Performance Approximation of Persistent Relay CSMA with Carry-over of Backoff Counter Freezing After Collision

KATSUMI SAKAKIBARA   TAKUYA HARADA   JUMPEI TAKETSUGU
Okayama Prefectural University
Department of Information and Communication Engineering
111, Kuboki, Soja, 719-1197
JAPAN
{sakaki, cd26037r, taketugu}@c.oka-pu.ac.jp

Abstract: Cooperative transmission with one or more relay nodes has been investigated. We propose incorporation of the carry-over of backoff counter freezing after collision to Persistent Relay Carrier Sense Multiple Access (PRCSMA), in which two or more relay nodes cooperatively support retransmission of frame originated from source node over a common channel. The performance of the proposed protocol is approximately analyzed by means of a Markovian model. The accuracy of the approximation is verified by compute simulations. By carrying over the backoff counter freezing, that is, by deferring the backoff counter decrement, the priority of frame transmission in the next time slot is given to only nodes involved in frame collision. Therefore, the possibility of consecutive collision can be mitigated. Numerical results reveal that the proposed protocol can greatly improve the performance of the original PRCSMA. By carrying over the backoff counter freezing, the possibility of consecutive frame collisions can be reduced. This successfully leads to avoidance of a catastrophic series of frame collisions and considerable reduction of cooperation phase.

Key–Words: Persistent relay CSMA, Cooperative retransmission control, IEEE 802.11 DCF, Markovian model

1 Introduction

Cooperative communications with relay nodes have been recognized as one of effective and promising techniques in wireless/mobile communication systems. Relay standards are on the way to successful implementation in Long Term Evolution (LTE)-Advanced by the Third Generation Partnership Project (3GPP) and 802.16 by IEEE [1]–[4]. Relay techniques have been enthusiastically investigated from the viewpoint of the physical (PHY) and data-link layers [3], [5], [6]. In PHY layer perspective, Multiple-Input and Multiple-Output (MIMO) and diversity techniques are attractive [6]. In the data-link layer perspective, a number of Cooperative Automatic Repeat reQuest (C-ARQ) protocols have been proposed and analyzed. Particularly, the design of Medium Access Control (MAC) protocols employed between relay nodes and the destination node influences the performance, when two or more relay nodes collaborate on an identical channel.

Not a few protocols for C-ARQ systems have been proposed recently. Dianati et al. [7] proposed a Node-Cooperation Stop-and-Wait (NCSW) ARQ protocol. The performance of NCSW with a single relay node was analyzed over two-state Markovian channels. Morillo and Garcia-Vidal [8] proposed a C-ARQ

scheme with an integrated frame combiner. They analyzed the performance with round-robin cooperation among relay nodes and with Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Recently, based on Markov chain theory, Berber et al. presented a new approach to calculate the channel capacity of a multi-relay communication system [9]. In [10], Nessa et al. discussed applicability of fountain codes to a mobile cooperative relay network.

Under a scenario with unknown number of relay nodes, Alonso-Zarate et al. [11], [12] proposed Persistent Relay CSMA (PRCSMA), which elaborately incorporates well-known IEEE 802.11 Distributed Coordination Function (DCF) [13]; de facto standard for wireless LANs. Notice that in this sense, the protocol in [8] is equivalent to PRCSMA over error-free channels. In [11], the performance of PRCSMA was analyzed based on a steady-state two-dimensional Markovian model proposed by Bianchi [14] in terms of the average duration of cooperation. From the viewpoint of the steady-state performance analysis of IEEE 802.11 DCF, Foh and Tantra presented an accurate three-dimensional Markovian model [15], which took into account a carry-over of backoff counter freezing after collision occurred. In [15], the accuracy of the new model is verified by computer simulation.
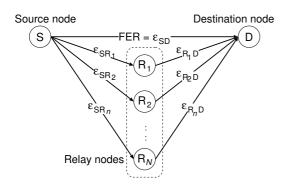
Figure 1: System model with N relay nodes.

The accuracy of Foh and Tantra's model was further improved in [16]. Note here that the protocol with CSMA/CA in [8] is equivalent to the original PRC-SMA [11] and that the protocol with round-robin in [8] requires overhead to obtain the number of relay nodes. Other protocols assume either only one relay node [7], or no MAC protocols [9], [10].

In this paper, we propose incorporation of the carry-over of backoff counter freezing after collision to PRCSMA. The performance of the proposed protocol is approximately analyzed by means of a Markovian model. The accuracy of the approximation is verified by compute simulations. By carrying over the backoff counter freezing, that is, by deferring the backoff counter decrement, the priority of frame transmission in the next time slot is given to only nodes involved in collision. Therefore, the possibility of consecutive collision can be mitigated.

The rest of the present paper is organized as follows: Section 2 presents a system model with relay nodes. PRCSMA is briefly reviewed in Section 3. In Section 4, the proposed protocol is described. In Section 5, we approximately analyze the performance of the proposed protocol as well as the original PRC-SMA, based on a Markovian model. Numerical results are presented in Section 6 to verify the accuracy of the approximation by means of computer simulations Finally, Section 7 concludes the present paper.

2 System Model

Consider a wireless network consisting of a pair of source node S and destination node D with N relay nodes; R_1, R_2,..., R_N, as shown in Fig. 1. All channels are half-duplex, so that a node can not transmit and receive simultaneously. All nodes are located within their transmission range. Hence, each node can overhear ongoing transmission originating from other nodes. Let $\varepsilon_{\mathrm{SD}}$, $\varepsilon_{\mathrm{SR}_n}$, and $\varepsilon_{\mathrm{R}_n\mathrm{D}}$ be the frame error probabilities on channels between source node S and

destination node D, between source node S and relay node R_n, and between relay node R_n and destination node D, respectively, for $n = 1, 2, \ldots, N$. If frame transmission from source node S resulted in erroneous reception at destination node D and if one or more relay nodes succeeded in error-free reception of the frame, then such relay nodes can collaboratively serve as supporters for frame retransmission. For effective use of cooperative communications, we generally assume that $\varepsilon_{\mathrm{SD}} > \varepsilon_{\mathrm{R}_n\mathrm{D}}$. The duration in which relay nodes collaborate frame retransmissions is referred to as a *cooperation phase* [11]. Note that every frame is assumed to include an appropriate header and an ideal Frame Check Sequence (FCS) for error/collision detection,[1] in addition to the payload.

3 PRCSMA

PRCSMA [11], [12] is a MAC protocol which elaborately resolves frame collisions among transmission from relay nodes, based on IEEE 802.11 DCF [13]. Similarly to IEEE 802.11 DCF, each relay node in PRCSMA inserts random backoff delay before every frame transmission in a distributed manner according to its own value of the contention window (CW) at that time. That is, the backoff interval is determined in proportion to a random integer between $[0, W]$, where W is the current CW value.

The operation of PRCSMA is summarized as follows. The detailed description can be found in [11]. After erroneous reception of a DATA frame transmitted by source node S, destination node D broadcasts a Call For Cooperation (CFC) frame following the Short Inter-Frame Space (SIFS). If one or more relay nodes receive both the DATA frame and the CFC frame, then the cooperation phase is invoked. Relay nodes which join in the cooperation phase is referred to as *active relay nodes*. Active relay nodes simultaneously start the DCF operation, after the reception of the CFC frame followed by the Distributed Inter-Frame Space (DIFS). It is regulated that DIFS is longer than SIFS in order to guarantee prior transmissions of control frames to those of data frames [13]. In addition, an idle period specified by ACKtimeout after DATA frame transmission notifies nodes of transmission failure. When destination node D correctly receives a DATA frame from one of the active relay nodes, it broadcasts an ACK frame to announce not only correct reception of the DATA frame to source node S but also completion of the cooperation phase to all the nodes.

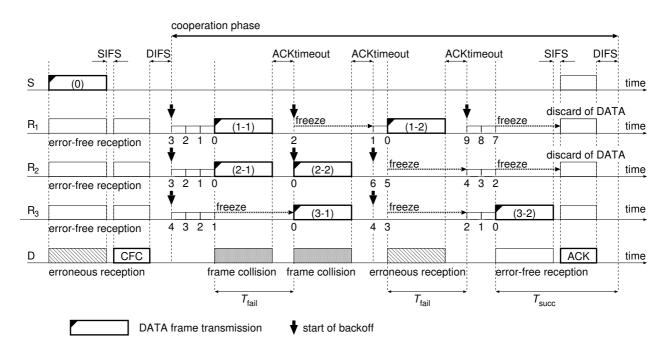[1]The term "ideal" implies that the probability of undetected errors can be neglected.

Figure 2: Illustrative example of PRCSMA with decrement of backoff counter according to Bianchi's method [14].
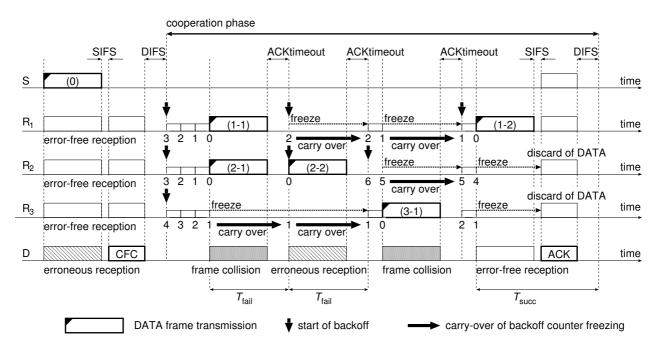

Figure 3: Illustrative example of proposed protocol (PRCSMA with decrement of backoff counter according to Foh & Tantra's method [15]).

An illustrative operational example with three active relay nodes, R_1, R_2 and R_3, is shown in Fig. 2. Active relay nodes R_1 and R_2 independently set their backoff counter to three and active relay node R_3 to four after reception of CFC frame from destination node D, which follows an erroneous reception of DATA frame (0). In Fig. 2, the start of backoff interval is marked by a short thick down arrow. The first

DATA frame transmission from active relay nodes R_1 and R_2, DATA frames (1-1) and (2-1), respectively, results in collision. Decrement of the backoff counter in the original PRCSMA [11] complies with Bianchi's model [14]. According to Bianchi's model, the backoff counter of all the relay nodes is decreased by one after the end of ACKtimeout following a busy period. Hence, DATA frame (3-1) collides with DATA frame

(2-2), if active relay node R_2 happens to randomly select zero backoff counter after ACKtimeout. It implies that all the relay nodes have the right to transmit DATA frame in the next time slot following ACKtimeout. Eventually, destination node D receives DATA frame (3-2) correctly, so that an ACK frame is broadcast and the cooperation phase is completed.

Notice here that source node S does not participate in a cooperation phase [11].

4   Proposed Protocol

In order to reduce the possibility of consecutive frame collisions in IEEE 802.11 DCF, Foh and Tantra [15] proposed a carry-over of backoff counter freezing after frame transmission failure. According to Foh and Tantra's method, nodes that are excluded from frame collision carry over their backoff counter freezing, so that they are unable to transmit the DATA frame in the next time slot following ACKtimeout. As a result, only the nodes included in frame collision have the right to retransmit the DATA frame in the next time slot following ACKtimeout. Taking advantage of Foh and Tantra's method, we propose an incorporation of Foh and Tantra's method to the original PRCSMA in order to improve the performance.

An illustrative operational example is depicted in Fig. 3. After frame collision between DATA frames (1-1) and (2-1) from active relay nodes R_1 and R_2, respectively, the two colliding active nodes randomly and independently select their next backoff interval, so that R_1 sets its backoff interval to two and R_2, to zero. Another active relay node R_3 carries over its backoff counter whose value is one. Consequently, only the active relay node R_2 retransmits DATA frame (2-2), that is, frame collision between DATA frames (2-2) and (3-1), shown in Fig. 2 can be avoided.

5   Performance Analysis

In this section, we construct a Markovian model with respect to the number of colliding relay nodes and, then, we theoretically analyze the average duration of cooperation phase. Let N denote the number of active relay nodes. For the sake of simplicity, we assume ideal error-free channels between any relay node and destination node D, that is, $\varepsilon_{R_1 D} = \varepsilon_{R_2 D} = \cdots = \varepsilon_{R_N D} = 0$. Furthermore, the CW value W is kept constant, even if frame transmission is unsuccessful, that is, no doubling process is employed as opposed to the legacy IEEE 802.11 [11].

5.1   Virtual Time Slot Duration

As shown in Fig. 2 and Fig. 3, all the active relay nodes operate in a synchronized manner subject to virtual a time slot. The virtual time slot duration consists of the frame duration and ACKtimeout, if frame transmission results in collision or erroneous reception. Meanwhile, the virtual time slot duration is the sum of the DATA frame duration, SIFS, the ACK frame duration and DIFS, if frame transmission succeeds, that is, it is the last virtual time slot in a cooperation phase. Hence, the virtual time slot durations for successful fame transmission and unsuccessful frame transmission are given by

$$T_{\text{succ}} = T_{\text{DATA}} + T_{\text{SIFS}} + T_{\text{ACK}} + T_{\text{DIFS}}, \quad (1)$$

$$T_{\text{fail}} = T_{\text{DATA}} + T_{\text{ACKtimeout}}, \quad (2)$$

respectively. The DATA frame duration T_{DATA} and the ACK frame duration T_{ACK} are given by

$$T_{\text{DATA}} = T_{\text{PHY}} + \frac{L_{\text{MAC}} + L_{\text{payload}}}{R_{\text{DATA}}}, \quad (3)$$

$$T_{\text{ACK}} = T_{\text{PHY}} + \frac{L_{\text{ACK}}}{R_{\text{cntr}}}, \quad (4)$$

respectively, where T_{PHY} is the physical header duration, L_{MAC} is the MAC header length in bits, L_{payload} is the payload length in bits, R_{DATA} is the transmission rate for DATA frame in bit-per-second, and R_{cntr} is the transmission rate for control frame in bit-per-second.

5.2   Markovian Model

Since a cooperation phase simultaneously starts with all the active relay nodes and terminates by the first successful exchange of DATA frame and ACK frame. It implies that the transient analysis suits to the performance analysis of the cooperation phase rather than the steady-state analysis. However, it is known that the transient analysis of IEEE 802.11 DCF is complicated due to not only backoff operations with memory but also the doubling process of the CW value W after frame transmission failure [17]. Actually, in the original PRCSMA and the proposed protocol, a DATA frame is transmitted with probability one after the backoff interval randomly selected between 0 and W expires.

In order to alleviate these complexities, we assume not only memoryless transmission of DATA frames, so that each active relay node transmits a DATA frame with probability τ in a virtual time slot, but also the constant CW value W [11], [12], [18]. With these assumptions, the DATA frame transmission probability in a slot is represented by
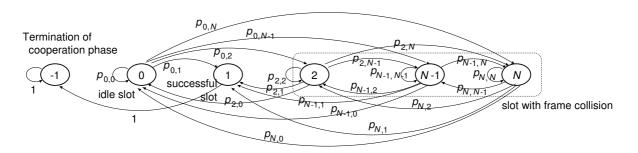
$$\tau = \frac{1}{W + 1}, \quad (5)$$

Figure 4: Markovian model with respect to the number of colliding nodes.

where W is the CW value.

Consider the trajectory of the number of colliding relay nodes in consecutive virtual time slots in a cooperation phase. Let $\Omega = \{-1, 0, 1, \ldots, N\}$ be the state space representing the number of colliding relay nodes, where State -1 denotes the termination of the cooperation phase and is an absorbing state. Then, we can construct a Markovian chain presented in Fig. 4. Note that only State 1 is permitted to transit to State -1, since a DATA frame transmission with no collision can terminate a cooperation phase. Also, once State 1 is reached, the transition to State -1 always occurs, since frame errors are assumed to be ignored.

We can calculate the transition probabilities $p_{j,i}$ from State j to State i as follows, where $i, j \in \Omega$, depending on which method is employed; Bianchi's method (original PRCSMA) or Foh and Tantra's method (proposed).

First, consider the original PRCSMA. In Bianchi's method, all the active relay nodes have permission to transmit their DATA frame in every time slot. It follows from the memoryless assumption that each active relay node transmits their DATA frame in an independent and identical manner. Hence, the transition probability $p_{j,i}$ from State j to State i in Bianchi's method can be evaluated as

$$p_{j,i} = \begin{cases} B(N, i, \tau) & \text{for } j \neq \pm 1 \text{ and } i \neq -1 \\ 1 & \text{for } j = 1 \text{ and } i = -1 \\ 1 & \text{for } j = i = -1 \\ 0 & \text{otherwise} \end{cases}, \quad (6)$$

where $B(n, k, \tau)$ is the binomial distribution defined by

$$B(n, k, \tau) = \binom{n}{k} \tau^k (1 - \tau)^{n-k} \quad (7)$$

for $0 \leq k \leq n$.

Next, consider the proposed protocol. In this method, only the colliding relay nodes have permission to access to the channel in the next time slot. Thus, the state transition from State j to State i is

possible, if $i \leq j$, and impossible, if $i > j$. As a result, the state transition probability $p_{j,i}$ from State j to State i can be given as

$$p_{j,i} = \begin{cases} B(N, i, \tau) & \text{for } j = 0 \text{ and } i \neq -1 \\ B(j, i, \tau) & \text{for } j \neq 0, \pm 1 \\ & \text{and } i = 0, 1, \ldots, j \\ 1 & \text{for } j = 1 \text{ and } i = -1 \\ 1 & \text{for } j = i = -1 \\ 0 & \text{otherwise} \end{cases}, \quad (8)$$

since independent frame transmissions are assumed.

5.3 Average Duration of Cooperation Phase

We then derive the probability generating functions with respect to the elapsed time after starting a cooperation phase. After that, we evaluate the average duration of cooperation phase.

Let Z be an indeterminant whose exponent represents the elapsed time. We denote by $g_i(Z|t)$ the probability generating function with respect to the elapsed time for State i in the tth virtual time slot for $i \in \Omega$ and $t = 1, 2, \ldots$. The probability conservation law

$$\sum_{i=-1}^{N} g_i(1|t) = 1 \quad (9)$$

holds for any $t = 1, 2, \ldots$. In the first time slot, depending the number of transmitted DATA frames, the cooperation phase consumes T_{slot}, T_{succ}, or T_{fail}, where T_{slot} is the slot duration defined in the legacy IEEE 802.11 standard, T_{succ} is given by (1) and T_{fail}, by (2). From the independent operation assumption among active relay nodes, the initial condition for $t = 1$ is given by

$$g_i(Z|1) = \begin{cases} 0 & \text{for } i = -1 \\ B(N, 0, \tau)Z^{T_{\text{slot}}} & \text{for } i = 0 \\ B(N, 1, \tau)Z^{T_{\text{succ}}} & \text{for } i = 1 \\ B(N, i, \tau)Z^{T_{\text{fail}}} & \text{for } i = 2, 3, \ldots, N \end{cases}. \quad (10)$$

Then, the probability generating functions $g_i(Z|t)$ evolve regarding the slot number t, so that they can be derived recursively. If the DATA frame transmission in the tth time slot results in success, that is, if no collision occurs, then the cooperation phase can terminate. Thus, for $i = -1$, we have a recursive expression for $g_{-1}(Z|t)$;

$$g_{-1}(Z|t+1) = g_{-1}(Z|t) + g_1(Z|t) \qquad (11)$$

for $t = 1, 2, \dots$. For $i = 0$ (idle slot), the idle slot duration T_{idle} is consumed. Then, we have

$$g_0(Z|t+1) = Z^{T_{\text{slot}}} \sum_{j=0, j\neq 1}^{N} p_{j,0} g_j(Z|t). \qquad (12)$$

In a similar manner, we have for $i = 1$ (no collision slot)

$$g_1(Z|t+1) = Z^{T_{\text{succ}}} \sum_{j=0, j\neq 1}^{N} p_{j,1} g_j(Z|t) \qquad (13)$$

and for $i = 2, 3, \dots, N$ (collision slot)

$$g_i(Z|t+1) = Z^{T_{\text{fail}}} \sum_{j=0, j\neq 1}^{N} p_{j,i} g_j(Z|t), \qquad (14)$$

since the successful virtual time slot duration T_{succ} and the unsuccessful virtual time slot duration T_{fail} are consumed, respectively.

Once the probability generating function can be obtained, we can obtain the average duration of cooperation phase T_{CP} by differentiating the probability generating function with respect to Z and by evaluating at $Z = 1$:

$$T_{\text{CP}} = \frac{d}{dZ}\left[\sum_{t=1}^{\infty} g_1(Z|t)\right]_{Z=1}. \qquad (15)$$

6 Numerical Results

We examine the accuracy of the approximated expressions derived in the previous section by comparing it with the results obtained from computer simulation. The simulation program is written in C language and the results are obtained by averaging 10^5 trials of cooperation phases. Each trail starts with N relay nodes which correctly receive both of the DATA frame from source node S and the CFC frame from destination node D. The values of parameters used in numerical results are tabulated in Table 1. With these values of frame format, the successful virtual time slot duration T_{succ} and the unsuccessful virtual time slot duration T_{fail} are calculated as $T_{\text{succ}} = 346$ [μsec] and

Table 1: Parameters used in numerical results

data rate: R_{DATA}	54 [Mbps]
control frame rate: R_{cntr}	6 [Mbps]
slot duration: T_{slot}	9 [μsec]
SIFS duration: T_{SIFS}	16 [μsec]
DIFS duration: T_{DIFS}	34 [μsec]
ACKtimeout: $T_{\text{ACKtimeout}}$	34 [μsec]
PHY header length: T_{PHY}	20 [μsec]
MAC header length: L_{MAC}	34 [byte]
ACK length: L_{ACK}	14 [byte]
DATA payload length: L_{payload}	1500 [byte]
CW value: W	15
frame error rate: $\varepsilon_{\text{R}_n\text{D}}$	0

$T_{\text{fail}} = 286$ [μsec], respectively. As assumed in the previous section, the CW value W at each relay node is constant at any time similarly to [11], [18], even if frame transmission suffers collision. Hence, no doubling process is employed as opposed to IEEE 802.11 DCF [13]. Furthermore, channels between any relay node R_n and destination node D are assumed error-free; $\varepsilon_{\text{R}_n\text{D}} = 0$ for any $n = 1, 2, \dots, N$. Frame transmission succeeds if it experiences no other simultaneous frame transmissions.

6.1 Average Duration of Cooperation Phase

The average duration of cooperation phase of the proposed protocol and the original PRCSMA is shown in Fig. 5. Solid lines represent the theoretically approximated results and circles and squares depict the results obtained from computer simulation. The theoretical results for the proposed protocol sufficiently approximate to the results from computer simulation while the theoretical results for the original PRCSMA provide only a lower bound. Differences in the analysis between the proposed protocol and the original PRCSMA lie in expressions of the transition probabilities $p_{j,i}$ in (6) and (8). We conjecture that the conversion from random backoff interval between 0 and W to the frame transmission probability τ in (5) be not sufficiently accurate, particularly when large number of relay nodes collide.

Compare the results for the proposed protocol with those for the original PRCSMA. Shorter duration of cooperation phase is preferred, since nodes can move to the next data transfer rapidly. It is evident that the proposed protocol can provide considerable performance improvement, compared to the original
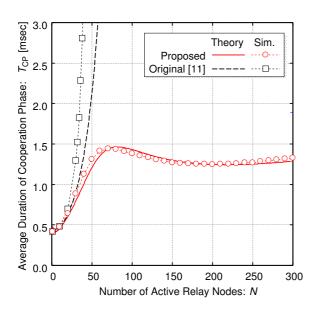
Figure 5: Average duration of cooperation phase of the proposed protocol and the original PRCSMA [11].

PRCSMA. In the original PRCSMA the duration of cooperation phase catastrophically increases in proportion to the number of active relay nodes. However, in the proposed protocol, the steep degradation in the original PRCSMA can be mitigated. The proposed protocol can rather reduce the average duration of cooperation phase successfully, even though the number of active relay nodes increases for approximately $70 < N < 200$.

6.2 Virtual Time Slot Distribution

In order to reveal the reason why the proposed protocol can succeed in drastically reducing the average duration of cooperation phase, we examine the average number of virtual slots in a cooperation phase. Since channel errors between relay nodes and destination node D are ignored, virtual slots can be classified into idle, collision, and successful slots, where every cooperation phase ends with a unique successful slot.

The numerical results of the virtual time slot distribution, obtained from computer simulation, are provided in Fig. 6. Note here that in Fig. 6(b), the results are shown for $N < 70$, since we stopped the execution of simulation trials due to extremely long task execution time for $N \geq 70$. From Fig. 6(b), it can be apparently observed that the average number of collision slots increases rapidly and that the average number of idle slots vanishes in the original PRCSMA. On the other hand, from Fig. 6(a), the proposed protocol can successfully suppress catastrophic growth of the number of collision slots in a cooperation phase. More precisely, a cooperation phase of the proposed

(a) Proposed protocol
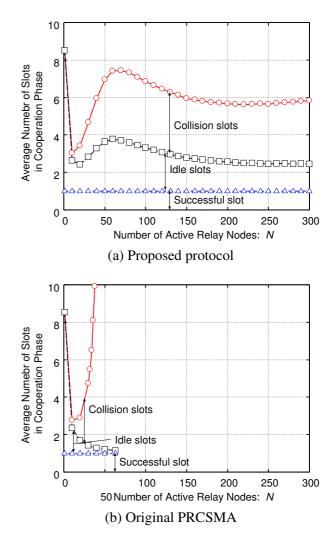

(b) Original PRCSMA

Figure 6: Average number of virtual time slots in cooperation phase of the proposed protocol and the original PRCSMA: idle, collision, and successful slots.

protocol consists of less than eight slots on the average. According to Foh and Tantra's method, only the relay nodes involved frame collision are permitted to transmit their frame in the next time slot. It implies that the possibility of consecutive occurrence of frame collisions in the time slot following frame collision can be mitigated, which may drastically reduce the number of collision slots in a cooperation phase of the proposed protocol. In addition, one or more idle slots are included in cooperation phase in the proposed protocol even for large N, in contrast with the original PRCSMA.

6.3 Consecutive Frame Collisions

As expected in the previous section, Foh and Tantra's method in the proposed protocol can lessen the possibility of consecutive occurrence of frame collisions. For instance, if n relay nodes collide in a certain vir-
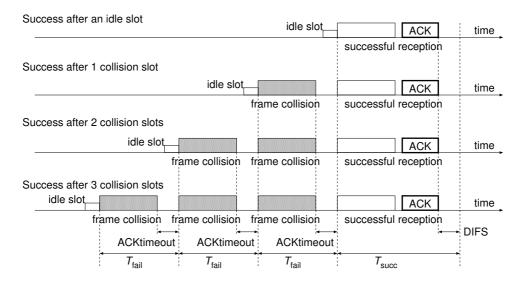
Figure 7: Classification of the number of consecutive frame collisions followed by successful DATA frame transmission.

tual time slot in the proposed protocol, then n/W nodes might re-collide in the next time slot on the average, where W is the CW value. Hence, if roughly W relay nodes collide, then the possibility of terminating the cooperation phase increases in the next time slot.

We then evaluate the distribution of the number of consecutive frame collisions followed by a successful DATA frame transmission, which entails the end of the cooperation phase. An illustrative description is shown in Fig. 7, where four cases are presented; success following an idle slot, success after one isolated collision virtual time slot, success after two collision virtual time slots, and success after three collision virtual time slots. According to the classification in Fig. 7, the ratio of the number of consecutive frame collision slots followed by successful DATA frame transmission, obtained from computer simulation, is shown in Fig. 8 for the proposed protocol and the original PRCSMA. Note that similarly to Fig. 6(b), the results of the original PRCSMA are provided only for $N < 70$ in Fig. 8(b).
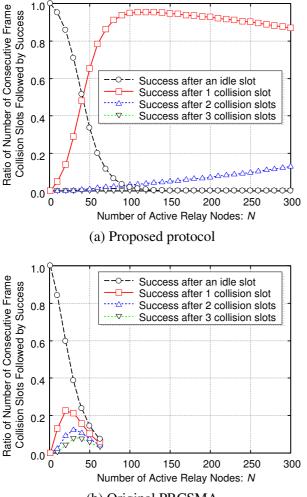
It follows from Fig. 8(a) that the ratio of successful DATA frame transmission following one collision slot after an idle slot sharply increases instead of successful transmission following an idle slot. For $N > 60$ when frame collision occurs, a cooperation phase ends in the next time slot with probability more than 0.8. Meanwhile, as shown in Fig. 8(b), not only the ratio of successful transmission after an idle slot but also that after one or more collision slots decrease for $N > 25$ in the original PRCSMA. It is involved that in the original PRCSMA, frame collision catastrophically lasts, once it happens. for large N.

Finally, from the above discussions Foh and Tantra's method is effective not only IEEE 802.11 DCF but also PRCSMA with large number of relay nodes. As discussed in [19], it is expected that thousands of devices may cooperate in machine-to-machine communication networks. The proposed protocol can can be effective in such a network consisting of huge but unknown number of nodes.

7 Conclusion

We have proposed incorporation of the carry-over of backoff counter freezing after collision to PRCSMA, in which unknown number of relay nodes cooperatively support retransmission of frame originated from source node. The carry-over of backoff counter was originally proposed by Foh and Tantra [15] for improving IEEE 802.11 DCF. The performance of the proposed protocol has been approximately analyzed by constructing a Markovian model whose state space is the number of colliding relay nodes in a virtual time slot. The accuracy of the approximation has been verified by compute simulations. By carrying over the backoff counter freezing, that is, by deferring the backoff counter decrement, the priority of frame transmission in the next time slot is given to only nodes involved in frame collision. Therefore, the possibility of consecutive collision can be mitigated.

Numerical results have revealed that the proposed protocol can greatly improve the performance of the original PRCSMA. By carrying over the backoff counter freezing, the possibility of successful DATA frame transmission after frame collision can be drastically improved. This leads to avoidance of a catas-

(a) Proposed protocol

(b) Original PRCSMA

Figure 8: Ratio of the number of consecutive collisions followed by successful DATA frame transmission of the proposed protocol and the original PRCSMA.

trophic series of frame collisions exhibited in the original PRCSMA, so that considerable reduction of cooperation phase can be achieved.

Further study includes, for example, the refinement of the approximation, the extension to bidirectional communication systems, and to the use of network coding.

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