Simulation Study of Persistent Relay CSMA with Random Assigning of Initial Contention Window Values

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***Abstract*—Based on IEEE 802.11 Distributed Coordination Function (DCF), Persistent Relay Carrier Sense Multiple Access (PRCSMA) was proposed for cooperative transmission with two or more relay nodes. We propose random assigning of the initial Contention Window (CW) value of each relay node at the beginning of cooperation phase in PRCSMA. Each relay node independently and randomly selects its initial CW value among a predefined set of integers, while in the original PRCSMA, a relay node fixes its CW value to a common given integer. Numerical results obtained from computer simulation reveal that the proposed protocol can improve the performance of the original PRCSMA. The proposed protocol makes it possible to reduce the possibility of frame collisions among relay nodes and successfully reduce the duration of cooperation. Also, the results demonstrate that the binary exponential backoff algorithm degrades the performance of PRCSMA.**

Keywords–persistent relay CSMA; wireless LAN; simulation; contention window.

I. Introduction

In order to compensate poor channel quality and improve communication reliability, 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 802.16m by IEEE [1] [2]. Relay techniques have been enthusiastically investigated from the viewpoint of the physical (PHY) and data-link layers [2] [3]. From the viewpoint of PHY layer, Multiple-Input and Multiple-Output (MIMO) and diversity techniques are known to be effective. 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.

Some MAC protocols for C-ARQ systems have been proposed recently. Morillo and Garcia-Vidal [4] 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). Alonso-Zarate et al. [5] [6] proposed Persistent Relay CSMA (PRCSMA), which elaborately incorporates well-known IEEE 802.11 Distributed Coordination Function (DCF) [7]; de facto standard for wireless LANs. When the number of relay nodes is unknown, contention-based MAC protocols are required for the data-link layer at a relay node. In [5], the performance of PRCSMA was analyzed in terms of the average duration of cooperation, based on a steady-state Markovian model proposed by Bianchi [8] For IEEE 802.11 DCF, Foh and Tantra presented an accurate three-dimensional Markovian model [9], which took into account a carry-over of backoff counter freezing after frame collision occurred. In [9], the accuracy of the new model is verified by computer simulation. In [10], the authors indicated that incorporation of Foh and Tantra's method to PRCSMA can greatly improve the performance. However, the Contention Window (CW) value of all the relay node is fixed in advance, as in the original PRCSMA [5].

In this paper, we propose random assigning of the initial CW value of each relay node at the beginning of cooperation phase in order to further improve the performance of PRCSMA. Each relay node independently and randomly selects its initial CW value among a predefined set of integers. The proposed protocol requires no information of the number of competing relay nodes. Random assigning of the initial CW value makes it possible to reduce the possibility of frame collisions among relay nodes before successful frame transmission which completes cooperative retransmissions. The performance of the proposed protocol is verified by computer simulation.

The rest of the present paper is organized as follows: Section II presents a system model with relay nodes. PRCSMA is briefly reviewed in Section III. In Section IV, the proposed protocol of random assigning of the initial CW value is described. Numerical results obtained by means of computer simulations are presented in Section V. Finally, Section VI concludes the present paper.

II. System Model

Consider a wireless network consisting of a pair of source node S and destination node D with N relay nodes; $\mathrm{R}_1, \mathrm{R}_2, \ldots, \mathrm{R}_N$, as shown in Figure 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. We assume that a node possesses no information on the number of relay nodes. Let $\varepsilon_{\mathrm{SD}}$, $\varepsilon_{\mathrm{SR}_n}$, and $\varepsilon_{\mathrm{R}_n\mathrm{D}}$ be the frame error rates 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

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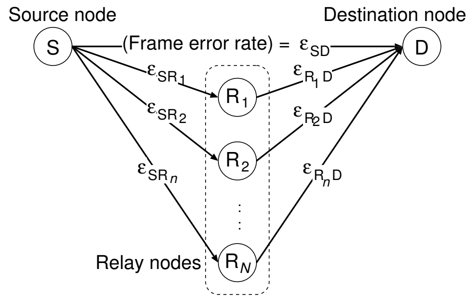

Figure 1. System model with N relay nodes.

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 $\varepsilon_{SD} > \varepsilon_{R_nD}$. The duration in which relay nodes collaborate frame retransmissions is referred to as a *cooperation phase* [5]. Note that every frame is assumed to include an appropriate header and an ideal Frame Check Sequence (FCS) for error/collision detection, in addition to the payload. Note that the term "ideal" implies that the probability of undetected errors can be neglected.

III. PRCSMA

PRCSMA [5] [6] is a MAC protocol which elaborately resolves frame collisions among transmission from relay nodes to destination node D, based on IEEE 802.11 DCF [7]. 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 current value of the CW. More precisely, if CW = w, then the initial value of the backoff counter is set to an integer randomly taken from the range $[0,\ w-1]$.

The operation of PRCSMA is summarized as follows. The detailed description can be found in [5]. 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 correctly receive both the DATA frame and the CFC frame, then the cooperation phase is invoked. A relay node which joins in the cooperation phase is referred to as an *active relay node*. 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 [7]. In addition, an idle period specified by ACKtimeout after DATA frame transmission notifies nodes of transmission failure. Then, a relay node involved in collision carries out another retransmission procedure with random backoff interval. 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.

In the original PRCSMA [5], the decrement of backoff counter at each relay node follows the method considered in [8]. In [10], the authors showed that by adopting the method in [9], the duration of the cooperation phase can be greatly decreased. Therefore, we consider the method in [9].

An illustrative operational example with three active relay nodes, R_1, R_2 and R_3, is shown in Figure 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 Figure 2, a short thick down arrow marks the start of backoff interval. The first DATA frame transmissions from active relay nodes R_1 and R_2, named as DATA frames (1-1) and (2-1), respectively, result in collision. In this period of frame collision, another active relay node R_3 freezes the decrement of backoff counter. The two colliding active nodes R_1 and R_2 recognize their frame transmission failure after ACKtimeout. They randomly and independently select their next backoff interval, so that R_1 sets its backoff interval to two and R_2, to zero. Complying with the method of Foh and Tantra [9], another active relay node R_3 carries over its backoff counter whose value is one. Then, only the active relay node R_2 retransmits DATA frame (2-2). Assume that destination node D receives DATA frame (2-2) erroneously, so that the cooperation phase continues. Finally, DATA frame (1-2) is received with no errors by destination node D. Then, ACK frame transmission from destination node D notifies other nodes of completion of the cooperation phase.

IV. Random Assigning of Initial CW Values

In PRCSMA, no specific backoff algorithm such as the binary exponential backoff (BEB) algorithm is prescribed in updating the CW values of relay nodes involved in frame collisions. For the sake of mathematical tractability, Alonso-Zarate et al. [5] and Predojev et al. [6] analyzed the performance of PRCSMA with constant CW values, that is, a relay node fixes the CW value to the initial CW value, which is regulated to be equal among all the relay nodes all the time, even after frame collisions. It is clear that small CW value may increase the probability of frame collision and that large CW value may insert a large number of unnecessary idle slots, both of which may enlarge the duration of cooperation phase. From the assumption that the number of relay nodes N is unknown to all nodes, neither adaptive nor optimization techniques with respect to the CW value based on N can be applied.

In order to mitigate undesired extension of cooperation phase, we propose a random assigning of the initial CW values to each active relay node at the beginning of the cooperation phase. Let us denote the minimum and maximum CW values by $\mathrm{CW_{min}}$ and $\mathrm{CW_{max}}$, respectively. Here, we define a set of D possible initial CW values;

$$\mathcal{W} = \{W_0,\ W_1,\ \ldots,\ W_{D-1}\}, \tag{1}$$

where

$$W_i = \min[2^i \mathrm{CW_{min}},\ \mathrm{CW_{max}}] \tag{2}$$

for $i = 0, 1, \ldots, D-1$. In the proposed protocol, each active relay node independently and randomly selects its initial CW value among $\mathcal{W}$. For example, we have

$$\mathcal{W} = \{32,\ 64,\ 128,\ 256,\ 512,\ 1024,\ 1024\} \tag{3}$$

for $\mathrm{CW_{min}} = 32$, $\mathrm{CW_{max}} = 1024$ and $D = 7$. An active relay node randomly selects one integer from $\mathcal{W}$. Since $D = 7$ and $\mathrm{CW_{max}} = 1024$ is doubly included in $\mathcal{W}$, as in (3), each integer is selected with probability 1/7 except for 1024, whose probability is 2/7. As another choice for $\mathcal{W}$ in (3), we

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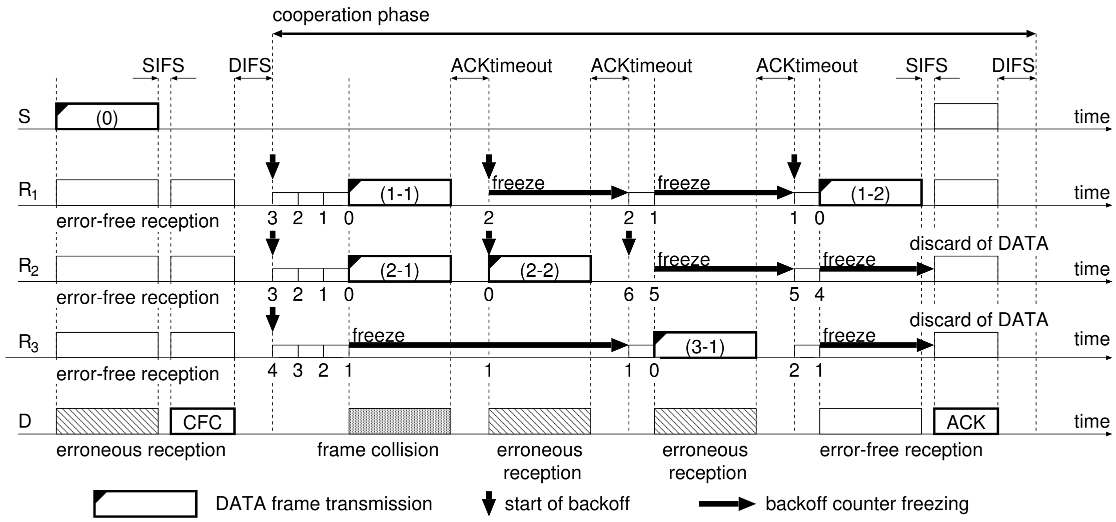

Figure 2. Illustrative example of PRCSMA with decrement of backoff counter according to Foh & Tantra's method [9].

can set $\mathcal{W}$ = {32, 64, 128, 256, 512, 1024} with $D = 6$ and probability 1/6 for each value. However, in the following numerical results, we permit unbalanced probabilities in order to enable us to compare the results for identical values of D.

Note here that for $D = 1$, the proposed protocol is degenerated into the original PRCSMA, since the initial CW value of all the relay node is $\mathrm{CW}_{\min}$.

V. Numerical Results

We evaluate the performance of the proposed protocol; random assigning of the initial CW values described in Section IV, in terms of the average duration of cooperation phase by means of exhaustive computer simulation. Comparisons with the original PRCSMA, in which each relay node fixes its CW values to the given integer all the time, are presented. We examine two cases for both the proposed protocol and the original PRCSMA. In the first case, each relay node keeps the assigned initial CW value after frame collision; without BEB, while in the second case, the CW value is doubled after frame collision until it reaches to $\mathrm{CW}_{\max}$ in a similar manner to IEEE 802.11 DCF; with BEB. 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 active relay nodes, which implies that all the relay nodes correctly receive both DATA frame from source node S and CFC frame from destination node D. The values of parameters used in simulations are tabulated in Table I, which are basically taken from IEEE 802.11a standard [7]. The values of $\mathrm{CW}_{\min}$ are taken by referring to IEEE 802.11e standard. Channels between relay node R_n and destination node D are assumed error-free; $\varepsilon_{\mathrm{R}_n\mathrm{D}} = 0$ for any $n = 1, 2, \ldots, N$. Hence, frame transmission succeeds if it experiences no other simultaneous frame transmissions.

A. Average Duration of Cooperation Phase

The average duration of cooperation phase of the proposed protocol and the original PRCSMA ($D = 1$) is shown for $\mathrm{CW}_{\min} = 4, 8, 16, 32$ in Figure 3 and Figure 4. In Figure 3, no BEB algorithm is employed, so that each relay node holds the assigned initial CW value after frame collision. In Figure 4,

TABLE I. Parameters Used in Simulations.

data rate	54	[Mbps]
control frame rate	6	[Mbps]
slot duration	9	[μsec]
SIFS duration	16	[μsec]
DIFS duration	34	[μsec]
ACKtimeout	34	[μsec]
round-trip time	0	[μsec]
PHY header length	20	[μsec]
MAC header length	34	[byte]
ACK length	14	[byte]
DATA payload length	1500	[byte]
$\mathrm{CW}_{\min}$	4,8,16,32	
$\mathrm{CW}_{\max}$	1024	
D (size of $\mathcal{W}$)	1,3,5,7	
frame error rate $\varepsilon_{\mathrm{R}_n\mathrm{D}}$	0	(error-free)

each relay node doubles its CW value unless it is greater than $\mathrm{CW}_{\max}$. Shorter duration of cooperation phase is preferred, since nodes can move to the next data transfer rapidly.

First, let us roughly compare the performance between the proposed protocol and the original PRCSMA. If the number of active relay nodes N is small, then the proposed protocol for large D is preferred. This tendency is outstanding for wider range of N, when $\mathrm{CW}_{\min}$ is smaller. On the other hand, if N is large, the original PRCSMA exhibits small average duration of cooperation phase. As a whole, we can observe from Figure 3 and Figure 4 that the proposed protocol for $\mathrm{CW}_{\min} = 8$ and $D = 7$ with no BEB algorithm indicates best average duration of cooperation phase, which is stable for wide range of the number of active relay nodes.

Next, compare the performance with and without BEB algorithm. An incorporation of the BEB algorithm generally enlarge the average duration of cooperation phase. An effectiveness of the BEB algorithm has been widely known and analyzed. In fact, the BEB algorithm is able to reduce the probability of frame collision and to improve the steady-state performance. However, it is revealed from Figure 3 and Figure 4 that the BEB algorithm may defer the occurrence of the first successful frame transmission, in particular, in dense networks. The results give us an insight that in the transient state, the CW values should be kept constant until some frames

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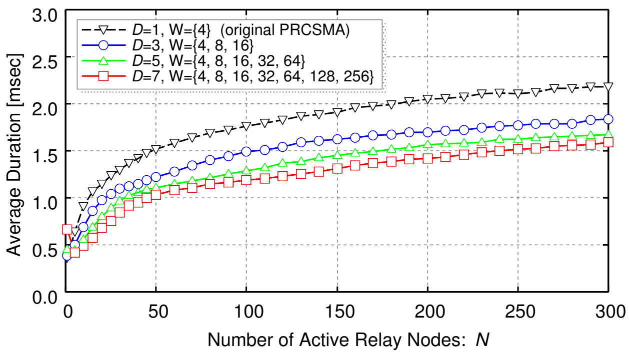
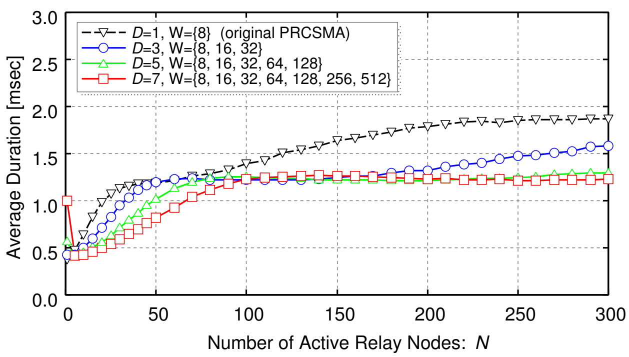
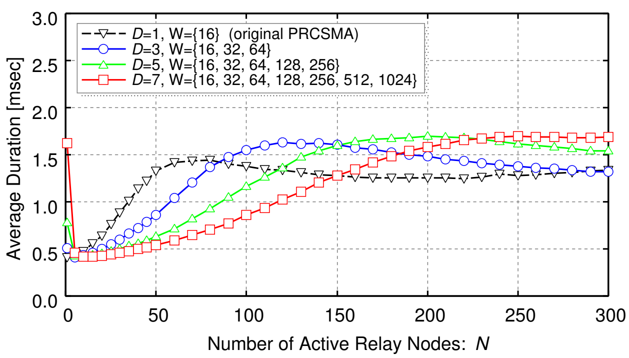


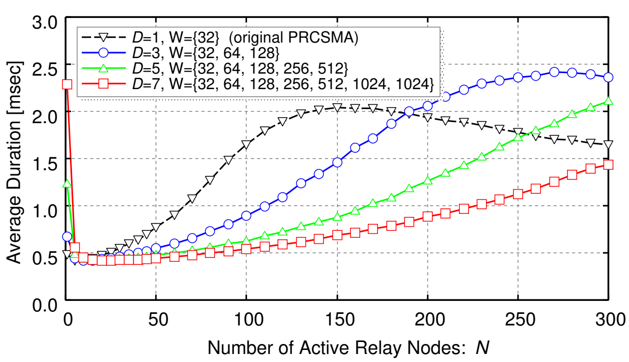
(a) without BEB for $CW_{min} = 4$



(b) without BEB for $CW_{min} = 8$

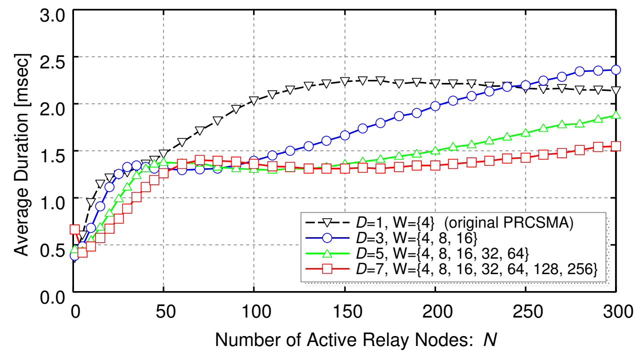


(c) without BEB for $CW_{min} = 16$

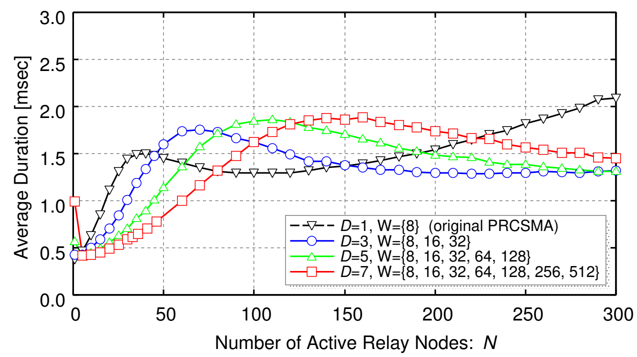


(d) without BEB for $CW_{min} = 32$

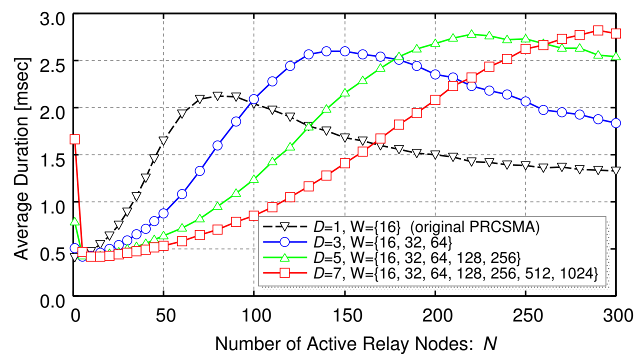
Figure 3. Average duration of cooperation phase without BEB algorithm for $CW_{min} = 4, 8, 16, 32$ and $D = 1, 3, 5, 7$.



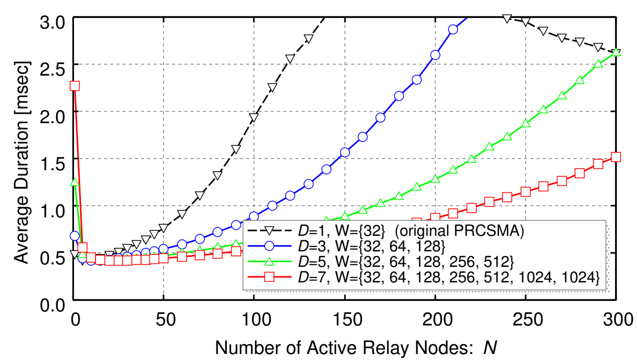
(a) with BEB for $CW_{min} = 4$



(b) with BEB for $CW_{min} = 8$

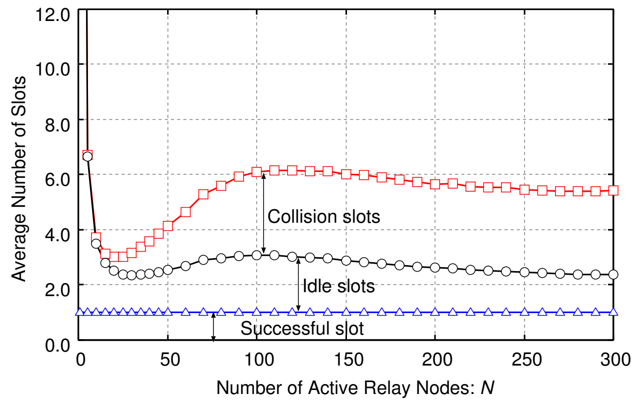


(c) with BEB for $CW_{min} = 16$

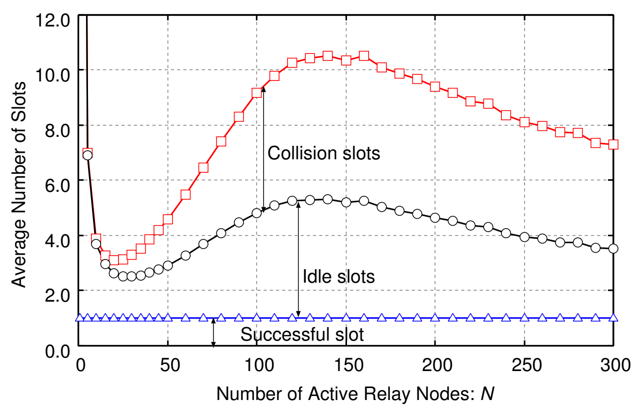


(d) with BEB for $CW_{min} = 32$

Figure 4. Average duration of cooperation phase with BEB algorithm for $CW_{min} = 4, 8, 16, 32$ and $D = 1, 3, 5, 7$.

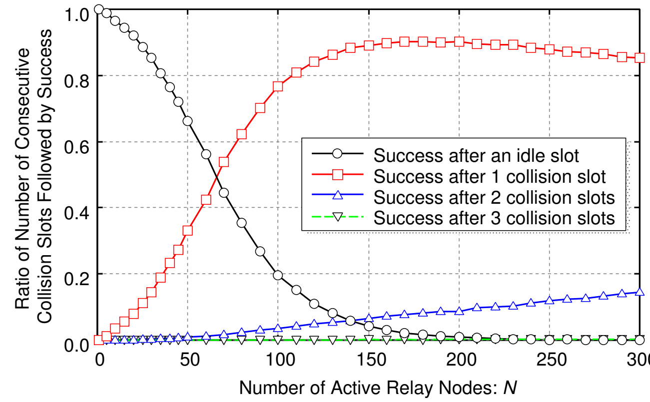


(a) without BEB

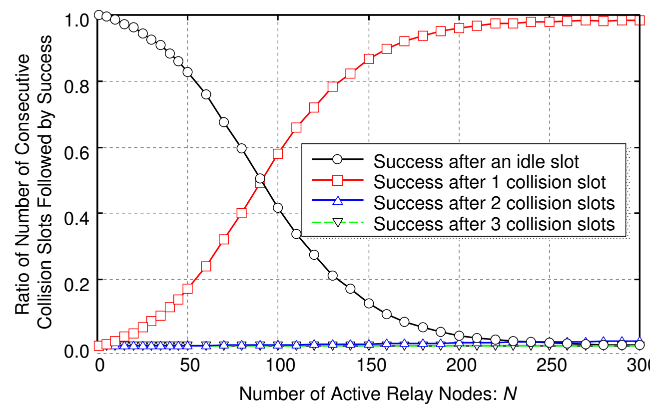


(b) with BEB

Figure 5. Distribution of average number of slots in cooperation phase for $\mathrm{CW}_{\min} = 8$ and $D = 7$.



(a) without BEB



(b) with BEB

Figure 6. Ratio of the number of consecutive collisions followed by successful DATA frame transmission of the proposed protocol and the original PRCSMA for $\mathrm{CW}_{\min} = 8$ and $D = 7$.

succeed in transmission, and then the BEB algorithm should be invoked.

B. Slot Distribution

In order to reveal the reason why the adoption of the BEB algorithm may bring about longer unnecessary time before the first success of frame transmission, we examine the average number of virtual slots in a cooperation phase. Since channel errors between relay nodes and destination node are ignored, virtual slots can be classified into idle, collision, and successful slots, where every cooperation phase ends with a unique successful slot.

We examine the distribution of the number of slots in a cooperation phase in average. The numerical results are shown in Figure 5 for the case of $\mathrm{CW}_{\min} = 8$ and $D = 7$. The results with no BEB algorithm are given in Figure 5(a) and those with the BEB algorithm, in Figure 5(b). Comparing two graphs in Figure 5, we can find that the number of collision slots and idle slots in Figure 5(b) increases for $N > 50$. For $\mathrm{CW}_{\min} = 8$ and $D = 7$, $N/7$ relay nodes start a cooperation phase with $\mathrm{CW} = 8$. If N is less than 50, about seven relay nodes start with $\mathrm{CW} = 8$ and other relay nodes, with $\mathrm{CW} \in \{16, \ldots, 1024\}$. Therefore, the probability of frame collision may be small, since the most possible collision among relay nodes with $\mathrm{CW} = 8$ may be rare. For $N > 50$, the probability of frame collision can be expected to increase, which causes a necessity of frame retransmissions. Recall here that according to Foh and Tantra's method [9], only the relay nodes involved frame collision are permitted to retransmit their frame in the next time slot, if their new backoff counter is zero. It implies that the possibility of consecutive occurrence of frame collision in the time slot following frame collision can be mitigated. However, the doubling process of CW values in the BEB algorithm may decrease the possibility to randomly select zero backoff counter, compared to the case without the BEB algorithm.

C. Consecutive Frame Collisions

Next, we evaluate the number of consecutive frame collisions followed by a successful DATA frame transmission, which entails the end of the cooperation phase.

In Figure 6, the ratio of the number of consecutive frame collision slots followed by successful DATA frame transmission is shown for the proposed protocol and the original PRCSMA for $\mathrm{CW}_{\min} = 8$ and $D = 7$ with and without the BEB algorithm. The results with no BEB algorithm are given in Figure 6(a) and those with the BEB algorithm, in Figure 6(b). An illustrative description of the number of consecutive collisions followed by successful frame transmission is shown in Figure 7. It follows from Figure 6(a) that in the case of with no BEB algorithm, the ratio of successful DATA frame transmission following an isolated frame collision slot after an idle slot; red curve, increases faster than the case with the BEB algorithm for $50 < N < 150$. For $N > 150$, red curve for the case with the BEB algorithm is greater than that for the

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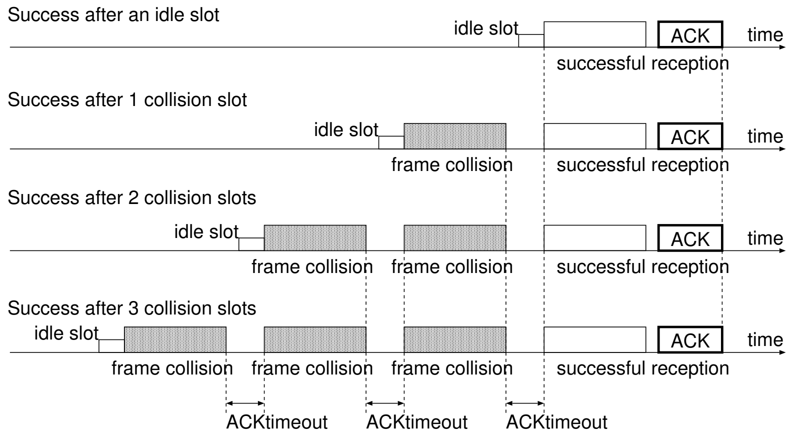

Figure 7. Description of the number of consecutive frame collisions followed by successful DATA frame transmission in Figure 6.

case without BEB algorithm. However, since the possibility of two or more consecutive frame collisions decreases in the case with the BEB algorithm, the corresponding curves; blue and black curves, are almost zero. This means that a number of idle slots are inserted in the case of BEB algorithm before successful frame transmission.

VI. Conclusion and Future Work

Random assigning of the initial CW value of each relay node at the beginning of cooperation phase has been proposed in PRCSMA. Each relay node independently and randomly selects its initial CW value among a predefined set of integers, while in the original PRCSMA, a relay node fixes its CW value to a common integer. Numerical results obtained from computer simulation have revealed that the proposed protocol can improve the performance of the original PRCSMA. The proposed protocol makes it possible to reduce the possibility of frame collisions among relay nodes before successful frame transmission which completes a cooperation phase. Also, the results demonstrate that the binary exponential backoff algorithm degrades the performance of PRCSMA.

Further work includes, for example, the extension to bidirectional communication systems and to the use of network coding. Also, the theoretical analysis through appropriate mathematical modeling of the proposed protocol should be investigated.

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