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# A Power Control Scheme to Exploit Capture Effect with Fairness Consideration in WLAN

**Szu-Lin Su[1] · Tsung-Hsiu Chih[1] · Yuan-Chun Tsai[1] · Hsieh-Cheng Liao[1] · Yu-Chia Wang[1]**

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## Abstract

In this paper, we develop a physical/medium-access-control cross layer design to improve system throughput with the consideration of fairness for IEEE 802.11 WLAN. From PHY layer perspective, when an access collision occurs, the access point can still decode the corresponding data successfully if the received signal to interference plus noise ratio is larger than the threshold. This phenomenon is referred to as the capture effect. To improve system throughput, this work proposes a Differential Reception-Power Power Control scheme to take advantage of the capture effect. However, the proposed power control scheme cannot provide a fair transmission environment even though it improves the system throughput. To resolve this problem, this work proposes two methods: the adjustment of contention window size and the modification of probability mass function for the selection of the backoff value. The simulation results demonstrate that the proposed schemes can not only remarkably improve system throughput, but also provide a fair transmission environment.

**Keywords** IEEE 802.11 WLAN · Transmit power control · Capture effect · Fairness

✉ Tsung-Hsiu Chih
daz@pcnw3.ee.ncku.edu.tw

Szu-Lin Su
ssl@ee.ncku.edu.tw

Yuan-Chun Tsai
yuan@pcnw3.ee.ncku.edu.tw

Hsieh-Cheng Liao
airhead@pcnw3.ee.ncku.edu.tw

Yu-Chia Wang
gpbt2408@pcnw3.ee.ncku.edu.tw

[1] Institute of Computer and Communication Engineering, Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan

# 1 Introduction

In the past decades, for the highly demanding data-traffic requirement of the Internet of Things (IoT), a wireless local area network (WLAN) based on IEEE 802.11 has been commonly used in homes and offices. It also helps to improve the service quality of cellular networks to reach an adequate standard, especially in public hotspots. In WLAN, if more than one station (STA) attempts to transmit the packets at the same time, all the involved transmissions are usually considered to have failed on the reception at the access point (AP). This is referred to as an access collision [1]. To reduce the probability of access collisions, the IEEE 802.11 WLAN adopts a carrier-sense-multiple-access (CSMA) based medium-access-control (MAC) protocol, called the distributed coordination function (DCF). Many new or modified MAC mechanisms have been proposed [2–6] to reduce the risk of collision and improve system throughput.

In terms of the physical (PHY) layer, in case of an access collision, the receiver can still decode the corresponding data successfully if the strength of the intended received signal is much higher than that of other signals. This phenomenon is called the *capture effect* [7–11]. If all the STAs in a basic service set (BSS) of the IEEE 802.11 WLAN transmit the packets with constant power (i.e., without power control), then the packet-reception at the AP will naturally hold the capture capability due to the spatial difference among STAs. Some studies have examined the impact of the capture effect on IEEE 802.11 WLANs [12–16]. In [12], the authors presented an analytical model based on Markov chain to demonstrate the probability of successful transmission is increased under capture effect and channel fading. Ge et al. [13] investigated the influence of the capture effect on the back-off mechanism and presented a new throughput model for WLANs. Another study [14] proposed a new Markov chain model for the binary exponential back-off scheme of the MAC layer considering the capture effect. Some researchers conducted a saturation throughput analysis of the IEEE 802.11 DCF under the capture effect [15]. Taking into account the erroneous channel and capture effect, Kumar and Krishnan [16] analyzed the performance of non-saturated traffic in IEEE 802.11 networks.

All of these studies [12–16] have indicated that the capture effect can increase the probability of successful reception and improve system throughput. However, the STAs that are located near the AP have more opportunities to take advantage of the capture effect, resulting in an unfair access environment. This may be resolved through implementation of a perfect power control scheme, where all the STAs transmit the packets with a controlled power so that all the received signal strengths at the AP are the same. However, the throughput gain of the capture effect is also lost. In a previous paper [17], we proposed a power control scheme with multiple levels of reception-power to exploit the capture effect for throughput improvement. Although the proposed scheme remarkably increased the system throughput, we did not address the unfair access problem. One study [18] discussed the spatial unfairness problem and analyzed system performance, and another [19] attempted to balance the unfair throughput under the capture effect by adjusting the transmission opportunity and inter-frame spacing. [20] proposed a power-hopping scheme in which STAs take turns to employ high and low reception-power levels, thus enhancing the STA throughput.

In this paper, we extend the power control scheme proposed in [17], called the Differential Reception-Power Power Control (DRP-PC) scheme, to improve the overall system throughput for WLANs. Unlike a perfect power control scheme with a constant reception-power level for all access transmissions, the proposed DRP-PC scheme has multiple reception-power levels, thus taking advantage of the capture effect. However, this scheme results in access unfairness, and to resolve this problem, we propose two schemes: a CW-size adjustment scheme and a modification of probability-mass-function (PMF) scheme. The simulation results demonstrate that the proposed schemes can improve both system throughput and access fairness.

The remainder of this paper is organized as follows. Section 2 introduces the considered system model. The proposed DRP-PC algorithm is described in Sect. 3. Section 4 presents the proposed fairness schemes. Section 5 describes the performance evaluations for the proposed schemes. Finally, Sect. 6 concludes this paper.

## 2 System Model

### 2.1 Network and Channel Model

This work focuses on a BSS of the IEEE 802.11 WLAN which contains an AP, located at the center of a circular BSS area, and a number of STAs. The STAs are assumed to be uniformly distributed over the whole area. Only the uplink access from STAs to the AP is considered, and it is assumed that any STA can hear the ongoing transmission (i.e., no hidden nodes). For the propagation channel, the simplified path loss model [21] is adopted, expressed as.

$$P_r = P_t K \left( \frac{d_0}{d} \right)^{\gamma}, \tag{1}$$

where $P_t$ and $P_r$ are the transmitted and received powers, respectively, $d$ is the distance between the AP and STA, $d_0$ is a reference distance, $\gamma$ is the path loss exponent, and $K$ is a system parameter related to the antenna design and is assumed to be constant.

For the IEEE 802.11a system, [22] listed the minimum signal to interference plus noise ratio (*SINR*) requirement for different transmission rates, as shown in Table 1. Here, we denote the minimum *SINR* requirement as $SINR_{th}$. The transmission power (power control) was adjusted on the basis of $SINR_{th}$ for different transmission rates. It is assumed that the transmitted packet can be decoded successfully when the received *SINR* is larger than $SINR_{th}$.

**Table 1** Minimum *SINR* requirement ($SINR_{th}$) for different transmission rate in the IEEE 802.11a system [22]

| Rate (Mbps) | $SINR_{th}$ (dB) |
|---|---|
| 54 | 24.56 |
| 48 | 24.05 |
| 36 | 18.80 |
| 24 | 17.04 |
| 18 | 10.79 |
| 12 | 9.03 |
| 9 | 7.78 |
| 6 | 6.02 |

### 2.2 Overview of the IEEE 802.11 MAC Protocol [23]

The main MAC protocol of IEEE 802.11 is called distributed coordination function (DCF). The DCF contains two key components to reduce collision probability. One component is the CSMA protocol for short data-packet transmission and CSMA/CA protocol for long data-packet transmission. The other component is the binary exponential backoff scheme for retransmission after an access collision has occurred. An STA with a newly generated data-packet monitors the channel state. If the channel is idle for a period longer than the duration of the distributed interframe space (DIFS), then the STA transmits the data-packet for a short data-packet and the RTS-packet for a long data-packet. If the channel is sensed to be busy, then the STA randomly chooses a value from the contention window [0, $CW_{min}$-1], where $CW_{min}$ is the initial contention window size, and enters the backoff stage. During the backoff period, the STA counts down the backoff timer only when the channel is sensed to be idle. Once the backoff counter reaches zero, the STA initiates the data-packet or RTS-packet transmission, irrespective of whether the channel is idle or not. A collision may occur if more than one STA is transmitted simultaneously. When a collision occurs, the involved STAs double the CW size and restart the same backoff process (called the binary exponential backoff scheme). However, if the transmission is successful, then the corresponding contention window size is reset to $CW_{min}$.

## 3 Power Control Strategy for the Capture Effect

For an IEEE 802.11 WLAN, perfect power control in which all the received signals of the incoming packets at the AP have the same strength can allow fair access among STAs located in different positions. However, such a scheme does not take advantage of the capture effect and loses some system throughput. By contrast, a WLAN without power control can naturally utilize the capture effect to increase the system throughput. However, the improvement is not remarkable because the probability that the capture effect holds is not high. Hence, this work proposes a novel power control scheme that aims to take advantage of the capture effect more frequently to increase the system throughput. Additionally, because this proposed power control scheme results in unfair access among STAs, this work presents two schemes to remedy this problem.

### 3.1 Differential Reception-Power Power Control (DRP-PC) Scheme

The proposed DRP-PC scheme is designed to have multiple reception-power levels at the AP instead of a single reception-power level to achieve a perfect power control scheme. The difference between any two distinct reception-power levels is sufficient to exploit the capture effect. As illustrated in Fig. 1, for the DRP-PC scheme, the whole BSS area is circularly divided into $K$ zones from the AP, denoted as Zone 1, Zone 2, …, Zone $K$. The STAs located in Zone $j$ ($1 \le j \le K$) are denoted as STA_js. The DRP-PC scheme mainly controls the transmission power of the first transmission in a data-packet transmission session (i.e., the RTS-packet for the long data-packets and the data-packet itself for the short data-packets). The rest of the data-packet transmission session adopts the perfect power control scheme as the conventional system. During the DRP-PC

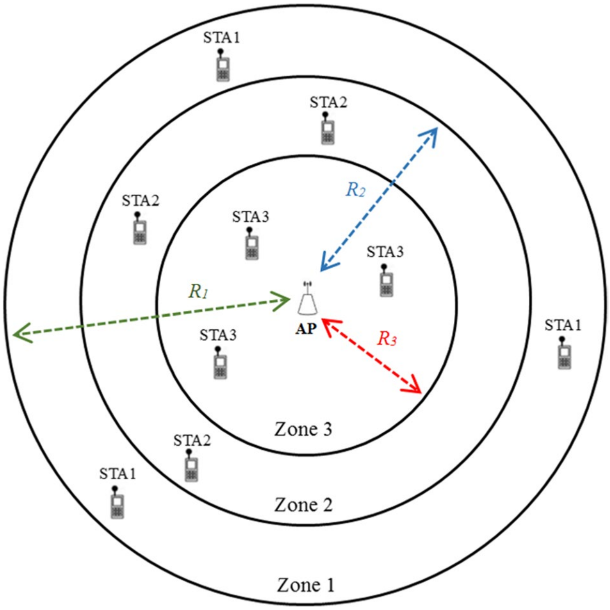



**Fig. 1** The basic service set (BSS) of IEEE 802.11 WLAN considered in this work

period, the transmission-power levels of the STA_js in Zone $j$ are adjusted to have the same reception-power level, denoted as $P_{rj}$. Thus, there are $K$ distinct reception-power levels, with each level corresponding to one of the $K$ zones. Moreover, it is requested that $P_{ri} < P_{rj}$, if $1 \le i < j \le K$.

With the DRP-PC scheme, the whole BSS area can be geographically divided into $K$ zones according to the distance to the AP, as shown in Fig. 1. In this case, any STA must estimate its location (the distance to the AP) with some aided tool (such as a GPS system) to determine its corresponding zone. In practice, the pathloss, another key factor for power control, can be used to determine the corresponding zone for each STA.

For simplicity, in the following discussion, we only consider the DRP-PC scheme with $K=2$ (i.e., a WLAN system with two reception-power levels). Thus, the reception-power level of the transmitted packet from every STA_1 is $P_{r1}$, that from every STA_2 is $P_{r2}$, and $P_{r2} > P_{r1}$. Next, when only one STA_1 or one STA_2 transmits, the AP can successfully decode the packet if

$$10 \log \left( \frac{P_{r1}}{P_N} \right) \ge SINR_{th}, \tag{2}$$

and

$$10 \log \left( \frac{P_{r2}}{P_N} \right) \ge SINR_{th}, \tag{3}$$

where $P_N$ is the background noise power.

To take advantage of the capture effect, the proposed design allows the AP to successfully decode the packet from an STA_2 when one STA_2 and one STA_1 transmit simultaneously, and it requires

$$10\log\left(\frac{P_{r2}}{P_{r1}+P_N}\right)\geq SINR_{th}. \tag{4}$$

From (2), we can obtain the minimum reception-power level for successful transmission of an STA_1 as follows:

$$P_{r1}=P_N 10^{\frac{SINR_{th}}{10}}. \tag{5}$$

From (4) and (5), we can also obtain the minimum reception-power level for the successful transmission of an STA_2, when there is one simultaneous STA_1 transmission:

$$P_{r2}=P_N\left(10^{\frac{2SINR_{th}}{10}}+10^{\frac{SINR_{th}}{10}}\right). \tag{6}$$

In summary, if both (5) and (6) are satisfied, then the AP can successfully decode at least one of the incoming packets when.

1. Only one STA_1 transmits.
2. Only one STA_2 transmits.
3. One STA_1 and one STA_2 transmit simultaneously, and the transmission of the STA_2 is successfully decoded with the capture effect.

In the proposed DRP-PC scheme, the STAs located at the edge of the zone require maximum transmitted power and those near the AP require less transmitted power. Thus, based on path loss models (1), (5) and (6), the adjustment ranges of transmitted power for STA_1 and STA_2 are [$P_{t1\_\min}$, $P_{t1\_\max}$] and [0, $P_{t2\_\max}$], respectively, where

$$P_{t1\_\min}=\frac{1}{K}\left(\frac{R_2}{d_0}\right)^{\gamma}P_{r1}=P_N\frac{1}{K}\left(\frac{R_2}{d_0}\right)^{\gamma}10^{\frac{SINR_{th}}{10}}, \tag{7}$$

$$P_{t1\_\max}=\frac{1}{K}\left(\frac{R_1}{d_0}\right)^{\gamma}P_{r1}=P_N\frac{1}{K}\left(\frac{R_1}{d_0}\right)^{\gamma}10^{\frac{SINR_{th}}{10}}, \tag{8}$$

$$P_{t2\_\max}=\frac{1}{K}\left(\frac{R_2}{d_0}\right)^{\gamma}P_{r2}=P_N\frac{1}{K}\left(\frac{R_2}{d_0}\right)^{\gamma}\left(10^{\frac{2SINR_{th}}{10}}+10^{\frac{SINR_{th}}{10}}\right). \tag{9}$$

### 3.2 Performance Comparison

For the system simulations in this section, it is assumed that there are $N$ busy STAs uniformly distributed over the whole BSS area. Because the performance improvement on the CSMA/CA-based long-packet-transmission due to the capture effect is not remarkable [13], only the CSMA-based short-packet-transmission is considered. Table 2 presents the detailed system configuration for the following system simulations.

Figure 2 compares the system throughput performance among the conventional system with perfect power control (Scheme 1), the conventional system without power control (Scheme 2), and the proposed DRP-PC scheme. Obviously, DRP-PC scheme outperforms

**Table 2** System configuration for short data-packet transmissions in the simulations

| | |
|---|---|
| Transmission rate | 24Mbps |
| $SINR_{th}$ | 17.04 dB |
| ACK length | 112 bits |
| Payload length | 250 bytes |
| DIFS | 34 µs |
| SIFS | 16 µs |
| Slot time | 9 µs |
| $CW_{min}$ | 16 |
| $CW_{max}$ | 1024 |
| Propagation model | Two-ray ground |
| Path loss exponent (γ) | 4 |
| Reference distance ($d_0$) | 1 m |
| Constant parameter ($K$) [21] | −31.54 dB |
| Thermal noise [24] | −90 dBm |
| $R_1/R_2$ | 100/70.71 m |

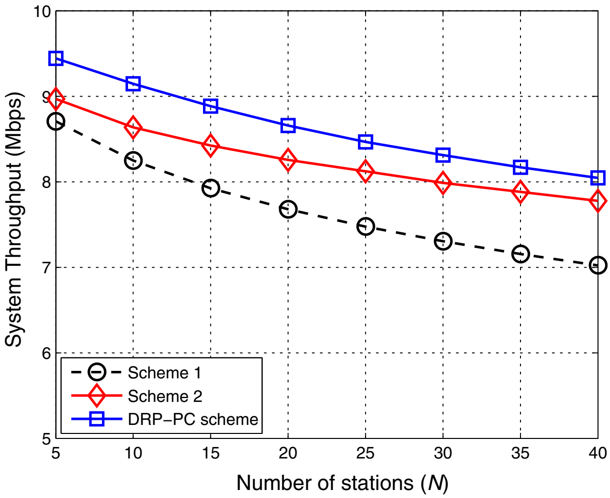



**Fig. 2** System throughput comparison of different schemes ($R_2$ = 70 m)

others. However, the proposed scheme results in an unfair problem, as shown in Fig. 3. The adopted fairness index is defined as follows [25]

$$F(x_1, x_2, \dots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n\sum_{i=1}^{n} x_i^2}, \tag{10}$$

where $x_i$ is the number of successful transmissions for STA_$i$ during the simulation period. Note that $0 \le F(\cdot) \le 1$, and $F = 1$ if the system is truly fair.

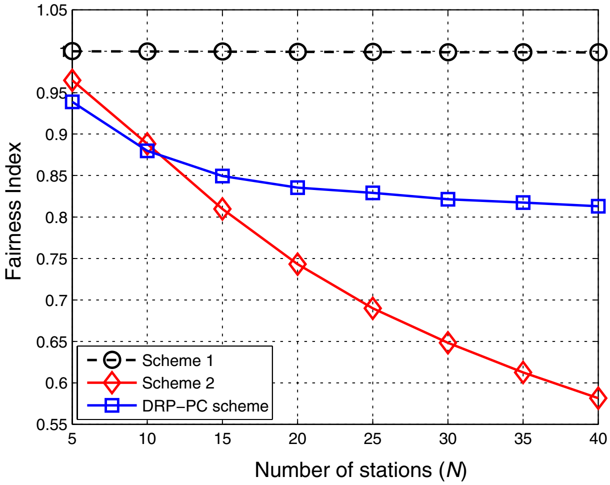



**Fig. 3** Fairness comparison of different schemes ($R_2 = 70$ m)

## 4 Fairness Schemes for the Capture Effect

Although the proposed DRP-PC scheme can remarkably improve system throughput, it results in an unfair access problem: STA_2s have a higher probability of successful transmission than STA_1s do as a result of the capture effect. Once transmission occurs, the STA throughput is directly related to two key factors: transmission probability and successful access probability. To remedy the unfairness, we propose two fairness schemes to offer the STA_1s a higher transmission probability to compensate for their lower successful access probability.

### 4.1 Fairness Scheme 1: CW-Size Adjustment

Assume that the numbers of STA_1s and STA_2s are $n_1$ and $n_2$, respectively, and that the transmission probabilities of any STA_1 and any STA_2 are $\tau_1$ and $\tau_2$, respectively. Hence, the throughput of any STA_1 is

$$P_{s,1} = \tau_1(1-\tau_1)^{n_1-1}(1-\tau_2)^{n_2}, \tag{11}$$

and the throughput of any STA_2 is

$$P_{s,2} = \tau_2(1-\tau_2)^{n_2-1}\left[\binom{n_1}{1}\tau_1(1-\tau_1)^{n_1-1} + (1-\tau_1)^{n_1}\right]. \tag{12}$$

Let $P_{s,1} = P_{s,2}$ for fair access. Next, we have

$$\tau_2 = \frac{\tau_1}{\binom{n_1}{1}\tau_1 + 1}. \tag{13}$$

According to [26], the transmission probability $\tau$ of a STA in IEEE 802.11 WLANs is related to the CW size:

$$\tau = \frac{2}{CW + 1}. \tag{14}$$

The CW size and transmission probability of a STA_i are denoted as $CW_i$ and $\tau_i$ ($i = 1, 2$), respectively. Next, the following equation is obtained:

$$\tau_1 = \frac{2}{CW_1 + 1}. \tag{15}$$

Moreover, from (13) and (15), we have

$$\tau_2 = \frac{2}{CW_2 + 1} = \frac{2}{(2n_1 + CW_1) + 1}. \tag{16}$$

Thus, if $CW_2 = 2n_1 + CW_1$, then any STA throughput in both zones is the same (i.e., $P_{s,1} = P_{s,2}$).

### 4.2 Fairness Scheme 2: PMF Modification

The main challenge of the CW-size adjustment scheme is that the number of STA_1s ($n_1$) must be known, and the AP must announce the adjusted CW-size or $n_1$ periodically, which is different from that specified in the IEEE 802.11 standard. To improve the fairness among STAs and avoid such drawbacks, one alternative is to adjust the PMF of the backoff-timer selection for different zones. Thus, to balance the successful transmission probability in different zones, the STAs with the advantage of the capture effect have a higher probability of choosing a larger backoff value within the same backoff window range. In this subsection, we introduce a method to modify the PMF of backoff-value selection for the STA_2s.

According to the IEEE 802.11 specification, the backoff value is randomly picked up within [0, CW-1]. Thus, the STA_1s select a backoff value based on the uniformly distributed PMF as

$$P_{1,i} = \frac{1}{CW}, \quad i = \{0, 1, \ldots, CW - 1\}. \tag{17}$$

For the STA_2s, after several possible functions have been tested out, the PMF of CW is heuristically proposed to follow an exponential distribution and is expressed as

$$P_{2,i} = \frac{2^i}{\sum_{x=0}^{CW-1} 2^x}, \quad i = \{0, 1, \ldots, CW - 1\}. \tag{18}$$

with such a PMF, the STA_2s have a higher probability of selecting a larger backoff value and reducing the transmission probability.

## 5 Performance Evaluation

To compare the system performance of the legacy IEEE 802.11 systems with/without power control schemes (Schemes 1 and 2, respectively) and the proposed DRP-PC scheme with/without fairness compensation, a discrete-time system simulation platform was constructed. Figure 4 illustrates the considered BSS for the simulations, and Table 3 summarizes the simulation parameters.

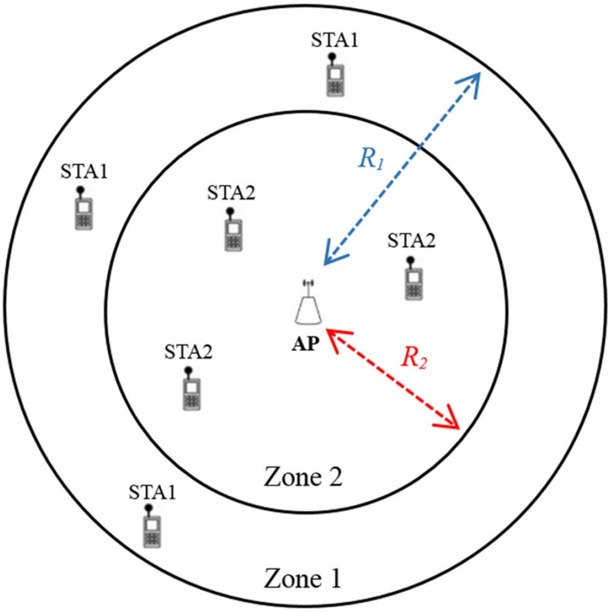



**Fig. 4** The basic service set (BSS) of the IEEE 802.11 WLAN for the simulations

**Table 3** System configuration in the simulations

| | |
|---|---|
| Transmission rate for signaling (basic rate) | 6 Mbps |
| $SINR_{th}$ for signaling | 6.02 dB |
| RTS length | 160 bits |
| CTS length | 112 bits |
| ACK length | 112 bits |
| Transmission rate for payload | 24 Mbps |
| $SINR_{th}$ for payload | 17.04 dB |
| Payload of short data-packet | 250 bytes |
| Payload of long data-packet | 2000 bytes |
| DIFS | 34 μs |
| SIFS | 16 μs |
| Slot time | 9 μs |
| $CW_{min}$ | 16 |
| $CW_{max}$ | 1024 |
| Propagation model | Two-ray ground |
| Path loss exponent ($\gamma$) | 4 |
| Reference distance ($d_0$) | 1 m |
| Constant parameter ($K$) [21] | −31.54 dB |
| Thermal noise [24] | −90 dBm |

In addition to throughput and fairness, energy efficiency (EE) is also considered in system performance comparison. Energy efficiency is defined as the ratio of system throughput and energy consumption during packet-transmissions:

$$\mathrm{EE} = \frac{System\ \ throughput}{Energy\ \ consumption}. \tag{19}$$

The legacy IEEE 802.11 WLAN with a perfect power control scheme (Scheme 1) has an energy consumption such that each STA transmits the packets with power $=P_N \frac{1}{K}\left(\frac{d}{d_0}\right)^{\gamma} 10^{\frac{SINR_{th}}{10}}$, where $d$ is the distance between the STA and AP; the conventional system without power control (Scheme 2) has an energy consumption such that each STA transmits the packets with fixed power $=P_N \frac{1}{K}\left(\frac{R_1}{d_0}\right)^{\gamma} 10^{\frac{SINR_{th}}{10}}$. For the proposed DRP-PC schemes, according to Eqs. (1), (5), and (6), the transmission power of the first transmission in a data-packet transmission session (i.e., the RTS-packet for the long data-packets and the data-packet itself for the short data-packets) can be expressed as follows

$$P_t = \begin{cases} P_N \frac{1}{K}\left(\frac{d}{d_0}\right)^{\gamma} 10^{\frac{SINR_{th}}{10}}, & \text{for STA\_1}, \quad 20 \\ P_N \frac{1}{K}\left(\frac{d}{d_0}\right)^{\gamma} \left(10^{\frac{2SINR_{th}}{10}} + 10^{\frac{SINR_{th}}{10}}\right), & \text{for STA\_2}, \quad 21 \end{cases}$$

where $d$ is the distance between the STA and AP, $SINR_{th} = 17.04$ dB for short data-packet transmission (without RTS/CTS) and $SINR_{th} = 6.02$ dB for long data-packet transmission (for the RTS packet). The transmission power for the remainder of the data-packet transmission session is the same as that for Scheme 1.

Figures 5 and 6 show the performance of system throughput and energy efficiency with various $R_2$ values in the DRP-PC scheme. As presented in Fig. 5, the best system throughput is obtained when $R_2$ is between 50 and 70 m. Figure 6 demonstrates that the energy efficiency increases as $R_2$ increases until $R_2$ is less than 40 m because as the number of STA_2s increases, the system throughput is improved as a result of the capture effect. However, the energy efficiency decreases if $R_2$ is larger than 40 m because some STA_2s, which are far from the AP, may consume more energy to exploit the capture effect. Considering the performance of both system throughput and energy efficiency, we assume $R_2$ is 50 m in the following system simulations.

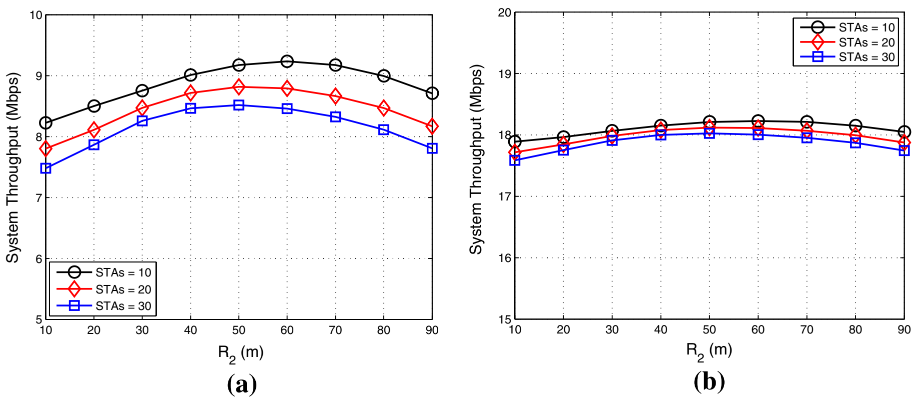



**Fig. 5** Throughput performance of the DRP-PC scheme with various $R_2$ values: (**a**) for short data-packet transmissions; (**b**) for long data-packet transmissions

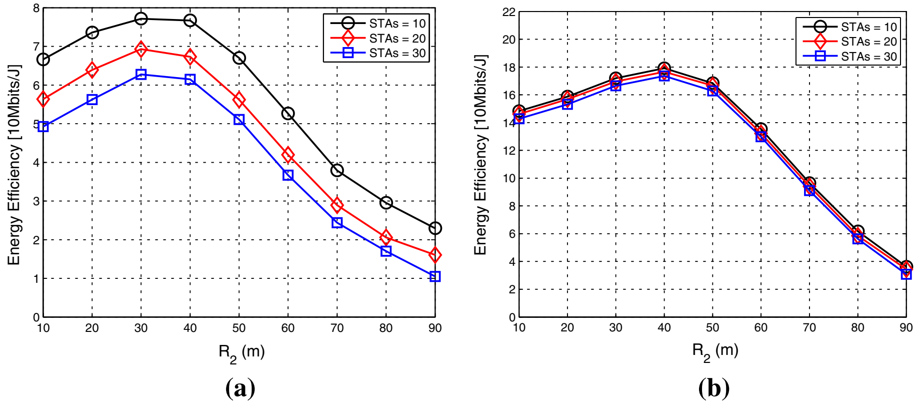



**Fig. 6** Energy efficiency of the DRP-PC scheme with various $R_2$ values: (**a**) for short data-packet transmissions; (**b**) for long data-packet transmissions

Figure 7 compares system throughputs among different schemes with various numbers of stations. It can be seen that the system throughput of the DRP-PC scheme outperforms the conventional Scheme 1 and Scheme 2. A comparison of fairness indices among different schemes (Fig. 8) reveals that the proposed DRP-PC with a CW-size adjustment scheme can not only improve the system throughput but also provide a fair access environment (fairness index > 0.95) that is similar to that of the perfect power control scheme. However, as mentioned, the use of a CW-size adjustment scheme requires knowing the number of STA_1s ($n_1$). Thus, the DRP-PC with the PMF-modification scheme, which can also improve the system throughput and offer a fairness index ≥ 0.85, may be a better choice for system design.

Figure 9 compares the energy efficiency of different schemes. For short data-packet transmissions, the DRP-PC scheme has lower EE than Scheme 1 does (perfect power control) because STA_2s with the DRP-PC scheme require a much higher transmission power for payload transmission compared with Scheme 1. By contrast, for long data-packet

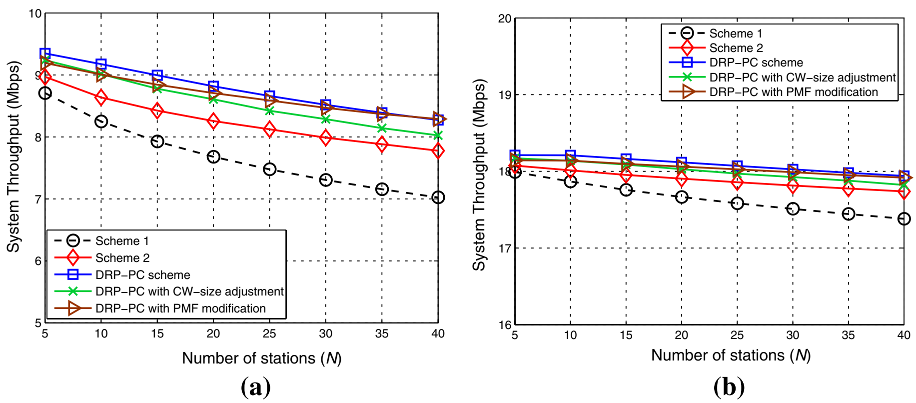
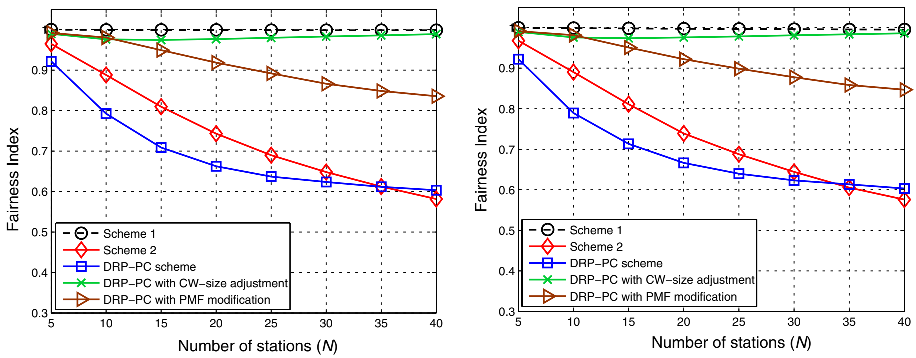
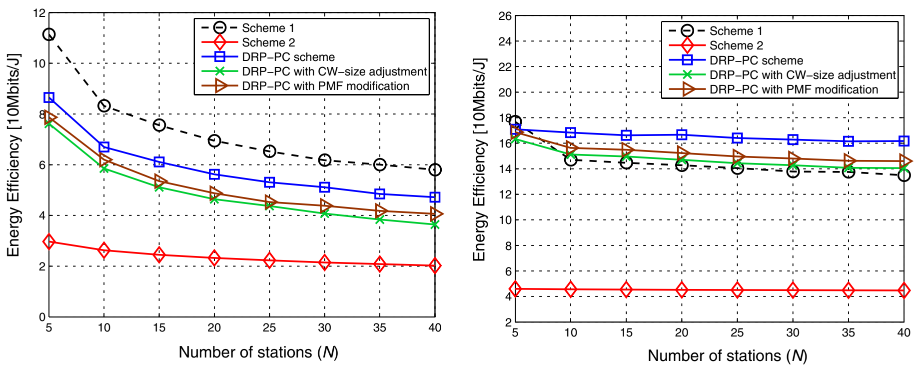



**Fig. 7** Comparison of system throughputs among different schemes ($R_2$ = 50 m): (**a**) for short data-packet transmissions; (**b**) for long data-packet transmissions




**(a)** **(b)**

**Fig. 8** Comparison of the fairness index among different schemes ($R_2 = 50$ m): (**a**) for short data-packet transmissions; (**b**) for long data-packet transmissions




**(a)** **(b)**

**Fig. 9** Comparison of energy efficiency among different schemes ($R_2 = 50$ m): (**a**) for short data-packet transmissions; (**b**) for long data-packet transmissions.

transmissions, STA_2s with the DRP-PC scheme need a higher transmission power only for the short RTS packet. Therefore, the DRP-PC scheme has better energy efficiency than Scheme 1.

## 6 Conclusion

This work proposes a DRP-PC scheme for the IEEE 802.11 WLAN that exploits the capture effect to improve system throughput. Because the proposed power control scheme results in an unfair access environment, we also present two compensation schemes—a CW-size adjustment scheme and a PMF-modification scheme. The simulation results demonstrate that the proposed schemes not only take advantage of the capture effect to improve the system throughput but also provide a fair transmission environment.

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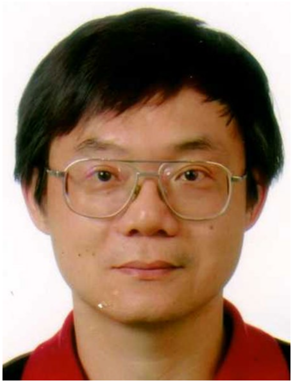

**Szu-Lin Su** received the B.S. and M.S. degrees from National Taiwan University, Taiwan, in 1977 and 1979, respectively, and the Ph.D. degree from the University of Southern California, USA, in 1985, all in electrical engineering. From 1979 to 1989, he was a research member of Chung Shan Institute of Science and Technology, Taiwan, working on the design of digital communication and network systems. Since 1989, he has been with National Cheng Kung Uni-versity, Taiwan, where he is currently a professor at the Department of Electrical Engineering and the Institute of Computer and Communication Engineering. His research interests are in the areas of wireless communication technologies, mobile communication networks, cross-layer design, and power line communications.

**Tsung-Hsiu Chih** received the M.S. degree in computer and communication from Shu-Te Uni-versity, Taiwan in 2010, and the Ph.D. degree in Institute of Computer and Communication Engineering from National Cheng Kung University, Taiwan, in 2019. His research interests include 4G and 5G mobile communication networks, resource management design, massive MIMO networks, cooperative communication and cross-layer system design.

**Yuan-Chun Tsai** received the B.S. degree and M.S. degree in electrical engineering from the National Tsing Hua University, Hsingchu, Taiwan, in 2005 and 2007, respectively, and the Ph. D. degree in the Institute of Computer and Communication Engineering from National Cheng Kung University, Taiwan, in 2015. His research interests include wireless local area networks, wireless ad hoc networks, cross-layer protocol design, QoS routing protocol design, and distributed MAC protocol design.

**Hsieh-Cheng Liao** received the B.S. degree in electrical engineering from the National Chiao Tung University, Hsingchu, Taiwan in 2012 and M.S. degree in Institute of Computer and Communication Engineering from the National Cheng Kung University, Tainan, Taiwan in 2014. His research interests include WLAN, wireless ad hoc networks, cross-layer design and QoS routing protocol design.

**Yu-Chia Wang** received the B.S. degree in electrical engineering from the National United University, Miaoli, Taiwan in 2015 and M.S. degree in Institute of Computer and Communication Engineering from the National Cheng Kung University, Tainan, Taiwan in 2017. His research interests include WLAN, multihop wireless ad hoc networks, cross-layer design, and distributed MAC protocol design.