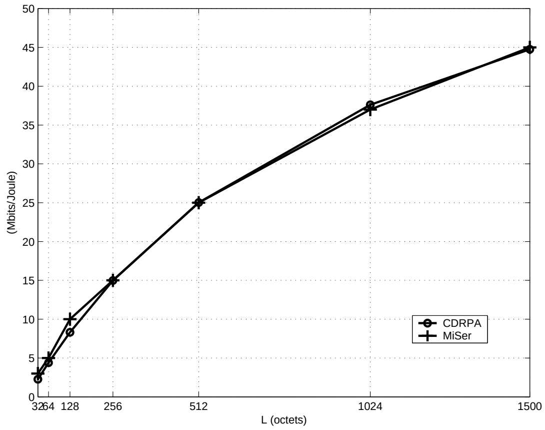


Fig. 6. The energy efficiency with different data payload length.

### C. *Under the Different Data Payload length*

Figure 6 compares the energy efficiency of MiSer and CDRPA algorithm with different payload length under the AWGN channel. As the payload length increases, the energy efficiency also increases. Because the larger the payload length, the smaller the ratio for the MAC header and control frames within a transmission cycle. Most energy in transmitting long payload is consumed for payload transmission instead of the MAC header and control frames. Therefore, as the payload length increases, the energy efficiency also increases.

## VI. Conclusions

We propose a fast joint rate and power adaptation algorithm for WLAN, and named as CDRPA. In the CDRPA algorithm, we reduce the size of rate/power selection due to the concept of reduce mode and the rate/power threshold. The reduce mode picks off the inefficiency PHY mode, and the rate/power threshold picks out the suitable rate and power combinations. From the numerical result, the performance of CDRPA is close to the optimal solution. However, the complexity of CDRPA as much less than the optimal solution.

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