A Fragmentation-based Data Collision Free MAC Protocol with Power Control for Wireless Ad Hoc Networks

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***Abstract*—Resolving hidden terminal problem is one of the major responsibilities in designing MAC protocols for wireless ad hoc networks. The paper proposes a fragmentation-based MAC protocol with power control, named *F-RCRC* MAC protocol, to avoid the LIRC (Large Interference Range Collision) problem, a kind of hidden terminal problem, for wireless ad hoc networks. F-RCRC designs a new interframe space, named FIFS, to reduce the overhead caused by the fragmentation scheme. With the fragmentation, the design of FIFS can effectively avoid the hidden STAs interfering with the receivers' receiving. Moreover, a dynamic transmission power scheme is devised to actively and timely warn the hidden STAs such that the possible collision is avoided. Thus, the LIRC problem can be solved and the network throughput is increased accordingly. In addition, F-RCRC can reduce the energy consumption and increase the spatial reuse due to the controlled transmission power. Simulation results show that F-RCRC performs much better than the related work in terms of network throughput as well as the power throughput.**

I. INTRODUCTION

A wireless ad hoc network is a network temporarily formed by a collection of stations (STAs) without relying on any established infrastructure. The communication among STAs is via message exchanges through multihop wireless links. Therefore, collision resolution is an important issue and needs to be well considered for wireless ad hoc networks.

Hidden terminal problem is a notorious collision problem in wireless ad hoc networks. Resolving hidden terminal problem becomes one of the major design considerations of MAC protocols. IEEE 802.11 DCF [1] is the most popular MAC protocol for wireless ad hoc networks. In IEEE 802.11 DCF, four-way handshake (RTS/CTS/DATA/ACK) is the underlying scheme to resolve hidden terminal problem. However, the success of the four-way handshake to prevent hidden terminal problem is based on the assumption that the hidden STAs are located within the transmission range of the receiver.

Nevertheless, it is possible that some STAs which are out of the transmission ranges of both the transmitter and the receiver may still interfere with the receiver. As a result, in [2], the authors reevaluated the effectiveness of the four-way handshake and pointed out that the four-way handshake still can not completely prevent hidden terminal problem. The reasons are as follows. It is well known that the signal strength of a signal will fade rapidly according to the distance the signal is propagated. If the distance between the sender and the receiver is away beyond a certain range, the signal strength reached to the receiver may be too small to resist the noise signal. Therefore, it is possible that a STA outside the transmission ranges of both the transmitter and the receiver, i.e. the STA can not receive the RTS and the CTS, is still possible to collide with the receiving of the receiver. Therefore, this kind of collision caused by the STA located in the interference range (defined later) but outside the transmission ranges of both the transmitter and the receiver is further referred as the *Large Interference Range Collisions (LIRC)* Problem.

Two schemes were proposed in [2] to solve the LIRC problem. One is to take the carrier-sensing range into consideration, not only consider the transmission range. That is, this scheme uses the transmitter's carrier-sensing range to cover hidden STAs in order to prevent the transmission of hidden STAs. It implies that the condition that a STA is allowable to transmit is more rigid. On the other hand, since interference happens at receivers, using the transmitter's carrier-sensing range to cover the hidden STAs requires a large carrier-sensing range. It also implies a great degradation of performance due to large prohibitions of transmissions. Therefore, this scheme can not help much. As a result, the second scheme, named Conservative CTS Reply (CCR), was proposed. The main idea of CCR is to restrict the reply of a CTS for an RTS request. That is, only when the received signal strength of an RTS is larger than a certain threshold (CTS-REPLY-THRESHOLD) will the receiver reply the CTS. However, to do so will reduce the effectiveness of the transmission range. Certainly, it will greatly affect the network connectivity.

Consequently, the paper proposes a fragmentation-based MAC protocol, named F-RCRC, to avoid the LIRC problem for wireless ad hoc networks. In our previous work [3], the RCRC (Receiver's Carrier-sensing Range Cover) MAC protocol is proposed to avoid the POINT problem [3] for wireless ad hoc networks. However, RCRC has a strong constraint on the frame length. Therefore, F-RCRC incorporates RCRC with fragmentation and power control schemes to adapt to solve the LIRC problem and to overcome the constraint on frame length. In F-RCRC, an new interframe space, named FIFS, is designed to defer the transmissions of hidden STAs as well as to reduce the overhead incurred by fragmentation. Moreover, a dynamic transmission power scheme is devised as well to reduce the energy consumption of STAs and warn hidden STAs timely and actively such that the LIRC problem can be avoided accordingly. F-RCRC can not only solve the LIRC problem, but also reduce the energy consumption due

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to controlled transmission power. Simulation results show that F-RCRC performs much better than the related work in terms of network throughput as well as the power throughput.

The rest of the paper is organized as follows. Section II describes the problem to be solved and introduces the related work. Section III, the proposed protocol, F-RCRC, is explained. Performance evaluation is depicted in Section IV. Finally, Section V concludes the paper.

II. PRELIMINARIES

A. Problem Statements

The definitions of the transmission range, the carrier-sensing range, and the interference range have been defined in several previous works [2]–[4]. 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 frame 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 frame loss. ■

Without loss of generality, let S and R be the sender and the receiver, respectively. The distance between S and R is denoted D_{SR}. The maximum power level is denoted P_{max}. Currently, all the discussions are on the assumption that the power level used by S to transmit is always P_{max}, if no otherwise notified. In other word, power control is not considered currently.

Obviously, IR is close related to D_{SR}, if power control is not taken into consideration. The relationship between IR and D_{SR} is $IR = 1.78 D_{SR}$, which has been derived in [2]. It is easy to obtain that when $D_{SR} > 0.56TR$, IR will be greater than TR. This implies when the receiver is far away from the sender in a certain distance, LIRC problem is probably to happen. Definition 4 gives the formal definition of the LIRC problem. The illustration of LIRC problem is depicted in Fig. 1.

*Definition 4 (***LIRC Problem):** In a wireless ad hoc network, P_{max} is always used by the transmitter and the receiver to exchange control and DATA frames. Without loss of generality, let S and R be respectively the sender and the receiver of some transmission pair. Suppose S' is an interferer at the receiver site. The LIRC (Large Interference Range Collisions) problem occurs when the following conditions are hold.

(C1) $D_{SR} > 0.56TR$,
(C2) $TR < D_{S'R} \leq 1.78 D_{SR}$. ■

Since F-RCRC is a modification of the RCRC protocol [3], for completeness, the RCRC MAC protocol is briefly described as follows.

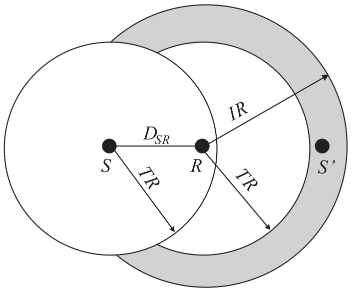


Fig. 1. An illustration of the LIRC problem, where S, R, and S' are the sender, the receiver, and the interfering STAs, respectively. In case that $D_{SR} > 0.56TR$, LIRC problem is caused by an interfering STA, say S', located outside the TR of both S and R, but within the IR of R colliding with the receiving of R.

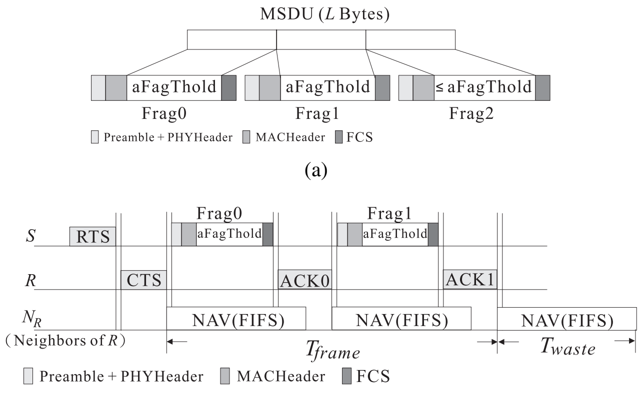
B. Receiver's Carrier-sensing Range Cover (RCRC) MAC Protocol

Originally, RCRC is devised to prevent the POINT problem [3]. However, the concept of RCRC can be used to solve the LIRC problem, if some modifications are made to RCRC. The main idea of RCRC is to let CR of the receiver's CTS cover the IR of the receiver to avoid collisions. That is, it requires $IR \leq CR$. In general, CR is larger than IR since, mostly, CR is twice of TR [5], [6] and IR is only $1.78TR$ in maximal. Nevertheless, that implies that the receiver need not transmit CTS in P_{max}. In other words, the receiver can use a smaller power, say P_{adopt}, to transmit CTS, instead of P_{max}.

However, the major drawback of RCRC is that RCRC requires that the duration to transmit a frame should be smaller than that of an EIFS. It is because RCRC uses the CR resulted from the signal of the receiver transmitting the CTS to cover its IR. The interfering STAs can only detect the signal and set its NAV to an EIFS. After the end of the EIFS, the interfering STAs will contend to transmit. As a result, the frame to be received by the receiver should be done within the duration of the EIFS; otherwise, collisions may happen. However, the EIFS is designed to provide enough time for the transmitter to receive the acknowledgement, so the duration of an EIFS is not long. As a result, the frame that is allowed to be transmitted in RCRC protocol will be short as well. It greatly affects the practicality of RCRC protocol.

III. THE PROTOCOL: F-RCRC MAC

Conservative scheme is not an effective solution to the LIRC problem because it always regards the transmission as a danger, that is, there always has at least one interferer around the receiver. Only when the transmission is ensured to be safe will the receiver reply the CTS. Therefore, the performance of a conservative scheme, such as CCR, is not good enough due to its pessimistic viewpoint and a conservative reaction. Actually, an effective scheme in solving the LIRC problem is to warn the hidden STAs in an optimistic fashion instead. Since hidden STAs are out of the transmission range of both the sender and the receiver, as a result, an alternative scheme is to warn the hidden STAs by means of the carrier-sensing



(a)

(b)

Fig. 2. Fragmentation in F-RCRC. (a) An MSDU is fragmented into fragments, each of length aFragThold. (b) The design concepts of aFragThold and the FIFS.

range. However, using the sender's carrier-sensing range to cover hidden STAs will cause severe capture effect. Therefore, the promising way to resolve the LIRC problem is to use the receiver's carrier-sensing range to cover hidden STAs.

F-RCRC is a MAC protocol incorporating RCRC with fragmentation and power control schemes to adapt to solve the LIRC problem and to overcome RCRC's constraint on the frame length. Therefore, the incorporation of RCRC with the fragmentation scheme is presented in Section III-A. On the other hand, to save the STA's energy consumption, the power control scheme is taken into consideration in F-RCRC and is described in Section III-B.

A. Incorporate RCRC with Fragmentation

As mentioned above, RCRC has a constraint on the frame length. RCRC requires that the frame length should be short enough to be transmitted within the duration of an EIFS. To overcome this drawback and avoid the collision, fragmentation or to extend the duration of an EIFS are possible solutions. As a result, RCRC is modified to combine the fragmentation scheme and a new interframe space, named FIFS, is devised such that a long frame can be transmitted without collision and the throughput will not be degraded as well.

Recall that the main purpose of the EIFS is designed to provide enough time for the transmitter to receive the acknowledgement. However, since an EIFS is too short, therefore, a long frame may need to be fragmented into many small fragments. It is well known that the overhead of multiple frame headers and tailers will rise substantially proportional to the number of fragments. Consequently, a new interframe space, FIFS, is devised, which is an acronym of F-RCRC Inter-Frame Space. The duration of an FIFS is longer than that of an EIFS such that the number of fragments that a long frame is fragmented can be reduced. The fragmentation scheme designed for the F-RCRC is illustrated in Fig. 2.

The main purpose of the FIFS is designed to provide enough time for another STA to receive one fragment successfully. However, to let the receiver receive the successive fragments successfully, FIFS is designed to let the interfering STA be able to detect the signal of the ACK the receiver acknowledging the success of the previous receiving fragment and to set its NAV to another FIFS to defer its transmission in order not to cause collision. Therefore, FIFS is designed as follows and is illustrated in Fig. 2(b).

$$FIFS = T_{frag} + 2 * \text{aSIFSTime} + T_{ACK}/2 \tag{1}$$

where T_{frag} is the transmission time of a fragment and T_{ACK} is the transmission time of an ACK frame. Therefore, to find the FIFS, T_{frag} should be determined first.

As mentioned above, too many fragments will cause a lot of frame headers and tailers overhead and result in performance degradation. Contrarily, if a fragment length is too long, it will cause a long waste after the last fragment since the hidden STAs will be prohibited from transmitting even though the medium is idle. Therefore, a suitable fragment length should be decided in order to balance between the fragmentation overhead and the waste time. Let aFragThold be the fragmentation threshold implying a frame of length exceeding the threshold should be fragmented into smaller fragments, each no larger than the threshold. In other words, the current goal is to find a suitable value of aFragThold such that the incurred overhead is the least.

Let L be the frame length and g the fragment size, $1 \leq g \leq 2312$. $Prob(L)$ is the probability to generate a frame of length L, where the probability adopts Gaussian distribution and the mean (m) and the standard deviation (σ) are assumed to 1500 and 1, respectively. Let n be the number of fragments. Obviously, $n = \lceil L/g \rceil$. Let r and r_B be the transmission rate and the basic rate, respectively. The way to find aFragThold can be obtained as follows.

$$\text{aFragThold} = \min_{g} \sum_{L} O(L, g) * Prob(L), \tag{2}$$

where

$$\begin{aligned} O(L,g) &= T_{frame}(L,g) + T_{waste}(L,g), \\ T_{frame}(L,g) &= n * T_{PLCP} + n * T_{MAC} + T_{DATA}(L) \\ &\quad + n * T_{ACK} + (2n-1) * \text{aSIFSTime}, \\ T_{waste}(g) &= T_{PLCP} + T_{MAC} + g * 8/r \\ &\quad + 2 * \text{aSIFSTime} + T_{ACK}/2, \\ T_{DATA}(L) &= L * 8/r, \\ T_{ACK} &= T_{PLCP} + 14 * 8/r_B, \\ T_{MAC} &= T_{MACHeader} + T_{FCS}, \\ T_{PLCP} &= T_{Preamble} + T_{PHYHeader}, \\ Prob(L) &= \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(L-m)^2}{2\sigma^2}}, m = 1500,\ \sigma = 1. \end{aligned}$$

As shown in Fig. 2(b), in Eq. (2), $O(L, g)$ means the channel occupancy time, which includes the frame transmission time, T_{frame}, and the FIFS prohibition waste time, T_{waste}, where $T_{frame}(L, g)$ is the time to transmit a frame of length L by fragmentation, each fragment of length g, and $T_{waste}(g)$ is

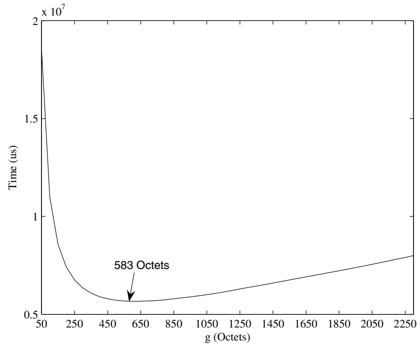


Fig. 3. An illustration to obtain the value of aFragThold.

the time wasted in the FIFS prohibition after the channel is released.

Fig. 3 is the obtained from Eq. (2), where $L = 1, \ldots, 2312$, $T_{MACHeader}$ = 240 μs, T_{FCS} = 16 μs, $T_{Preamble}$ = 144 μs, $T_{PHYHeader}$ = 48 μs, r_B = 1 Mbps, and r = 2 Mbps. Obviously, the lowest value is at 583 Octets. According to [1], the length of a fragment MPDU shall always be an even number of octets. Therefore, aFragThold is set to 584 Octets instead. On the other hand, T_{frag} in Eq. (1) can be represented as follows.

$$T_{frag} = T_{PLCP} + T_{MAC} + \text{aFragThold} * 8/r.$$

As a result, T_{frag} = 2784 μs. Consequently, by Eq. (1), FIFS = 2956 μs.

In sum, the design of the FIFS can make sure that the interfering STAs will defer its transmission and not interfere with the receiver's receiving and, furthermore, at the end of FIFS deferral let the interfering STAs again detect the signal caused by the CR of the receiver replying the ACK and then defer another FIFS for the receiver to receive the successive fragments successfully. As a result, the hidden STAs, at the sender site or at the receiver site, will not interfere with either the sender or the receiver receiving the ACK or the fragment frames, respectively. Therefore, the LIRC problem is avoided accordingly.

The F-RCRC MAC protocol is described by an example shown in Fig. 4, where S and R are respectively the sender and the receiver, and $D_{SR} > 0.56TR$. S' and S'' are the interferers within the interference range, but outside the transmission range of the receiver and the sender, respectively. If the frame to be transmitted by S is longer than aFragThold, the frame will be fragmented. Each frame, including RTS, CTS, ACK, and fragments, is transmitted by P_{max} in order to warn the potential interfering STAs. In the example, S'' will set its NAV to an FIFS since it detects the signals of RTS, Frag0, Frag1, and so on. Likewise, S' will also set its NAV to an FIFS for the detection of the signals of CTS, ACK0, ACK1, etc. Therefore, the transmissions between S and R can be successfully received. As a result, the LIRC problem is avoided both at the sender and the receiver sites since S' and S'' can always perceive signals on the medium and they will defer their transmissions for an FIFS repeatedly.

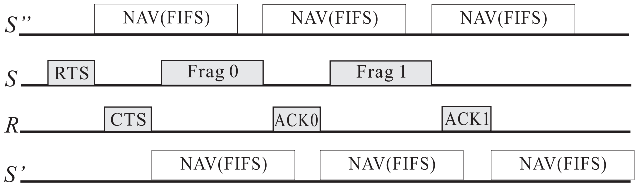


Fig. 4. An illustration of F-RCRC MAC protocol.

B. Incorporate F-RCRC with Power Control Scheme

As mentioned in Section II-B, in RCRC, the receiver can use a smaller power, say P_{adopt}, to transmit the CTS, instead of P_{max}. On the other hand, if the sender's energy consumption can be further reduced, the amount of energy to be saved would be much great. Therefore, power control scheme can be further incorporated into F-RCRC in order to reduce the energy consumption of STAs. However, how to incorporate F-RCRC with power control scheme needs to be paid more attention in order not to cause additional collisions.

As described above, the main concept of RCRC is to use CR of the receiver's CTS to cover the IR of the receiver. That is, $IR \leq CR$. It is possible to reduce the transmission power of CTS, say P_{adopt}, such that $IR \leq CR(P_{adopt})$, where $CR(P)$ means the carrier-sensing range induced by the transmission power P. Similar usage can be applied to TR and IR as well. On the other hand, if the sender's energy is going to be saved, the best way is to reduce the transmission power in transmitting the DATA frames. Furthermore, the most energy saving approach for a sender to transmit the DATA frames is to use the least power level, say P_{min}, to transmit, where P_{min} is the minimal required power level such that the receiver can received the DATA frames successfully. However, if the sender use P_{min} to transmit the DATA frames, the interference range of the receiver induced by the power P_{min} will expand. Hence, the CR should be large enough to cover the IR induced by the power P_{min}. Therefore, it implies that

$$IR(P_{min}) \leq CR(P_{adopt}). \tag{3}$$

According to Corollary 1 in [3],

$$\begin{aligned} CR(P_S) &= 2 * TR(P_S) = 2 * (\frac{P_S}{P_{thold}})^{\frac{1}{4}}, &(4)\\ IR(P_S) &= 1.78 * (\frac{P_{max}}{P_S})^{\frac{1}{4}} D_{SR}, &(5) \end{aligned}$$

where P_S is the transmission power of the transmitter and P_{thold} is the received signal strength threshold. Therefore, P_{adopt} can be derived by substituting Eqs. (4) and (5) to Eq. (3), as shown below.

$$P_{adopt} \geq \frac{0.89^4 * P_{max} * D_{SR}^4 * P_{thold}}{P_{min}}. \tag{6}$$

Consequently, if the receiver uses P_{adopt} to reply the CTS while it receives the RTS, the CR of the CTS can cover the IR caused by the sender transmitting DATA with the minimum power, P_{min}, after receiving the CTS. As a result, the hidden STAs located within the IR of the receiver will detect the signal resulted from the CR of the CTS and set its NAV to an FIFS. According to the design of the FIFS described in the previous subsection, at the end of an FIFS, an interfering STAs commencing to contend the medium to transmit will start a CCA (clear channel assessment) process and it will again detect the signal caused by the CR of the ACK transmitted by the receiver to acknowledge the previous received fragment. Likewise, the interfering STAs will also set another FIFS and defer its transmission for another FIFS. Therefore, the hidden STAs at the receiver site will not interfere with the receiving of the receiver, as illustrated in Fig. 5.

On the other hand, although the sender can use P_{min} to transmit the fragments successfully, it does not mean that the sender can successfully receive the ACKs without collision due to the hidden STAs at the sender site. Besides, according to [5], 15 μs should be adequate for carrier sensing, and time required to increase output power (power on) from 10% to 90% of maximum power or (power-down) from 90% to 10% of maximum power. As a result, in order to ensure that the sender can receive the ACKs successfully, the sender has to raise the transmission power from P_{min} to P_{adopt} at the last 20 μs transmission of each fragment should be less than 2 μs. Thus, 20 μs should be enough to power up (2 μs), sense the signal (15 μs), and power down (2 μs). to warn the hidden STAs at the sender site, as shown in Fig. 5. The hidden STAs at the sender site can detect the raised signal and set its NAV to another FIFS. It is because P_{adopt} is obtained from $IR(P_{min}) \leq CR(P_{adopt})$ and the receiver replies the CTS with P_{adopt}, which is larger than P_{min}. Therefore, the IR at the sender site induced by the receiver replying ACK with power P_{adopt} can be covered by the CR induced by the raised signal of fragment transmission with power P_{adopt}. That is, $IR(P_{adopt}) < CR(P_{adopt})$ since $IR(P_{adopt}) < IR(P_{min})$. This scheme to raise the transmission power from P_{min} to P_{adopt} at the last 20 μs transmission of each DATA frame is called *dynamic transmission power scheme*.

Comprehensively, the interfering STAs, either at the sender or at the receiver sites, can always perceive the signals on the medium and they will defer their transmissions for an FIFS repeatedly. As a result, the transmissions between the sender and the receiver can be successfully received. Consequently, the LIRC problem is avoided both at the sender and the receiver sites.

IV. PERFORMANCE EVALUATION

To verify the effectiveness of the F-RCRC protocol, IEEE 802.11 DCF [1], CCR [2], and RCRC [3] are compared in the simulation. Moreover, to observe the impact of power control on the performance, F-RCRC without power control (denoted F-RCRC w/o PC in the simulation illustrations) is simulated as well. The metrics to be evaluated include the network throughput, energy consumption, and energy efficiency (throughput per joule), respectively. In the simulation, 100 STAs are randomly deployed in a 1000m*1000m area. Besides, the traffic model adopts the Poisson distribution model, and the data packet size is fixed at 2000 octets. The transmitter-receiver pairs are generated randomly, and the total simulation time is 60 sec. On the other hand, the simulation is conducted by $ns2$ simulator [6], and the other simulation settings are shown in Table I.

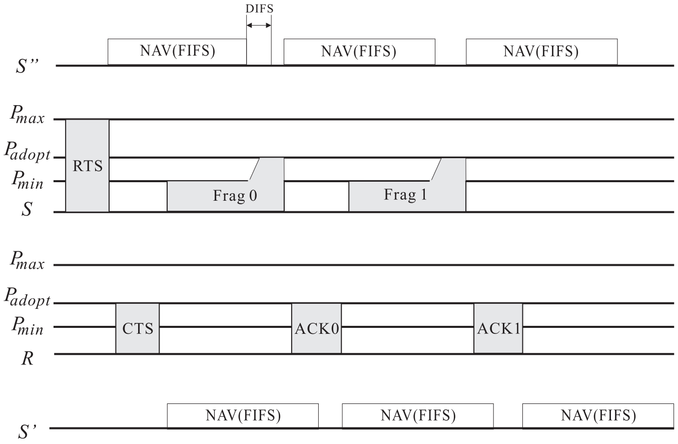
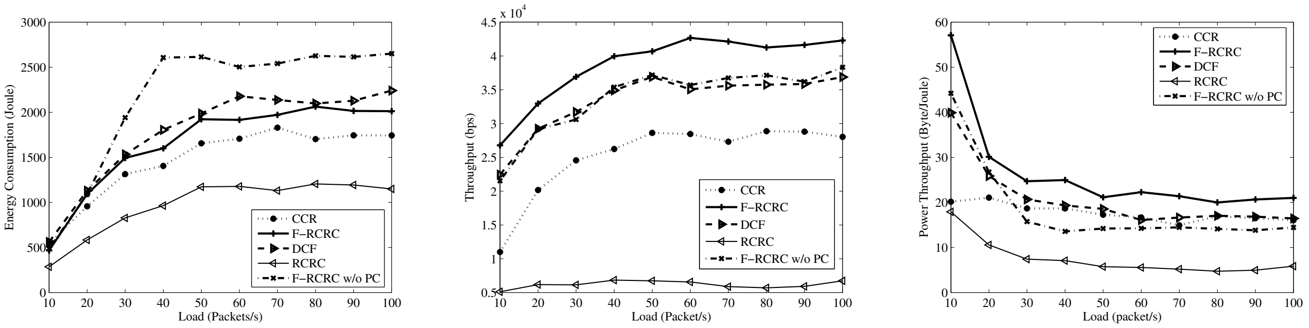


Fig. 5. An illustration of the F-RCRC MAC protocol with power control scheme, where S and R are respectively the sender and the receiver, and $D_{SR} > 0.56TR$. S' and S'' are the interferers within the interference range, but outside the transmission range of the receiver and the sender, respectively. S uses P_{max} to transmit RTS. S'' will set its NAV to an FIFS. R replies CTS with P_{adopt}. Similarly, S' will also set its NAV to an FIFS. Then, S uses dynamic transmission power scheme to transmit DATA. That is, at the beginning of the DATA transmission, S uses P_{min} to transmit. Before 20 μs to the end of the transmission, S adjust the power level to P_{adopt} inorder to warn S''. After that, R uses P_{adopt} to reply ACK. S' and S'' will defer their transmissions for an FIFS repeatedly. Therefore, the LIRC problem is avoided both at the sender and the receiver sites.

TABLE I
SIMULATION SETTINGS.

Parameter	Value
$TR(P_{max})$	250 m
$CR(P_{max})$	500 m
Transmission rate	2 Mb/s
P_{max}	28.183 mW
P_{thold}	$3.652 * 10^{-7}$ mW

Fig. 6(a) illustrates the energy consumption of the F-RCRC MAC protocol against IEEE 802.11 DCF, CCR, RCRC, and F-RCRC w/o PC. In RCRC MAC protocol, DATA is always sent with P_{min}. Therefore, the energy consumption of RCRC is the lowest. It is worth mentioning that CCR performs better than IEEE 802.11 DCF, F-RCRC w/o PC, and F-RCRC. The reason for the phenomenon is the limitation of the D_{SR}. If D_{SR} is larger than $0.56D_{SR}$, the transmission will be denied by the receiver. Hence, the energy consumption in CCR is inherent lower than those of IEEE 802.11 DCF, F-RCRC w/o PC, and F-RCRC. On the contrary, F-RCRC w/o PC always adopts P_{max}, irrelevant to D_{SR}, to transmit. Based on Fig. 6(a), it is obvious that the energy consumption of the F-RCRC w/o PC is the worst. Moreover, Fig. 6(a) also shows that the heavier the traffic load is, the more the energy consumes.



(a)

(b)

(c)

Fig. 6. Comparisons of F-RCRC, RCRC, IEEE 802.11 DCF, F-RCRC w/o PC, and *CCR* in terms of (a) energy consumption, (b) network throughput, and (c) energy efficiency (Byte/Joule), for different traffic load varied from 10 packets/s to 100 packets/s.

Fig. 6(b) shows the throughput of the five protocols in terms of the traffic load varied from 10 to 100 packets/s. Since the length of the DATA frame is set 2000 octets, the DATA transmission time will be longer than an EIFS. Thus, RCRC will suffer the LIRC problem seriously. It is why the performance of the RCRC is the worst. In CCR, the allowable transmission range is restricted within $0.56D_{SR}$. Therefore, some transmission pairs will be multi-hop transmissions, and thus, result in a worse performance. However, F-RCRC w/o PC uses the fragmentation to avoid the LIRC problem. Therefore, F-RCRC w/o PC gets higher throughput than RCRC and CCR. Moreover, the throughput of F-RCRC w/o PC is very close to that of DCF in low traffic load in the simulation. F-RCRC not only uses the fragmentation scheme, but also adopts the dynamical transmission power scheme. Therefore, the number of parallel transmissions is increased and F-RCRC gets the best throughput.

Fig. 6(c) compares the energy efficiencies of the five protocols in terms of the traffic load varied from 10 to 100 packet/s. Energy efficiency is defined as the number of bits transmitted per unit of energy consumption. The energy efficiency of RCRC performs the worst since it has a serious LIRC problem, even though it has the best energy consumption. For F-RCRC w/o PC, the throughput of F-RCRC w/o PC is very close to that of DCF. However, F-RCRC w/o PC consumes much power due to fragmentation overhead. Therefore, the energy efficiency of F-RCRC w/o PC performs worse than that of DCF. It is interesting that CCR has a stable energy efficiency, not much related to the variation of the traffic load. On the other hand, F-RCRC uses P_{min} for DATA transmissions and a smaller power, P_{adopt}, for the CTS transmissions. As a result, the parallel transmissions are increased. Therefore, F-RCRC performs the best. In Fig. 6(c), the performance of CCR is close to that of the IEEE 802.11 DCF, when the traffic load is getting heavier.

V. CONCLUSIONS

F-RCRC is a modification of RCRC (Receiver's Carrier-sensing Range Cover), but combines with the fragmentation scheme to release the RCRC's constraint on the frame length and add the power control scheme to save STAs' energy consumption and increase the spatial reuse as well as further raise the network throughput. F-RCRC designs a new interframe space, named FIFS, to reduce the overhead caused by the fragmentation scheme. With fragmentation, the design of the FIFS can effectively avoid the interfering STAs interfering with the receivers' receiving. Moreover, The hidden STAs can be warned by the dynamic transmission power scheme. Thus, the LIRC problem can be solved and the network throughput is increased accordingly. F-RCRC can not only solve the LIRC problem, but also reduce the energy consumption due to controlled transmission power. Simulation results show that F-RCRC performs much better than the related work in terms of network throughput as well as the power throughput.

Actually, F-RCRC can also solve the POINT problem [3], [4] and work correctly in multi-rate environments. However, due to the space limitation, the verifications of how F-RCRC solves the POINT problem and how F-RCRC works correctly in multi-rate environments are omitted.

ACKNOWLEDGEMENT

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