# Effect of Random Assigning of Initial Contention Window Value on Performance of Persistent Relay CSMA with and without Binary Exponential Backoff Algorithm

KATSUMI SAKAKIBARA NAOYA YODA KENTO TAKABAYASHI
Department of Information and Communication Engineering
Okayama Prefectural University
111, Kuboki, Soja, 719-1197
JAPAN
{sakaki, cd29046m, kent.hf}@c.oka-pu.ac.jp

*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 and evaluate its performance with and without binary exponential baskoff (BEB) algorithm. 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 BEB algorithm is inefficient for PRCSMA, since it introduces redundant idle slots and more collision slots before the first success of frame transmission.

*Key–Words:* Persistent relay CSMA, Wireless LAN, Simulation, Contention window

## 1 Introduction

Compensation for poor quality of radio channels is imperative, as explosive magnification of demands for wireless communications of higher speed and quality. In such scenarios, cooperative communications with relay nodes have been recognized as one of effective and promising techniques in wireless/mobile communication systems. Some standards incorporating cooperative relay nodes are on the way to successful implementation in Long Term Evolution (LTE)-Advanced by the Third Generation Partnership Project (3GPP) [1], [2] and 802.16 by IEEE [3]–[5]. Relay techniques have been enthusiastically investigated from the viewpoint of the physical (PHY) and data-link layers [4], [6], [7]. In PHY layer perspective, Multiple-Input and Multiple-Output (MIMO) and diversity techniques are attractive [7]. In the data-link layer perspective, a number of Cooperative Automatic Repeat reQuest (C-ARQ) protocols have been proposed and analyzed. When two or more relay nodes collaborate on an identical radio channel, it is apparent that the design of Medium Access Control (MAC) protocols employed between relay nodes and the destination node influences the performance.

Not a few protocols for C-ARQ systems have been proposed recently. Dianati et al. [8] 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 [9] 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). Based on Markov chain theory, Berber et al. presented a new approach to calculate the channel capacity of a multi-relay communication system [10]. In [11], 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. [12], [13] proposed Persistent Relay CSMA (PRCSMA), which elaborately incorporates well-known IEEE 802.11 Distributed Coordination Function (DCF) [14]; de facto standard for wireless LANs. In [12], the performance of PRCSMA was analyzed in terms of the average duration of cooperation, based on a two-dimensional

Markovian model which was proposed for analyzing the steady-state performance of IEEE 802.11 DCF by Bianchi [15]. It was assumed that all the relay nodes possess an identical value of CW and that the value of CW was fixed to its initial value during the cooperation phase; that is, no doubling operation of CW values was employed in contrast to IEEE 802.11 DCF [12]. From the viewpoint of the steady-state performance analysis of IEEE 802.11 DCF, Foh and Tantra presented an accurate three-dimensional Markovian model [16], which took into account a carry-over operation of backoff counter freezing after collision period. In [16], the accuracy of the new model is verified by computer simulation. The accuracy of Foh and Tantra's model was further improved in [17]. Difficulties in analyzing the transient performance of IEEE 802.11 DCF are mentioned in [18]. Note here that the protocol with CSMA/CA in [9] is equivalent to the original PRCSMA [12] and that the protocol with round-robin in [9] requires overhead to obtain the number of relay nodes. Other protocols assume either only one relay node [8], or no MAC protocols [10], [11]. Recently, the authors showed that by carrying over backoff counter freezing after collision period, we can improve the performance of PRCSMA [19], [20].

In this paper, we propose random assigning of the initial CW value of each relay node at the beginning of cooperation phase and investigate its effect on the performance of PRCSMA with and without Binary Exponential Backoff (BEB) algorithm. At the beginning of cooperation phase, 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 may make 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 2 presents a system model with relay nodes. The operation of PRCSMA is briefly reviewed in Section 3. In Section 4, 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 5. Finally, Section 6 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

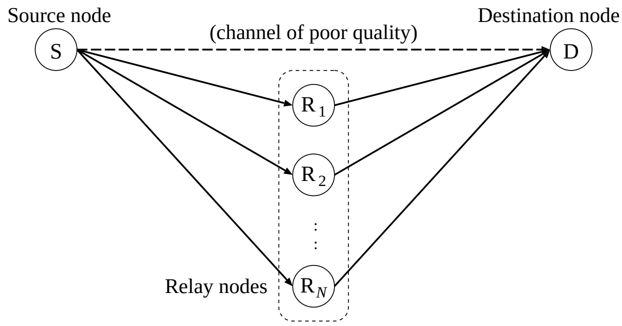



Figure 1: System model with $N$ relay nodes.

nodes; $\mathrm{R}_1$, $\mathrm{R}_2, \ldots,$ $\mathrm{R}_N$, as shown in Fig. 1. Channel quality between source and destination nodes is assumed to be poor. Thus, an information frame is transfered from source node S to destination node D by way of relay nodes. 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. 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. The duration in which relay nodes collaborate frame retransmissions is referred to as a *cooperation phase* [12]. 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.

# 3 PRCSMA

PRCSMA [12] [13] is a MAC protocol which elaborately resolves frame collisions among transmission from relay nodes to destination node D, based on IEEE 802.11 DCF [14]. 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 $\mathrm{CW} = w$, 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 [12]. After erroneous reception of a DATA frame transmitted by source node S, destination node D broadcasts a Call For Cooperation (CFC) frame following the

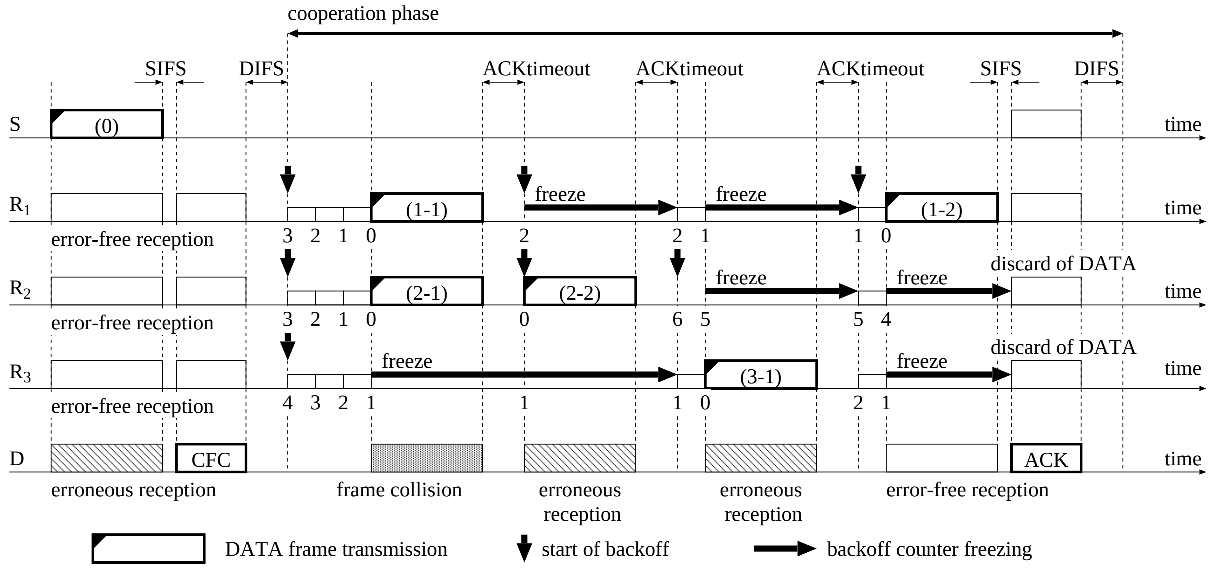



Figure 2: Illustrative example of PRCSMA with decrement of backoff counter according to Foh & Tantra's method [16].

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 such as a CFC frame to those of data frames [14]. 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 but also completion of the cooperation phase to all the nodes.

In the original PRCSMA [12], the decrement of backoff counter at each relay node follows the method considered in [15]. In [20], the authors showed that by adopting the method in [16], the duration of the cooperation phase can be greatly decreased. Therefore, we consider the method in [16] hereafter.

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 a CFC frame from destination node D, which follows an erroneous reception of DATA frame (0). In Fig. 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 [16], 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.

## 4 Random Assigning of Initial CW Value

In PRCSMA, no specific backoff algorithm such as the 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. [12] and Predojev et al. [13] 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 random assigning of the initial CW value 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 $D = 7$. 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 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 $\mathrm{CW}_{\min}$.

# 5 Numerical Results

We evaluate the performance of the proposed protocol; random assigning of the initial CW values described in Section 4, in terms of the average duration of cooperation phase by means of exhaustive computer simulation. Comparisons with the original PRCSMA, in which all the relay nodes fix their CW value to an identical integer, 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; referred to as *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; named as *with BEB*. Simulation program is written in C language and the results are obtained by averaging $2 \times 10^4$ trials of cooperation phases. Each trail starts with $N$ active relay nodes, which corresponds to the case 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 1, which are basically taken from IEEE 802.11a standard [14]. The values of $\mathrm{CW}_{\min}$ are taken by referring to IEEE 802.11e standard. Channels between relay node $\mathrm{R}_n$ and destination node D are assumed error-free for any $n = 1, 2, \ldots, N$. Hence, frame transmission from an active relay node succeeds if it experiences no other simultaneous frame transmissions.

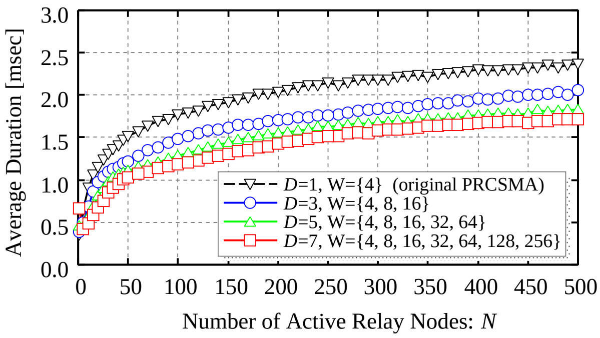
Table 1: Parameters used in simulations

| | |
|---|---|
| data rate | 54 [Mbps] |
| control frame rate | 6 [Mbps] |
| slot duration | 9 [$\mu$sec] |
| SIFS duration | 16 [$\mu$sec] |
| DIFS duration | 34 [$\mu$sec] |
| ACKtimeout | 34 [$\mu$sec] |
| round-trip time | 0 [$\mu$sec] |
| PHY header length | 20 [$\mu$sec] |
| 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 |

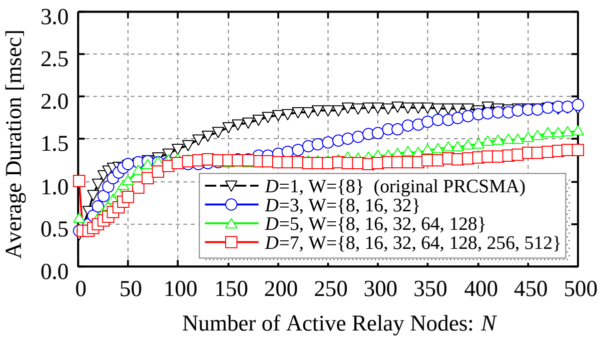
## 5.1 Average Duration of Cooperation Phase

The average duration of cooperation phase of the proposed protocol and the original PRCSMA ($D = 1$) is shown in Fig. 3 and Fig. 4. In Fig. 3, no BEB algorithm is employed, so that each relay node holds the assigned initial CW value after frame collision. In Fig. 4, each relay node doubles its CW value unless it is greater than $\mathrm{CW}_{\max}$. Shorter duration of cooperation phase is preferred, since source node S can move to the next data transmission rapidly.

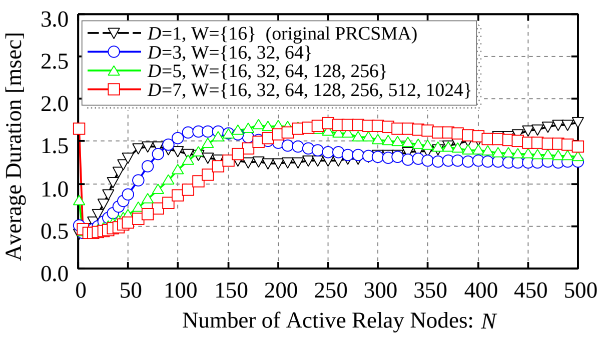
First, let us roughly compare the performance between the proposed protocol and the original PRCSMA. If the number of active relay nodes $N$ is small, then the proposed protocol for large $D$ is preferred.



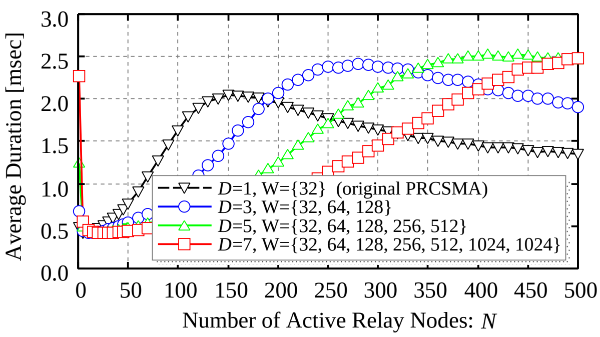

(a) without BEB for $\mathrm{CW}_{\min} = 4$




(b) without BEB for $\mathrm{CW}_{\min} = 8$

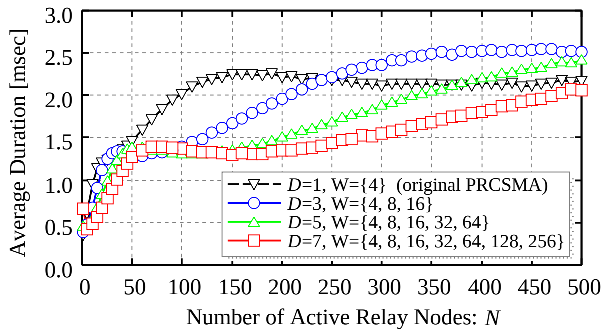



(c) without BEB for $\mathrm{CW}_{\min} = 16$

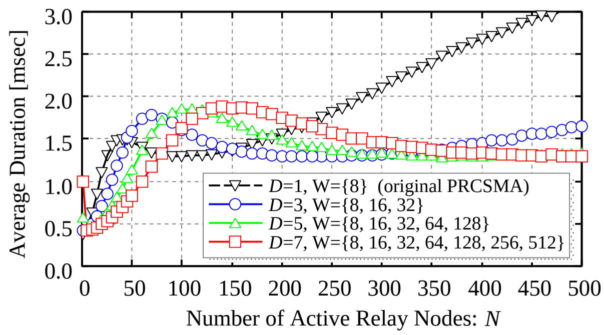



(d) without BEB for $\mathrm{CW}_{\min} = 32$

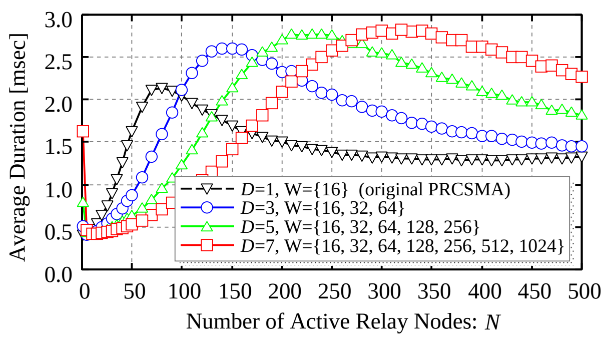
Figure 3: Average duration of cooperation phase without BEB algorithm for $\mathrm{CW}_{\min} = 4, 8, 16, 32$ and $D = 1, 3, 5, 7$.



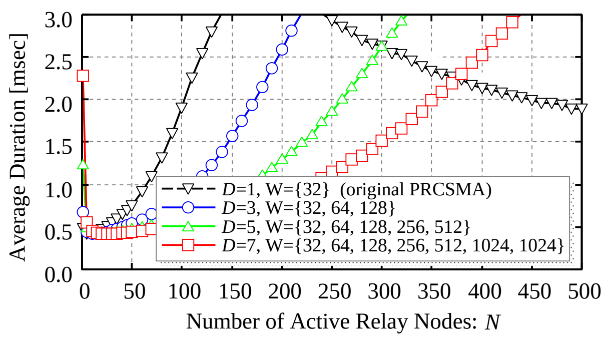

(a) with BEB for $\mathrm{CW}_{\min} = 4$




(b) with BEB for $\mathrm{CW}_{\min} = 8$




(c) with BEB for $\mathrm{CW}_{\min} = 16$



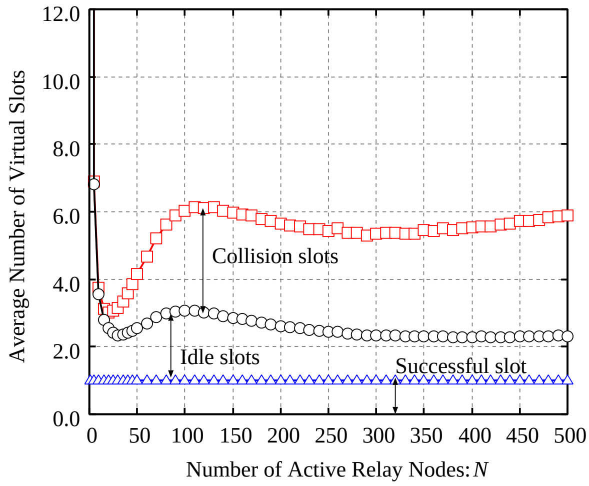

(d) with BEB for $\mathrm{CW}_{\min} = 32$

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

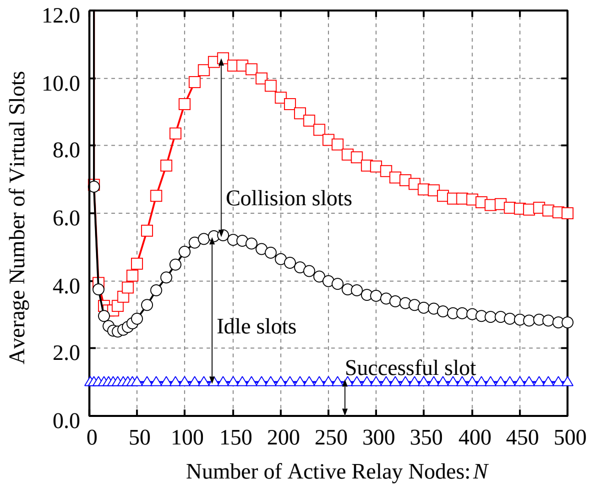
On the other hand, if $N$ is large, the original PRCSMA exhibits small average duration of cooperation phase. In the proposed protocol with large $D$, a small fraction of active relay nodes with small initial CW value contends for the channel in the beginning of cooperation phase. Therefore, the possibility of successful frame transmission increases for small $N$, while it may decrease due to frame collision for large $N$. To view Fig. 3 and Fig. 4 as a whole widely, we can observe that the proposed protocol for $\mathrm{CW_{min}} = 8$ and $D = 7$ without BEB algorithm indicates best average duration of cooperation phase, which is stable for wide range of the number of active relay nodes. In this case, we have

$$\mathcal{W} = \{8,\ 16,\ 32,\ 64,\ 128,\ 256,\ 512\}. \quad (4)$$

Next, compare the performance of the protocols 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 in IEEE 802.11 DCF has been widely known and analyzed in the literature [15]–[17]. 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 Fig. 3 and Fig. 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 succeed in transmission, and then the BEB algorithm should be invoked.




(a) without BEB



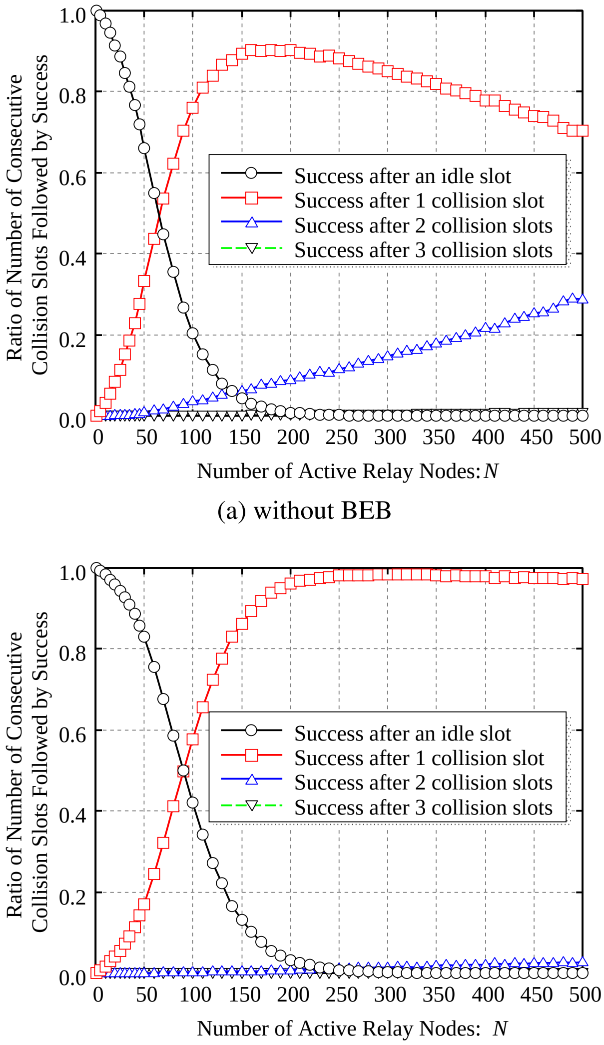

(b) with BEB

Figure 5: Average number of virtual slots in cooperation phase for $\mathrm{CW_{min}} = 8$ and $D = 7$.

## 5.2 Slot Distribution in Cooperation Phase

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 occurs, we examine the distribution of 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.

The average number of virtual slots in a cooperation phase is shown in Fig. 5 for the case of $\mathrm{CW_{min}} = 8$ and $D = 7$. The results without BEB algorithm are given in Fig. 5(a) and those with the BEB algorithm, in Fig. 5(b). Comparing two graphs in Fig. 5, we can find that the number of collision slots and idle slots in Fig. 5(b) increases for $N > 50$. For $\mathrm{CW_{min}} = 8$ and $D = 7$, where a set of initial CW values $\mathcal{W}$ is given in (4), $N/7$ active relay nodes start a cooperation phase with $\mathrm{CW} = 8$. If $N$ is less than 50, approximately seven relay nodes start with $\mathrm{CW} = 8$ and other active relay nodes, with $\mathrm{CW} \in \{16, \ldots, 512\}$. Therefore, the probability of frame collision may be small, since the most possible collision among active 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. For the case with the BEB algorithm, this brings more idle and collision slots, compared to the case without the BEB algorithm. Recall here that according to Foh and Tantra's method [16], 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 [20]. In fact, from Fig. 5(b) the average number of idle slots with the BEB algorithm decrease for $N > 150$, which




(a) without BEB

(b) with BEB

Figure 6: Ratio of corporation phases classified according to 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 $D = 7$.

results in slight improvement of the average duration of corporation phase, as shown in Fig. 4(b). 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.

### 5.3 Consecutive Frame Collisions

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

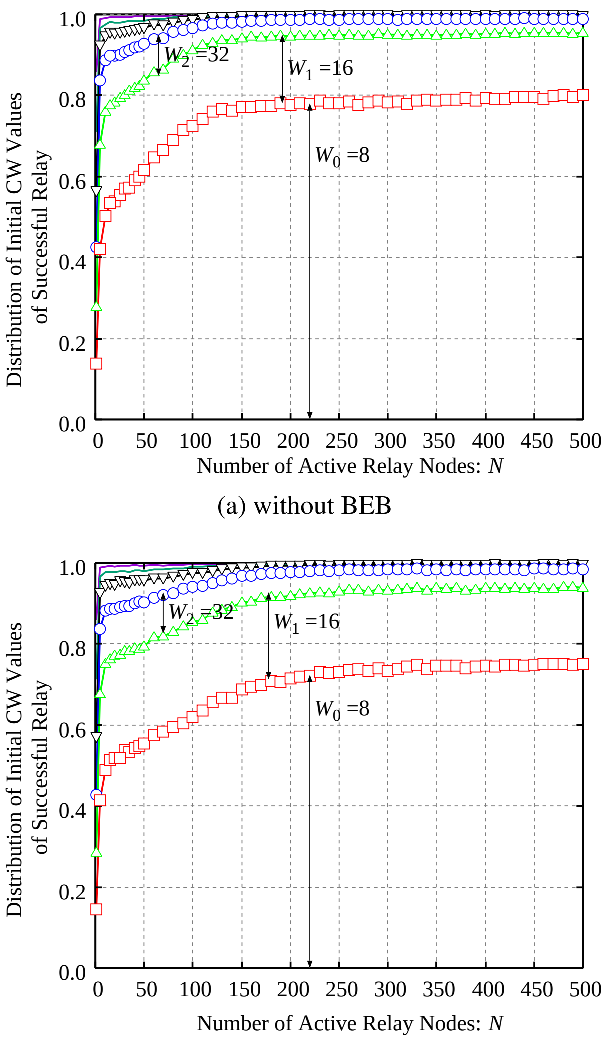
In Fig. 6, the ratio of corporation phases classified according to the number of consecutive frame collision slots followed by successful DATA frame transmission of the proposed protocol with and without the BEB algorithm is shown for $\mathrm{CW}_{\min} = 8$ and $D = 7$. The results without BEB algorithm are given in Fig. 6(a) and those with the BEB algorithm, in Fig. 6(b). It follows from Fig. 6(a) that in the case without BEB algorithm, the ratio of corporation phases with 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 $N < 150$. For $N > 150$, red curve for the case with the BEB algorithm is greater than that for the 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 implies that a number of idle slots are inserted in the case with the BEB algorithm before successful frame transmission.

### 5.4 Distribution of Initial CW Value of Successful Relay Nodes

Finally, we examine the initial CW value of successful active relay node. The distribution of the initial CW values of successful active relay nodes is given in Fig. 7. The results without BEB algorithm are given in Fig. 7(a) and those with the BEB algorithm, in Fig. 7(b). Comparing both graphs, the ratio that an active relay node with initial $\mathrm{CW} = 8$ succeeds is greater for the case without the BEB algorithm. For $N > 150$ and without BEB, 80% of corporation phases are completed by an active relay node with initial $\mathrm{CW} = 8$. For the case with BEB, the doubling process for an active relay node with initial $\mathrm{CW} = 8$ defers the next retransmission of the relay node. In the interim, another relay node with initial $\mathrm{CW} = 16$ or more may succeeds.

## 6 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. The effect of the BEB algorithm on the performance of PRCSMA is also investigated. 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 success-




(a) without BEB



(b) with BEB

Figure 7: Distribution of the initial CW values of successful relay nodes for $\mathrm{CW}_{\min} = 8$ and $D = 7$.

ful 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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