

Adaptive Range-Based Power Control for Collision Avoidance in Wireless Ad Hoc Networks

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Abstract—The paper analyzes the relationships among the transmission range, carrier sensing range, and interference range in case that power control is adopted and proposes an adaptive range-based power control (ARPC) MAC protocol for wireless ad hoc networks to avoid collisions. Based on the analysis results, four mechanisms, STRC, RTRC, SCRC, and RCRC are proposed to prevent from collisions. The paper further analyzes the superiority of each mechanism under certain situations and proposes the ARPC MAC protocol to make use of the advantages of the four mechanisms to avoid collisions. The proposed protocol can not only reduce energy consumption of STAs, but also prevent from collisions. Simulation results also verify the advantages of the proposed protocol.

I. INTRODUCTION

A wireless ad hoc network is a network temporarily formed by a collection of stations (STAs) without relying on any established infrastructure. Efficient energy management is much critical for wireless ad hoc networks because STAs are usually battery-powered. In general, power control mechanism can decrease STAs energy consumption, and further increase the network lifetime. Therefore, a lot of researchers pay their attention on power control recently [1]–[10].

In [1], [2], similar power control mechanisms are proposed, where RTS/CTS are sent at the maximum power level (P_{max}), and DATA/ACK are sent at the minimum necessary power level (P_{min}) as long as the receiver's received signal to noise ratio (SNR) is above a threshold value. These mechanisms are referred to the basic power control mechanism. Unfortunately, when the basic power control mechanism is used, two kinds of collision problems may happen [3], [6].

A STA may interfere with current transmission due to the shrink of the carrier sensing range if power control is adopted. This collision is termed as the first collision problem [3]. FEC code and additional transceiver for busy tone transmission are required to prevent from the first collision problem in [4], [5], respectively. In [3], the schemes similar to the basic power control mechanism are proposed, which periodically uses P_{max} , instead of P_{min} , for DATA transmission to avoid the first collision problem. The scheme in [3] needs no additional hardware cost. However, this protocol may not prevent from the second collision problem, which is also the most important problem to be solved.

A STA interfering with current transmission due to the expansion of the interference range if power control is adopted causes the second collision problem. The collision problem is

also termed the *POINT* problem [6]. In [6]–[10], the *POINT* problem can be solved completely. In [6], [8]–[10], CTS is exploited to avoid the *POINT* problem. In [8], [9], a power level larger than P_{max} is required for CTS transmission. Thus, the mechanisms in [8], [9] can tolerate of larger interference, and DATA can be transmitted in a lower power level. On the other hand, in [7], a special topology, mesh network, is assumed.

In the paper, four mechanisms, Sender's Transmission Range Cover (STRC), Receiver's Transmission Range Cover (RTRC), Sender's Carrier-sensing Range Cover (SCRC), and Receiver's Carrier-sensing Range Cover (RCRC) are proposed. These four mechanisms have their superiorities in different scenarios. Hence, an adaptive range-based power control (ARPC) MAC protocol combining the advantages of RTRC, SCRC, and RCRC is proposed as well. Simulation results show that ARPC achieves better network throughput and lower packet loss rate than the related work. ARPC can indeed avoid the *POINT* problem and enhance the network throughput of wireless ad hoc networks.

The rest of this paper is organized as follows. Section II formally derives the transmission range, carrier sensing range, and the interference range induced by some power. STRC, RTRC, SCRC, and RCRC schemes are formulated and analyzed in Section III. In addition, the energy consumptions of STRC, RTRC, SCRC, and RCRC schemes are compared in this section. In Section IV, an adaptive range-based power control (ARPC) MAC protocol is proposed. Simulation results are presented in Section V. Section VI concludes the paper.

II. PRELIMINARIES

The definitions of the transmission range, the carrier sensing range, and the interference range have been defined in previous work [11]. For completeness, the definitions of these three ranges are restated as follows.

Definition 1 (Transmission Range, TR): is defined as the range within which a packet can be successfully received and correctly identified. ■

Definition 2 (Carrier-sensing Range, CR): is defined as the range within which the signal can be detected, and the medium will be set in busy state. ■

Definition 3 (Interference Range, IR): is defined as the range within which the receiving STA will be interfered by other STAs and thus suffer a packet loss. ■

TR and CR much depend on the antenna sensitivity. In general, the antenna sensitivity of TR is usually higher than or equal to the antenna sensitivity of CR . Without loss of generality, we assume $CR = \delta * TR$, where $\delta \geq 1$. In addition, TR , CR , and IR also vary according to the transmission power of the sender. In this paper, $TR(P)$, $CR(P)$ and $IR(P)$ denote TR , CR , and IR induced by the transmission power P of the sender, respectively. $TR(P)$ and $IR(P)$ have been derived in [6]. We conclude these derivations as the following theorem.

Theorem 1: Suppose the radio propagation model is two-way ground model [12]. The distance between the sender, S , and the receiver, R , is denoted as D_{SR} . S uses the power P_S to transmit. Therefore, the transmission range of S , $TR(P_S)$, the carrier-sensing range of S , $CR(P_S)$, and the interference range of R , $IR(P_S)$, are as follows.

$$TR(P_S) = (c \frac{P_S}{P_\alpha})^{\frac{1}{4}}, \quad (1)$$

$$CR(P_S) = \delta * TR(P_S) = \delta * (c \frac{P_S}{P_\alpha})^{\frac{1}{4}}, \quad (2)$$

$$IR(P_S) = (\frac{c' P_{max}}{\frac{c P_S}{D_{SR}^4 SNR_{thold}} - P_{CN}})^{\frac{1}{4}}, \quad (3)$$

where c and c' are two constants, $P_\alpha = \max\{P_{thold}, P_N * SNR_{thold}\}$, P_N is the maximum tolerant noise, P_{CN} is the current noise, P_{thold} and SNR_{thold} are respectively the received signal strength threshold and the SNR threshold such that a STA can successfully receive and identify a packet, and P_{max} is the maximum transmission power. ■

For simplicity, let the current noise, P_{CN} , and constants, c and c' , be ignored. In practice, when $P_{CN} = 0$, $P_N * SNR_{thold}$ is always smaller than P_{thold} . Thus, we can get $P_\alpha = P_{thold}$. In addition, SNR_{thold} and δ are set to 10 and 2 [11], respectively. As a result, the following corollary is obtained accordingly.

Corollary 1: Suppose SNR_{thold} and δ are set to 10 and 2, respectively. If the current noise, P_{CN} , constant c and constant c' are ignored, Theorem 1 can be simplified as follows.

$$TR(P_S) = (\frac{P_S}{P_{thold}})^{\frac{1}{4}}, \quad (4)$$

$$CR(P_S) = 2 * TR(P_S) = 2 * (\frac{P_S}{P_{thold}})^{\frac{1}{4}}, \quad (5)$$

$$IR(P_S) = 1.78 * (\frac{P_{max}}{P_S})^{\frac{1}{4}} D_{SR}. \quad (6)$$

According to Theorem 1, the IR of the receiver is deeply related to the transmission power of the sender. When P_{min} is adopted, the IR of the receiver will expand. Therefore, the *POINT* problem may happen [6]. For completeness, the definition of the *POINT* problem is described as follows.

Definition 4 (POINT Problem): In power control mechanism, S and R use P_{max} to exchange RTS/CTS and use P_S to exchange DATA/ACK, where $P_S \leq P_{max}$. Suppose $D_{SR} \leq 0.56 * TR(P_{max})$. In this case, $IR(P_S) \leq TR(P_{max})$

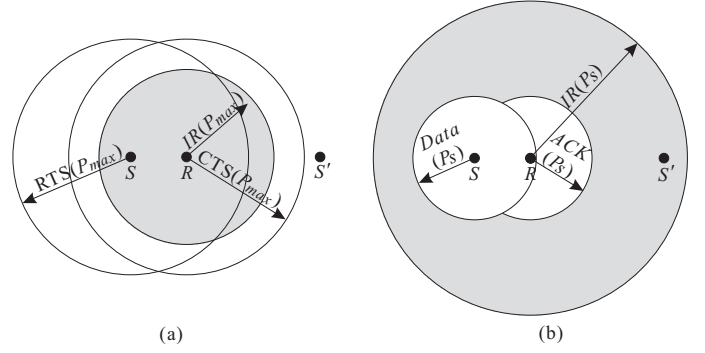


Fig. 1. The *POINT* problem. (a) $D_{SR} \leq 0.56TR(P_{max})$. S and R use P_{max} to exchange RTS/CTS. The gray area is $IR(P_{max})$, which is smaller than $TR(P_{max})$ since $D_{SR} \leq 0.56TR(P_{max})$. S' , a source of interference, is outside both $TR(P_{max})$ and $IR(P_{max})$. (b) S and R use the reduced power, P_S , to exchange DATA/ACK. $IR(P_S)$ will be larger than $TR(P_{max})$ due to the reduction of the sender's power strength. As a result, S' is within $IR(P_S)$ and may cause collision.

[11]. Assume S' is a STA out of the $TR(P_{max})$ of R . In other words, S' can not overhear CTS transmitted by R . In the meanwhile, S' intends to transmit using P_{max} . If S uses P_S to transmit to R , IR of S will expand and S' will be within $IR(P_S)$. Therefore, S' will interfere R . The collision is denoted as *POWer control INduced hidden Terminal problem (POINT problem)*. □

III. RANGE COVER MECHANISMS

In this section, four techniques, SCRC, RCRC, STRC, and RTRC, are proposed to avoid the *POINT* problem. In addition, the energy consumption of these four schemes is also analyzed in this section.

A. Sender's Carrier-sensing Range Cover Mechanism (SCRC)

1) *Concept of SCRC:* A physical carrier-sense mechanism is provided to avoid collisions in IEEE 802.11 standard. The STAs within CR of the sender can detect the signal and set the medium in busy state to defer their transmissions. Thus, CR of the sender can be used to solve the *POINT* problem if $IR(P_{SCRC})$ of the receiver can be completely covered by $CR(P_{SCRC})$ of the sender where P_{SCRC} is the power level used by the sender to transmit. Therefore, we have

$$CR(P_{SCRC}) \geq D_{SR} + IR(P_{SCRC}). \quad (7)$$

2) Derivation of Transmission Power and Restriction:

• Derivation of Transmission Power

Based on the previous description, the *POINT* problem can be avoided if the sender adopts the power level, P_{SCRC} , to transmit DATA. According to Corollary 1 and Eq. (7), P_{SCRC} can be obtained as follows.

$$P_{SCRC} \geq (\frac{1}{4} P_{thold}^{\frac{1}{4}} (D_{SR} + (\beta D_{SR})^{\frac{1}{2}}))^4, \quad (8)$$

where $\beta = D_{SR} + 14.24 * P_{thold}^{-\frac{1}{4}} P_{max}^{\frac{1}{4}}$. As a result, the sender can use P_{SCRC} to transmit DATA to avoid the *POINT* problem completely.

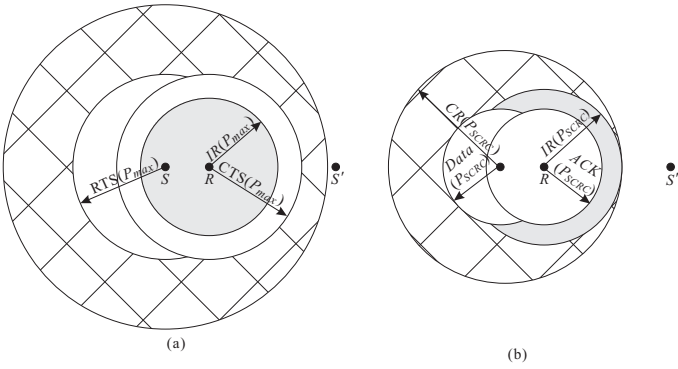


Fig. 2. The concept of SCRC. (a) S and R use P_{max} to exchange RTS/CTS. The gray area is $IR(P_{max})$, which, in this case, is covered by $CR(P_{max})$ since $D_{SR} \leq 0.72TR(P_{max})$. S' , a source of interference, is outside both $TR(P_{max})$ and $IR(P_{max})$. (b) S and R use P_{SCRC} to exchange DATA/ACK, where P_{SCRC} is set to the power level that satisfies $CR(P_{SCRC}) = D_{SR} + IR(P_{SCRC})$.

- **Restriction**

Since P_{SCRC} is limited to P_{max} , if $P_{SCRC} = P_{max}$, we can get

$$D_{SR} \leq 0.72 * TR(P_{max}). \quad (9)$$

That implies when the D_{SR} is smaller than $0.72 * TR(P_{max})$, the CR of DATA can fully cover the IR of the receiver.

3) *SCRC MAC Protocol*: The concept of SCRC MAC protocol is shown in Fig. 2. Suppose STA S wants to communicate with R . Following CSMA/CA mechanism, S successfully contends the medium access right and uses P_{max} to send RTS to R . If R successfully receives the RTS packet, by Eq. (8), R evaluates P_{SCRC} and attaches this information in its CTS packet. R then uses P_{max} to reply CTS to S . Finally, S and R use P_{SCRC} to exchange DATA and ACK. Therefore, SCRC can totally avoid the *POINT* problem.

B. Receiver's Carrier-sensing Range Cover Mechanism (RCRC)

1) *Concept of RCRC*: The main idea of RCRC is to let CR of CTS cover IR of the receiver to avoid the *POINT* problem. That is, it requires

$$IR \leq CR. \quad (10)$$

According to Eq. (6), IR is greatly related to the sender's transmission power. Let P_{min} be the minimum power of the sender required transmitting to the receiver. If the transmission power is P_{min} , it will cause the maximum IR . The following theorem derives the maximum IR caused by P_{min} .

Theorem 2: When the sender adopts P_{min} to transmit, IR of the receiver, $IR(P_{min})$, will be always equal to $1.78 * TR(P_{max})$, which is independent of D_{SR} .

Proof: Since P_{min} is the minimum necessary transmission power level for the sender to transmit, therefore, $TR(P_{min}) = D_{SR}$. According to Eq. (4) in Corollary 1, P_{min} can be obtained as below.

$$P_{min} = P_{thold} \cdot D_{SR}^4. \quad (11)$$

Substituting P_{min} by the above equation into Eq. (6), $IR(P_{min})$ of the receiver can be obtained as follows.

$$IR(P_{min}) = 1.78 \left(\frac{P_{max}}{P_{thold}} \right)^{\frac{1}{4}}. \quad (12)$$

It implies

$$IR(P_{min}) = 1.78 * TR(P_{max}). \quad (13)$$

Obviously, D_{SR} does not affect the interference range if S uses P_{min} to transmit to R . ■

Therefore, if CR of CTS can cover the maximum IR , the *POINT* problem can be avoided. According to Corollary 1, $CR(P_{max})$ is twice of $TR(P_{max})$. However, based on Eq. (13), the maximum IR is 1.78 times $TR(P_{max})$. Hence, $IR(P_{min}) < CR(P_{max})$. As a result, $IR(P_{min})$ of the receiver is always smaller than $CR(P_{max})$ of CTS. That implies the receiver needs not transmit CTS in P_{max} . In other words, the receiver can use a smaller power, say P_{RCRC} , to transmit CTS instead of P_{max} . However, P_{RCRC} should satisfy

$$IR(P_{min}) \leq CR(P_{RCRC}). \quad (14)$$

As a result, the receiver can use P_{RCRC} to reply CTS and the sender can use P_{min} to transmit DATA to avoid the *POINT* problem.

2) Derivation of Transmission Power and Restriction:

- **Derivation of Transmission Power**

According to Corollary 1 and Eq. (14), we can get

$$1.78 * \left(\frac{P_{max}}{P_{min}} \right)^{\frac{1}{4}} D_{SR} \leq 2 * \left(\frac{P_{RCRC}}{P_{thold}} \right)^{\frac{1}{4}}.$$

Thus, P_{RCRC} can be obtained as follows.

$$P_{RCRC} \geq \frac{0.89^4 * P_{max} * D_{SR}^4 * P_{thold}}{P_{min}}. \quad (15)$$

The P_{RCRC} derived from Eq. (15) can ensure that $IR(P_{min}) \leq CR(P_{RCRC})$. However, P_{RCRC} still needs to make sure that CTS of R can be received by S . Therefore, P_{RCRC} still has to satisfy $TR(P_{RCRC}) \geq D_{SR}$. Thus, by Eq. (4), $P_{RCRC} \geq D_{SR}^4 * P_{thold}$. Consequently,

$$P_{RCRC} \geq \max \left(\frac{0.89^4 * P_{max}}{P_{min}}, 1 \right) * D_{SR}^4 * P_{thold}. \quad (16)$$

- **Restriction**

Since $IR(P_{min}) < CR(P_{max})$, P_{RCRC} is always smaller than P_{max} . Dislike SCRC, RCRC has no power restriction. However, RCRC has a restriction on DATA length. In IEEE 802.11 standard, a STA which does not correctly receive the last frame shall defer a period of time, EIFS, after the medium is determined to be idle. Since, in RCRC, IR is covered by CR of CTS, the interfering STAs located in CR of the receiver will set an EIFS to defer its transmission. Therefore, in RCRC, the duration of the DATA transmission should be shorter than an EIFS. Otherwise, collisions may happen. Consequently,

$$\frac{L \times 8}{r} + aSIFSTime \leq aEIFSTime, \quad (17)$$

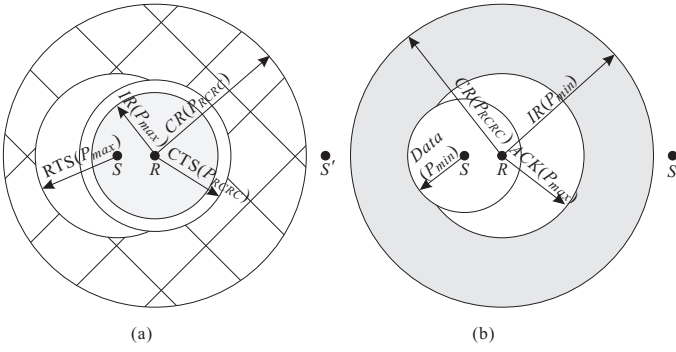


Fig. 3. The concept of RCRC. (a) S uses P_{max} to send RTS and R adopts P_{RCRC} to reply CTS, where P_{RCRC} is set to the power level such that $IR(P_{min}) = CR(P_{RCRC})$. S' is outside $IR(P_{min})$. (b) S uses P_{min} to send DATA and R uses P_{max} to reply ACK. S' is still outside $IR(P_{min})$.

where L is the DATA length in bytes and r is the transmission rate in Mbps. On the basis of IEEE 802.11 standard, $EIFS = SIFS + DIFS + [(8 \times ACKsize) + PreambleLength + PLCPHeaderLength] / BitRate$ [13], where BitRate is the PHY's lowest mandatory rate. Accordingly, EIFS is equal to $364 \mu s$ under 1 Mbps channel bit rate. In DSSS PHY, aSIFSTime is set to $10 \mu s$. Therefore, by Eq. (17), L should satisfy that

$$L \leq 44.25 * r. \quad (18)$$

Therefore, the restriction of RCRC is that the length of DATA should be shorter than $44.25 * r$ bytes.

3) *RCRC MAC Protocol*: The concept of RCRC MAC protocol is shown in Fig. 3. Suppose S wants to transmit to R . If S successfully contends the medium access right and the DATA length to be sent is shorter than or equal to $44.25 * r$ bytes, S uses P_{max} to send RTS. If R successfully receives the RTS packet, by Eq. (16), R evaluates P_{RCRC} and uses P_{RCRC} to reply CTS to S . As a result, S and R use P_{min} and P_{max} to exchange DATA and ACK packets, respectively. In such a way, not only the sender can adopt the minimum power to transmit DATA and save its power consumption, but also the *POINT* problem can be completely and effectively avoided.

C. Sender's Transmission Range Cover Mechanism (STRC) and Receiver's Transmission Range Cover Mechanism (RTRC)

In IEEE 802.11 standard [13], the virtual carrier-sense mechanism is provided to avoid hidden terminal problem. Under virtual carrier-sense mechanism, the hidden STAs can predict the subsequent traffic on the medium based on the duration information announced in RTS or CTS to defer their transmissions. Therefore, STRC or RTRC figure out an appropriate power level, P_{STRC} or P_{RTRC} , for the sender to transmit DATA, such that $IR(P_{STRC})$ or $IR(P_{RTRC})$ can be covered by the TR of RTS or the TR of CTS, respectively. However, due to the lack of space, the paper just shows the derivation results of P_{STRC} and P_{RTRC} as follows.

$$P_{STRC} \geq 10 * (P_{thold}^{-\frac{1}{4}} D_{SR}^{-1} - P_{max}^{-\frac{1}{4}})^{-4} \quad (19)$$

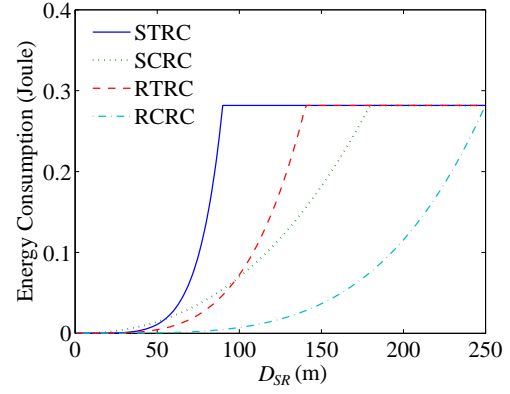


Fig. 4. Comparisons of energy consumption among STRC, RTRC, SCRC and RCRC in terms of D_{SR} .

and

$$P_{RTRC} \geq 10 * D_{SR}^4 * P_{thold}. \quad (20)$$

D. Comparisons of the Four MAC Protocols

In the previous section, P_{STRC} , P_{RTRC} , P_{SCRC} , and P_{min} are adopted by STRC, RTRC, SCRC, and RCRC for the sender to send DATA, respectively. Although the energy consumption of RCRC is the least, the usage of RCRC is restricted in DATA length. Actually, the four mechanisms have their superiority at different aspects. Therefore, it is important to compare the energy consumption of the four mechanisms.

On the basis of the analysis in the previous section, the values of P_{STRC} , P_{RTRC} and P_{SCRC} in terms of D_{SR} are shown in Fig. 4. Obviously, the energy consumption of P_{STRC} is always higher than that of P_{RTRC} . It is because STRC needs more power than RTRC to cover the IR of the receiver. Thus, we can conclude that RTRC is more energy efficient than STRC. As Fig. 4 indicates, the energy consumption of P_{RTRC} is not always higher than that of P_{SCRC} . In order to get the intersection point of P_{RTRC} and P_{SCRC} , we assume

$$P_{RTRC} = P_{SCRC}. \quad (21)$$

Take Eq. (20) and Eq. (8) into Eq. (21), the intersection point is occurred when

$$D_{SR} = 0.39 * P_{thold}^{-\frac{1}{4}} P_{max}^{\frac{1}{4}}. \quad (22)$$

From Eq. (4), Eq. (22) can be modified as follows.

$$D_{SR} = 0.39 * TR(P_{max}). \quad (23)$$

Eq. (23) means that when D_{SR} is $0.39 * TR(P_{max})$, the energy consumption of RTRC is the same as SCRC. Accordingly, when D_{SR} is smaller than $0.39 * TR(P_{max})$, the energy consumption of RTRC is less than that of SCRC. On the contrary, SCRC is more energy efficient than RTRC when D_{SR} is larger than $0.39 * TR(P_{max})$. As a consequence, the comparisons among STRC, RTRC, SCRC, and RCRC are summarized in Table I.

TABLE I
COMPARISONS AMONG STRC, RTRC, SCRC, AND RCRC.

	CTS	DATA	ACK	Superiority
STRC	P_{max}	P_{STRC}	P_{STRC}	none
RTRC	P_{max}	P_{RTRC}	P_{RTRC}	$D_{SR} \leq 0.39TR(P_{max})$
SCRC	P_{max}	P_{SCRC}	P_{SCRC}	$0.39TR(P_{max}) \leq D_{SR}$ $\leq 0.72TR(P_{max})$
RCRC	P_{RCRC}	P_{min}	P_{max}	$L \leq 44.25 * r$ Bytes

IV. ADAPTIVE RANGE-BASED POWER CONTROL (ARPC) MAC PROTOCOL

According to previous analyses, SCRC, RTRC, and RCRC have their merits in different scenarios. In this section, an adaptive range-based power control MAC protocol (ARPC) combining the advantages of the SCRC, RTRC, and RCRC is proposed for solving the *POINT* problem. The detailed procedure of ARPC is stated as follows.

Suppose S intends to transmit to R . If S successfully contends the medium access right, P_{max} will be adopted to send RTS. If the length of DATA is shorter than $44.25 * r$ bytes, RCRC MAC protocol is adopted for the subsequent steps of a four-way handshake, where r is the transmission rate. Otherwise, D_{SR} is taken into consideration for R to decide which MAC protocol will be used. If $D_{SR} \geq 0.39 * TR(P_{max})$, SCRC will be used for the following steps of a four-way handshake. Otherwise, RTRC is adopted.

V. PERFORMANCE EVALUATIONS

To verify the effectiveness of SCRC, RTRC, RCRC, and ARPC protocols, the four protocols as well as IEEE 802.11 DCF [13] are simulated and compared. The metrics to be evaluated include throughput, energy consumption, and energy efficiency (throughput per joule). The simulations are conducted by *ns-2* simulator [14]. Simulation settings are shown in Table II.

TABLE II
SIMULATION SETTINGS.

Parameter	Value
$TR(P_{max})$	250 m
$CR(P_{max})$	500 m
Transmission rate	1 Mb/s
P_{max}	28.183 mW
P_{thold}	$3.652 * 10^{-7}$ mW
SNR_{thold}	10
Traffic model	CBR
Mean frame length	2312 octets

A linear topology is employed to observe the behaviors of RTRC, SCRC, RCRC, ARPC, and IEEE 802.11 DCF, where four STAs A , B , C , and D form a line in turn. A , C , and D are stationary and B will change its position toward C in the simulation. The distances between A and D as well as C and D are respectively fixed to 800 m and 250 m. The distance

between A and B is denoted D_{AB} , which is varied from 10 m to 250 m. There are two CBR flows, $A \rightarrow B$ and $C \rightarrow D$, in the simulation. Since the transmission probabilities of the two flows are not fair [15], the interarrival time of $A \rightarrow B$ is set to 0.00001 sec and that of $C \rightarrow D$ is set to 0.001 sec in the simulation.

Fig. 5(a) illustrates the energy consumption of the proposed power control protocols against IEEE 802.11 DCF. In power control mechanisms, the distance between the sender and the receiver directly affects STAs' energy consumption. The longer the distance is, the more the energy consumes. On the contrary, IEEE 802.11 DCF always consumes the maximum power, irrelevant to the distance between the sender and the receiver since no power control is adopted. By Fig. 5(a), it is obvious that the energy consumption of IEEE 802.11 DCF is the worst. On the other hand, the energy consumptions of RTRC, SCRC, and RCRC are consistent with the analyzed results shown in Fig. 4. The energy consumption of RCRC performs the best due to the minimum power for DATA transmission and a smaller power for CTS transmission. Moreover, the performance of RTRC is better than that of SCRC when D_{AB} is shorter than 97.5 m, which is equal to $0.39 * TR(P_{max})$. Otherwise, SCRC performs better than RTRC. Since the packet length used in the simulation is larger than $44.25 * r$, as a result, RCRC will never be adopted by ARPC. Thus, except RCRC, ARPC performs the best against RTRC, SCRC, and IEEE 802.11 DCF.

Fig. 5(b) demonstrates the throughput of the five protocols in terms of D_{AB} varied from 10 m to 250 m. When D_{AB} is shorter than 50 m, the two flows can transmit simultaneously without interference. Therefore, the five protocols have the same throughput. However, when D_{AB} is equal to or larger than 50 m, B is within CR of C . Thus, the two flows will interfere with each other. That is the reason why the throughput of the five protocols drops. Moreover, in RCRC protocol, when D_{AB} is larger than 105 m, C is located in the IR of B because, in RCRC, the sender always uses the minimum power for DATA transmission and the interference range is always $1.78 * TR(P_{max})$, which is equal to 445 m. As a result, when D_{AB} is larger than 105 m, the throughput of RCRC will drop again. Nevertheless, the other four protocols will not be affected by the phenomenon. However, when D_{AB} is larger than 198 m, C is within the IR of B for the four protocols, except RCRC. Therefore, the throughput of the four protocols drops and the four protocols have the same throughput with that of RCRC. It is worth noting that RTRC and SCRC will use the maximum power to transmit when D_{AB} is respectively larger than 0.56 and 0.72 times the maximum transmission range. As a result, RTRC, SCRC, and ARPC will have the same throughput with that of IEEE 802.11 DCF.

Fig. 5(c) compares the energy efficiencies of the five protocols in terms of D_{AB} varied from 10 m to 250 m. Energy efficiency is defined as the number of bits transmitted per unit of time and per unit of energy consumption, which can be obtained by dividing throughput by energy consumption.

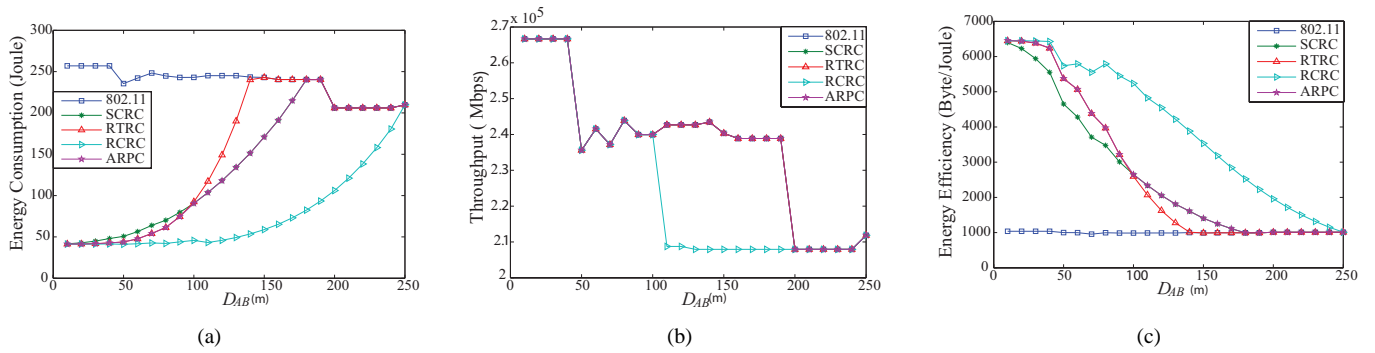


Fig. 5. RTRC, SCRC, RCRC, ARPC, and IEEE 802.11 DCF are compared for D_{AB} varied from 10 m to 250 m in terms of (a) the energy consumption, (b) the throughput, and (c) the energy efficiency, respectively.

The energy efficiency of IEEE 802.11 DCF performs the worst since it always uses the maximum power to transmit, even though it has the best throughput performance. On the contrary, RCRC always uses the minimum transmission power for DATA transmission. Although RCRC has poor throughput when B is approaching to C and C is located in the IR of B , RCRC still has the best energy efficiency. As for RTRC and SCRC, the two protocols have the same throughput. When D_{AB} is shorter than $0.39 * TR(P_{max})$, RTRC has better energy efficiency than SCRC since the energy consumption of RTRC is less than that of SCRC. Otherwise, SCRC has better energy efficiency than RTRC. It is worth noting that the energy efficiencies of RTRC and SCRC have the same performance with that of IEEE 802.11 DCF when D_{AB} is respectively larger than 0.56 and 0.72 times the maximum transmission range. It is because, in those situations, RTRC and SCRC will use the maximum power to transmit.

VI. CONCLUSIONS

The paper analyses the relationships among the transmission range, carrier-sensing range, and interference range under different transmission power level and reveals that the transmission range of the sender, transmission range of the receiver, the carrier-sensing range of the sender, and furthermore the carrier-sensing range of the receiver can be used to cover the interference range in order to avoid the *POINT* problem. Thus, STRC, RTRC, SCRC, and RCRC MAC protocols are presented and analyzed. An adaptive range-based power control (ARPC) MAC protocol for collision avoidance in wireless ad hoc networks is proposed as well, which makes use of the advantages of the four mechanisms to reduce energy consumption and avoid collisions. Simulation results show that ARPC can not only reduce the energy consumption without sacrificing network throughput, but also avoid the *POINT* problem accordingly. As a consequence, ARPC is an effective and efficient power control MAC protocol in wireless ad hoc networks.

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REFERENCES

- [1] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian, "Conserving transmission power in wireless ad hoc networks," in *Proceedings of the IEEE International Conference on Network Protocols (ICNP)*, 2001, pp. 24–34.
- [2] S.-L. Wu, Y.-C. Tseng, C.-Y. Lin, and J.-P. Sheu, "A multi-channel MAC protocol with power control for multi-hop mobile ad hoc networks," *Computer Journal*, vol. 45, no. 1, pp. 101–110, 2002.
- [3] E. S. Jung and N. H. Vaidya, "A power control MAC protocol for ad hoc networks," in *Proceedings of the ACM International Conference on Mobile Computing and Networking (MOBICOM)*, 2002, pp. 36–47.
- [4] A. Muqattash and M. Krunz, "A single-channel solution for transmission power control in wireless ad hoc networks," in *Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC)*, 2004, pp. 210–221.
- [5] S.-L. Wu, Y.-C. Tseng, and J.-P. Sheu, "Intelligent medium access for mobile ad hoc networks with busy tones and power control," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 9, pp. 1647–1657, 2000.
- [6] K.-P. Shih and Y.-D. Chen, "CAPC: A collision avoidance power control MAC protocol for wireless ad hoc networks," *IEEE Communications Letters*, vol. 9, no. 9, pp. 859–861, 2005.
- [7] J. Zhu, X. Guo, L. L. Yang, and W. Steven, "Leveraging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing," in *Proceedings of the IEEE International Conference on Communications (ICC)*, vol. 7, 2004, pp. 4004–4011.
- [8] D. Qiao, S. Choi, A. Jain, and K. G. Shin, "Miser: An optimal low-energy transmission strategy for IEEE 802.11a/h," in *Proceedings of the ACM International Conference on Mobile Computing and Networking (MOBICOM)*, 2003, pp. 161–175.
- [9] J. Zhang, Z. Fang, and B. Brahim, "Adaptive power control for single channel ad hoc networks," in *Proceedings of the IEEE International Conference on Communications (ICC)*, 2005, pp. 3156–3160.
- [10] Y. Zhou and S. M. Nettles, "Balancing the hidden and exposed node problems with power control in CSMA/CA-based wireless networks," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, 2005, pp. 683–688.
- [11] K. Xu, M. Gerla, and S. Bae, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks?" in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM)*, vol. 1, 2002, pp. 72–76.
- [12] T. Rappaport, *Wireless Communications: Principles and Practice (2nd Edition)*. Prentice Hall, New Jersey, 2002.
- [13] *IEEE Std 802.11-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE, Aug. 1999.
- [14] *The Network Simulator - 2*, [Online] Available: <http://www.isi.edu/nsnam/ns/>.
- [15] J. Shi, T. Salonidis, and E. W. Knightly, "Starvation mitigation through multi-channel coordination in CSMA multi-hop wireless networks," in *Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC)*, 2006.