Performance Analysis of a Novel Distributed C-ARQ Scheme for IEEE 802.11 Wireless Networks

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Abstract

It is well-known that the cooperative communication and error control technology can improve the network performance, but most existing cooperative MAC protocols have not focused on how to cope with the contention process caused by cooperation and how to reduce the bad influence of channel packet error rate on the system performance. Inspired by this, this paper first modifies and improves the basic rules of the IEEE 802.11 Medium Access Control (MAC) protocol to optimize the contention among the multi-relay in a cooperative ARQ scheme. Secondly, a hybrid ARQ protocol with soft combining is adopted to make full use of the effective information in the error data packet and hence improve the ability of the receiver to decode the data packet correctly. The closed expressions of network performance including throughput and average packet transmission delay in a saturated network are then analyzed and derived by establishing a dedicated two-dimensional Markov model and solving its steady-state distribution. Finally, the performance evaluation and superiority of the proposed protocol are validated in different representative study cases through MATLAB simulations.

Keywords: IEEE 802.11, MAC protocol, cooperative ARQ, super PRCSMA, multi-relay, two-dimensional Markov model

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1. Introduction

IEEE 802.11 standard has become one of the most popular network transmission standards to support infrastructure Wireless Local Networks (WLANs) with Access Point (AP) and wireless *ad hoc* networks without AP for its cheap, convenience and flexibility. The Medium Access Control (MAC) layer in the Open System Interconnection (OSI) model is very importint because it determines the time when a wireless user accesses the channel, i.e., the prominent element for the success of IEEE 802.11 is its MAC protocol that provides robust and adaptive schemes, which can be tailored to varing conditons[1]. MAC protocols can be classified as polling-based and contention-based methods according to the different access modes, i.e., Point Coordination Function (PCF) and Distributed Coordination Function (DCF). However, PCF is not widely deployed because of its complexity and inefficiency, In contrast, DCF using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) has become the most widely studied and used basic access mode both in infrastructure wireless networks and *ad hoc* wireless networks. More detailed description of IEEE 802.11 can be found in [2].

With the increasing demand of wireless users for emerging multimedia services and related Quality of Service (QoS), the wireless communication environment is becoming more and more diversified and complicated. The innate drawbacks of the wireless channel, such as the signal fading or path loss caused by the buildings or distance between any source and its destination, can considerably degrade the performance of a wireless network. How to overcome the poor channel conditions to meet the needs of wireless users for QoS has become one of the most urgent problems to be solved. As an effective and popular anti-fading technology, the Cooperative Communication (CC) [3], which exploits the broadcast nature of the radio channel, mainly introduces a relay (R) to assist a source (S) in communicatng with its destination (D) by asking R to forward D an amplified, compressed or recoded copy of the original data received correctly from S, a virtual Multiple Input Multiple Output (MIMO) system which can provide cooperative diversity is formed without actually requiring the deployment of physical antenna arrays and enables D to reconstruct a weak signal by properly combining multiple copies obtained from various independent transmission paths. So CC can not only improve the performance of communication networks but also enhance the reliability of communication link, playing a vital role in future standardization bodies.

However, since the introduction of relays in CC breaks the traditional point-to-point communication mode of non-cooperative wireless networks, the IEEE 802.11 MAC protocol shows obvious deficiencies in CC mode. In order to maximize the gain brought by CC, a large number of improved cooperative MAC protocols based on IEEE 802.11 have been proposed in recent years. Some representative state-of-the-art protocols and their basic ideas are summarized in **Fig. 1** and classified in **Fig. 2** according to [1].

From **Fig. 2**, because the idle time slots brought by backoff mechanism at every contention period is one of the major factors that cause the performance degradation of 802.11 wireless networks, in the BTC category which aims at optimizing the backoff window, both C-MAC[4] and CR-TDMA[12] protocol reduce the number of idle slots and improve the system performance and fairness by modifying the backoff window. For instance, the backoff counters in C-MAC[4] protocol are divided into two types: the one for collided nodes and the one for non-collided nodes based on the principle that the collided nodes have a higher priority than the other nodes in the light of transmitting packets. Although it shows that C-MAC outperforms the IEEE 802.11 DCF in the aspect of short-term fairness and throughput, a detailed backoff mechanism algorithm needs to be designed in BTC category, increasing the complexity of network software programs.

- **2004** — Cetinkaya. C and Orsun. F [4] proposed the Cooperative Medium Access Protocol for Dense Wireless Networks (**C-MAC**) to mainly address the short term fairness and throughput degradation in dense wireless networks.
- **2005** — Sai S N, Chou C T and Ghosh M [5] presented both the Cooperative-MAC (**CMAC**) and Forward Error Correction CMAC (**FCMAC**) protocols in the context of 802.11e networks to enhance the system performance and robustness.
- **2006** — Dianati M and Ling X *et al.* [6] studied the Node Cooperative Stop and Wait (**NCSW**) protocol to improve the performance of the ARQ schemes for wireless *ad hoc* networks.
- **2007** — Liu P and Tao Z *et al.* [7] designed two versions of the Cooperative MAC (**CoopMAC**) protocol in 802.11b WLANs to solve the performance anomaly problem caused by the DCF multi-rate capability by introducing a CoopTable that stores a lot of system information used to make decisions on cooperation.
- **2008** / **2009** — Alonso-Zárate J *et al.* [8] conceived the Persistent Relay Carrier Sense Multiple Access (**PRCSMA**) protocol which allows distributed ARQ schemes and further analyzed it in [9] to improve performance and extend communication coverage by studying the contention process and avoiding collisions among active relays.
- **2010** — Hu Z and Tham C K [10] surveyed the Coordinated Cooperative MAC (**CCMAC**), which considers the concurrent cooperative transmission for uplink from nodes to Access Point (AP), supports three different transmission modes: basic, half and enhanced modes according to the channel conditions and the status of relays.
- **2013** — Nischal S and Sharma V [11] proposed the Cooperative Opportunistic ARQ (**COARQ**) protocol for downlink from AP to clients in an infrastructure WLAN. Results show an significant throughput improvement in AP compared with the IEEE 802.11 DCF.
- **2014** — Lee J K, Noh H J and Lim J. [12] proposed and analyzed a Cooperative Relaying Time Division Multiple Access (**CR-TDMA**) MAC protocol for wireless multi-hop relaying networks to reduce channel waste by allowing a packet which is pre-assigned to a busy relay to be reassigned to a neighbor node with an empty queue.
- **2015** — Liu K, Chang X and Liu F *et al.* [13] focused on a Cooperative MAC protocol with Rapid Relay Selection (**RRS-CMAC**) to improve the cooperation efficiency and multiple access performance in wireless *ad hoc* networks.
- **2016** — Mahmud M T, Rahman M T and Rahman M O, *et al.* [14] designed a Distance-Aware Data Rate Adaptive Cooperative (**D^{2}RAC**) MAC protocol for wireless cooperative networks to ensure a higher reliability, data rate and lower delay by using two distance thresholds to select the optimal relay and exploiting the residual energy of nodes to balance the energy consumption between nodes.
- **2017** — Zhang X, Guo L and Anpalagan A *et al.* [15] presented an Energy-Efficient Cooperative MAC (**EECO-MAC**) protocol using power control in mobile *ad hoc* networks and a best partnership selection algorithm was proposed.

Fig. 1. Timeline of cooperative MAC protocols in IEEE 802.11

On the other hand, since the most significant advantage of CC is that two-hop transmissions at a faster data rate (by using relays) can be used to replace the slower single-hop (direct transmission from S to D), most existing works belong to the Min-TX category which is devoted to minimize packet transmission delay by selecting the optimal relays, such as CoopMAC[7], D^{2}RAC-MAC[14] and EECO-MAC[15] protocol and so on. The cooperative MAC protocols in this category usually require the support of other technologies such as power control [15], concurrent cooperative transmission [10] and the introduction of CoopTable [7]. For example, CoopMAC protocol enables nodes to measure their Signal-to-Noise Ratio (SNR), estimate relative distances and select the modulation scheme by creating a CoopTable, which stores information such as the transmission rates from S to R (and R to D), the MAC addresses of potential relay node and the update time of CoopTable, for each node in the network. When S has packets to send, it can search the CoopTable to select the bset candidate. Although CoopMAC gives beter results in terms of throughput and access delay, it comes at the cost of extra system overhead caused by the generation and maintenance of CoopTable. It is obvious that cooperative MAC protocols in this category not only require the receiver to obtain a better network information, such as the Channel State Information (CSI) and Received Signal Strength Indicator (RSSI), but also have higher requirements on hardware devices of the communication network, which cannot be met sometimes in practical applications.

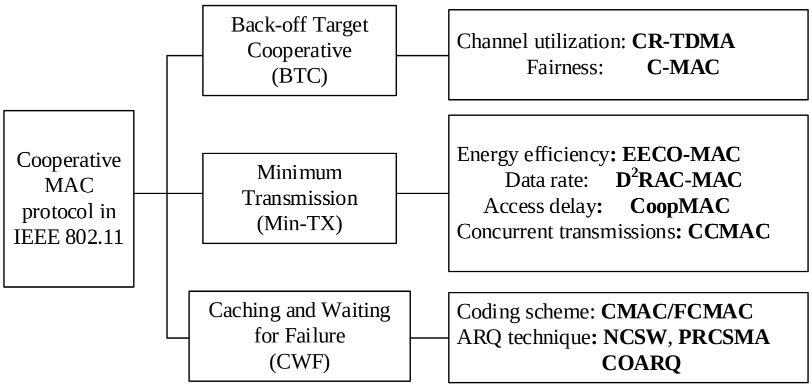


Fig. 2. Classification of cooperative MAC protocols in IEEE 802.11

The above protocols are aimed at solving some interesting cooperative issues, while none of them have been designed to implement the distributed cooperative ARQ schemes in wireless networks, protocols designed for this purpose mainly includes CMAC (FCMAC)[5], NCSW [6] and PRCSMA[8] protocol in CWF category (COARQ protocol is designed for infrastructure WLANs). The main operation of CWF is to exploit the nature that neighbor nodes sense the transmission from S to D, if D broadcasts a Negative ACKnowledgment (NACK), the cooperation is triggered and neighbor nodes execute retransmission to improve system performance. CMAC (FCMAC) [5] uses Forward Error Correction (FEC) and retransmission combining techniques to enhance robustness and ensure a certain QoS in cooperation, NCSW[6] proves a cooperation among a small number of nodes can signficantly improve the throughput, average delay and delay jitter by establishing a two-state Markovian process, but both of them do not consider the contention process caused by multiple relays contend for the access to channel, which is important in distributed cooperative scheme. To the best of our knowledge, PRCSMA[8] is the first cooperative MAC protocol designed for this purpose. The seminal idea of PRCSMA originates from the Multiple Relay Access Control (MRAC) protocol[16] proposed by Alonso-Zárate J *et al.* in 2006 and the further analysis is shown in [9]. However, there are some obvious defects existing in PRCSMA. Fistly, in the aspect of the details of the protocol, [8] just assumes that the relays use the last value of the backoff counter for a new cooperation phase, which is not reasonable because the IEEE 802.11 backoff mechanism stipulates that the relay should reset its backoff counter right after a successful transmission. Secondly, in terms of system modeling, [8] just uses the existing embedded two-dimensional Markov chain model, which does not consider the state that the backoff is frozen, of Wu *et al.*[17], obviously lacking the accuracy for modeling the PRCSMA protocol. Although a dedicated model was established for PRCSMA protocol in [9], it just is a simple one-dimensional embedded Markov chain by defining the size of the contention window as constant W and ignoring the analysis of the backoff stage. Finally, in the light of performance evaluation, both [8] and [9] only take the average packet transmission delay as the single performance index to be calculated and simulated, but other indicators are not involved in disscusion.

On the other hand, it is known that both FEC and ARQ are two commonly used error control technologies for Data Link Layer (DLL) in wireless networks, and their combination, i.e., Hybrid ARQ (HARQ) protocol[18], is put forward to combat the higher Packet Error Rate (PER) caused by poor channel conditions. Moreover, unlike ARQ which directly discards the error packets and requests a retransmission of correct one, HARQ with soft combining[19,20] can make full use of the effective information in each error packet received by D to achieve a more reliable diversity combining gain than ARQ by asking D to store the error packet into buffer and jointly decode it with packets obtained subsequently. It is obvious that HARQ can achieve a higher performance, but up to the knowledge of us, no cooperative MAC protocol with HARQ has been proposed in existing works yet.

Consequently, this paper, inspired by these ideas, proposes an enhanced distributed C-ARQ scheme—SPRCSMA (Super PRCSMA) as the IEEE 802.11 standard cooperative MAC protocol by utilizing the HARQ technology with soft combining and modifying the deficiencies of PRCSMA. Then the closed expressions of network performance including the throughput and the average packet transmission delay are derived by the theoretical analysis. Finally, the performance evaluation and superiority of SPRCSMA protocol are validated and compared with other schemes in some evaluation cases through MATLAB, providing strong theoretical support and basis for the design of the new network system.

The main contributions of this paper are the following:

1) A novel distributed C-ARQ scheme called SPRCSMA protocol is proposed from the perspective of optimizing the contention problem caused by multi-relay, which makes the transmission of network more efficient and flexible.

2) A dedicated two-dimensional Discrete Time Markov Chain (DTMC) model is presented for the SPRCSMA protocol, and two stochastic processes, the backoff stage and backoff counter, are examined simultaneously to describe the improved protocol more accurately.

3) The closed expressions of system throughput and average packet transmission delay are obtained by solving the steady-state distribution of the system.

4) The advantages of SPRCSMA over other protocols are verified and the effects of different initialized network parameters on system performance are investigated by different study cases, providing some theoretical references for future network designing.

The rest of this paper is organized as follows. Section 2 is fully devoted to the description and operational example of SPRCSMA. Section 3 presents the corresponding Markov chain and its related theoretical analysis. Throughput and average packet transmission delay are analyzed in Section 4. The numerical simulation results are presented in Section 5 to evaluate the performance of SPRCSMA protocol under different configurations and to compare with other schemes. Finally, we conclude the paper and give a few remarks in Section 6.

2. SPRCSMA Protocol

2.1 Protocol Description

This paper considers a saturated wireless network composed by a source (S), a destination (D) and any number of neighbor nodes (stations), where every terminal is equipped with one antenna and a half-duplex radio frequency transceiver. All neighbor nodes listen to each ongoing transmission to help failed transmission between S and D. We assume that the feedback channel is ideal and the PER is p_e, i.e., D receives an error packet with probability p_e. In the SPRCSMA protocol, those neighbor nodes which can overhear the original data packet from S correctly become active relays (R), try to get access to the channel by implementing the DCF and forward their cooperative packets in a persistent manner. Specifically, whenever D receives an error data packet from S, it stores the packet and broadcasts an AFC (Ask For Cooperation) message to initiate a cooperation phase in which active relays receiving AFC packet from D successfully form the so-called *relay set* and get ready to retransmit the packet copies in a time orthogonally way to assist the failed transmission. Retransmission is performed only by relays and they execute either the basic access mode or the collision avoidance (COLAV) mode during a cooperation phase. It is worth noting that the detailed relay selection strategy is beyond the scope of this paper and if there has no relay participates in the retransmission after the cooperation phase is initiated, i.e., there is no neighbor node can decode the data frame successfully in the previous time slots when D broadcasts AFC message, the retransmission is executed by S in the subsequent time slots until the emergence of active relays, but in order to study the contention process among multi-relay, this paper assumes that there always exist active relays after AFC broadcasting, that is, the cooperation phase must be initiated. Obviously, the contention among active relays will inevitably be incurred because they use the MAC rules based on the DCF, namely a station that has packets to transmit needs to listen to the channel for a Distributed Inter-Frame Space (DIFS) before trying to transmit. If the channel is sensed free, it transmits packets; otherwise the Binary Exponential Backoff (BEB) algorithm is executed. That is, the relay sets a randomized backoff counter within the interval $\left[0, W_i\right]$ where W_i represents the size of the backoff window at the *i*th backoff stage ($i \in \left[0, m\right]$, m is the maximum backoff stage) and the value is initially set to a predefined value W_0. The counter is decreased by one unit after each slot as long as the channel is idle. Whenever the timer expires, i.e., reaches zero, the station attempts a transmission. If the transmission successes, W_i will reset to the minimum size W_0 and a positive ACKnowledgment (ACK) will be sent back to S. However, once the transmission fails or encounters a collision, D will feed back a NACK and W_i will double up to reduce the probability of collision in subsequent transmission attempts, i.e., $W_i = 2^i W_0, W_{\max} = 2^m W_0$. R keeps retransmitting the packet copies to D until its retransmission number reaches the predefined maximum number $N_{\max}$ (we will discuss the impact of the different values of m and $N_{\max}$ on the system performance in section 3.1). Both R and D will discard the packet if D still fails to decode the original data packet after the $N_{\max}$th retransmission and D will report to the upper layer.

According to the above operation of SPRCSMA protocol, some modifications based on the basic rules of the IEEE 802.11 DCF are proposed as follows:

1) The AFC packet can be obtained by marking the empty field for address 4 of CTS packet to differentiate the normal CTS.

2) Because of using HARQ technology with soft combining, R does not need feedback message (i.e., ACK/NACK) from D for each retransmission in the cooperation phase.

3) R will reset the value of their backoff counter when a new cooperation phase is initiated.

2.2 Operational Example

Compared to the operational process of IEEE 802.11 DCF shown in **Fig. 3**, an operational example of SPRCSMA is presented in **Fig. 4** to elaborate this improved protocol more directly. In **Fig. 3** and **Fig. 4**, we assume that D can decode the original packet after active relays successfully retransmit copies twice, i.e., $K = 2$.

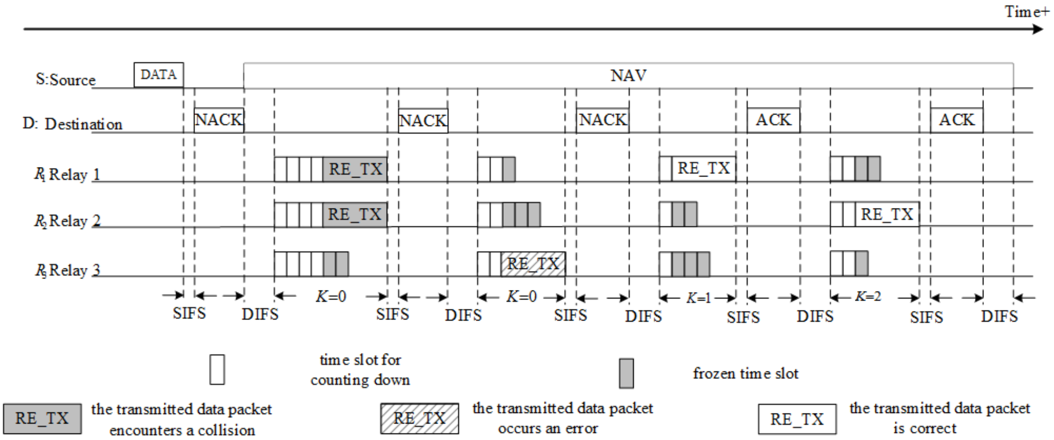


Fig. 3. An operational example of original DCF scheme in IEEE 802.11 MAC protocol

In **Fig. 4**, there are 5 stations in a network: a pair of communication nodes S and D is assisted by three active relays (R_1, R_2 and R_3) and all of them are in the transmission range of each other. We assume that the direct transmission from S to D is bound to unsuccessful, i.e., the cooperation phase must be initiated. Initially, S transmits a data packet to D. After a Short Inter-Frame Space (SIFS), an AFC packet is broadcasted by D to initiate a cooperation phase. Three active relays select a random value within the range of $(0, W_0 - 1)$ for their respective backoff counters. In this example, R_1, R_2 and R_3 select the value 4, 4 and 6, respectively. Therefore, after 4 time slots, R_1, R_2 attempt to retransmit simultaneously and a collision occurs, and R_3 freezes the value of the remaining counter (2), which proves to be a failed retransmission ($K = 0$). After a DIFS, R_1, R_2 reselect at random the value of their backoff counters from $(0, W_1 - 1)$ to attempt a new transmission (3,5 respectively) and R_3 resumes its backoff counter to continue the retransmission. Obviously, after 2 slots, the backoff counter of R_3 expires firstly and it retransmits a packet, although it is an error packet copy, unlike 802.11 DCF and PRCSMA protocols where D discards this copy directly and requests a completely correct packet, D in SPRCSMA stores the error one into buffer to utilize the useful information in the error copy and jointly decode the original packet with copies received subsequently, i.e., the error copy also represents a partially successful retransmission in SPRCSMA. As for R_1 and R_2, they freeze their countdown because the channel is occupied by R_3. Similarly, after a DIFS which is used to ensure that no ACK has been sent by D, R_3 reselects its backoff counters (4) and R_1, R_2 resume their remaining value (1 and 3 respectively). This time, R_3 is the fastest one who hits zero and thus completes the second transmission ($K=2$). Finally, D broadcasts an ACK packet to acknowledge the reception of the original packet and inform the end of the cooperation phase because it can decode the original packet by properly combining the information of the original transmission from S plus the two retransmissions from R_1 and R_3. This indicates that S has transmitted a packet to D, and then it will send the next packet to D in the subsequent slots.

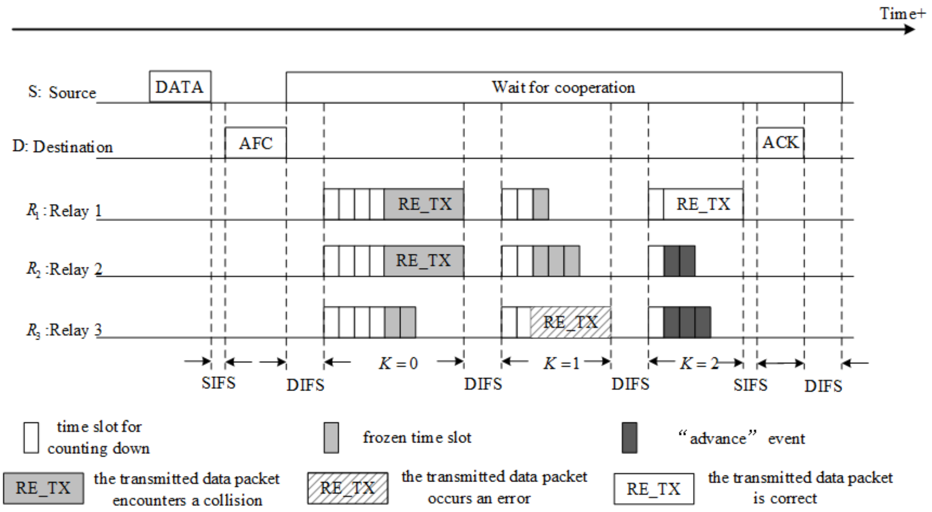


Fig. 4. An operational example of SPRCSMA

Unlike the IEEE 802.11 DCF, however, there appears a special event in SPRCSMA. As described in **Fig. 4**, when R_1 retransmits the second packet successfully, which meets the requirement for completing the cooperation phase (i.e., $K=2$), R_2 and R_3 no longer need to count down the remaining window values (2 and 3, respectively), but they reset directly by reselecting a new value from $(0, W_0 - 1)$ to prepare for the next cooperation phase. In other words, there exists an event that the cooperation phase is completed in advance before the backoff counter counts down to zero. According, we name this event as "advance" event and represent it with probability p_{ec}.

Obviously, $p_{ec}=0$ when the active relay number $n=1$. This is because that when there is only one relay in the network help to retransmit copies, all transmission tasks can only be fulfilled by it, the cooperation phase will not be completed until the only relay retransmits successfully K times, i.e., there will not appear the so-called "advance" event when $n=1$. On the contrary, in the case of multiple relays ($n>1$), each of them will be scrambling to try to retransmit copies, making some "slower" relays encounter a special situation that cooperation phase has been completed before they transmit even one packet. As shown in **Fig. 4**, two successful retransmissions are done by R_3 and R_1 respectively, while R_2 receives an ACK at the end of the cooperation phase without transmitting even one packet.

3. System Model and Analysis

3.1 Markov model and state transfer probability

The main design goal of SPRCSMA is to enable the stations operating in IEEE 802.11 DCF to ask their neighbor nodes to retransmit copies persistently. In order to study the contention process caused by multiple relays, the cooperation backoff counter of a single SPRCSMA relay can be modeled with a two-dimensional DTMC $\{(i,j), i \in (0,m), j \in (0, W_i - 1)\}$ illustrated in **Fig. 5**, and in which any (i,j) pair represents the current value of the backoff counter j at the backoff stage i. We denote p_1, p_2 and p_{ec} as the probability of a channel idle, busy and "advance" event happening, respectively. m is the maximum backoff stage, W_0 represents the size of the initial backoff window, and $W_i = 2^i W_0$ is the size of the backoff window at the *i*th stage. The one-step transition probabilities are:

1) $(i,k+1) \to (i,k)$ represents the situation that the channel is sensed idle by the relay and the value of the backoff counter reduces one:

$$P\{i,k \mid i,k+1\} = p_1 \qquad 0 \le i \le m, 0 \le k \le W_i - 2 \tag{1}$$

2) $(i,k) \to (i,k)$ represents the situation that the channel is sensed busy by the relay and the value of the backoff counter is frozen:

$$P\{i,k \mid i,k\} = p_2 \qquad 0 \le i \le m, 0 \le k \le W_i - 1 \tag{2}$$

3) $(i-1,0) \to (i,k)$ represents the situation that an unsuccessful transmission occurs at backoff stage $i-1$ when its backoff counter expires, the backoff stage increases by one, and the new size of the backoff window k is uniformly chosen in the range of $(0, W_i - 1)$:

$$P\{i,k \mid i-1,0\} = \frac{p_2}{W_i} \qquad 1 \le i \le m, 0 \le k \le W_i - 1 \tag{3}$$

4) $(m,0) \to (m,k)$ represents the situation that the backoff stage is not increased in subsequent packet transmissions once it reaches the value m:

$$P\{m,k \mid m,0\} = \frac{p_2}{W_m} \qquad 0 \le k \le W_m - 1 \tag{4}$$

5) $(i,0) \to (0,k)$ represents the situation that a new packet following a successful packet transmission starts with backoff stage 0, and thus the value of the backoff window is initially chosen in the range of $(0, W_0 - 1)$:

$$P\{0,k \mid i,0\} = \frac{1-p_2}{W_0} \qquad 0 \le i \le m, 0 \le k \le W_0 - 1 \tag{5}$$

6) $(i,k)\to(0,j)$ represents the situation that the cooperation phase ends before the backoff counter expires, i.e., the occurrence of the "advance" event:

$$P\{0,j\mid i,k\}=\frac{p_{ec}}{W_0} \qquad 0\le i\le m, 1\le k\le W_i-1, 0\le j\le W_0-1 \tag{6}$$

We assume that $b_{i,k}$ is the stationary distribution for a relay with backoff stage i and backoff timer k. According to the Markov chains regularities, we can derive the following formulas:

$$\begin{cases} b_{i-1,0}\cdot p_2=b_{i,0}\Rightarrow b_{i,0}=p_2^i b_{0,0} & 0<i<m \\ b_{i-1,0}\cdot p_2=(1-p_2)b_{i,0}\Rightarrow b_{m,0}=\dfrac{p_2^m}{(1-p_2)}b_{0,0} & i=m \end{cases} \tag{7}$$

and then:

$$b_{i,0}=\begin{cases} p_2^i b_{0,0} & 0\le i<m \\ \dfrac{p_2^m}{(1-p_2)}b_{0,0} & i=m \end{cases} \tag{8}$$

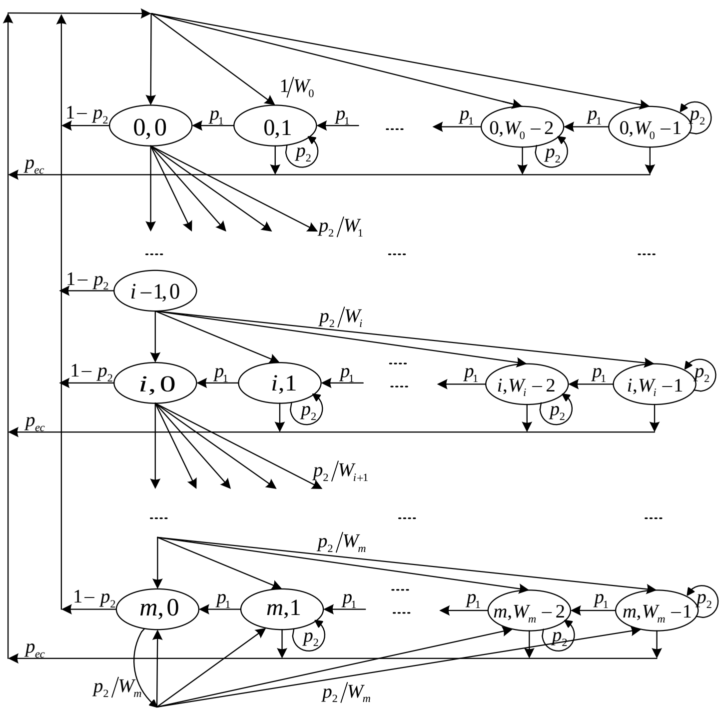


Fig. 5. Markov chain to model the backoff window of the SPRCSMA

by the same token, we have:

$$b_{i,k}=\frac{W_i-k}{W_i\left(p_1+p_{ec}\right)}\cdot\begin{cases}\left[\left(1-p_2\right)\sum_{i=0}^{m}b_{i,0}+p_{ec}\sum_{i=0}^{m}\sum_{j=1}^{W_i-1}b_{i,j}\right] & i=0\\ p_2\cdot b_{i-1,0} & 0<i<m\\ p_2\left(b_{m-1,0}+b_{m,0}\right) & i=m\end{cases} \tag{9}$$

by (7) and **Fig. 5**, we can get:

$$\left(1-p_2\right)\sum_{i=0}^{m}b_{i,0}+p_{ec}\sum_{i=0}^{m}\sum_{j=1}^{W_i-1}b_{i,j}=b_{0,0} \tag{10}$$

$$p_2\cdot b_{i-1,0}=p_2^ib_{0,0}=b_{i,0} \tag{11}$$

$$p_2\left(b_{m-1,0}+b_{m,0}\right)=p_2\cdot p_2^{m-1}b_{0,0}+p_2\cdot\frac{p_2^m}{\left(1-p_2\right)}b_{0,0}=p_2^m\left(1+\frac{p_2}{1-p_2}\right)b_{0,0}=\frac{p_2^m}{\left(1-p_2\right)}b_{0,0}=b_{m,0} \tag{12}$$

so based on the above analysis, it is easy to obtain the closed-form solution for this model:

$$b_{i,k}=\frac{W_i-k}{W_i\left(p_1+p_{ec}\right)}\cdot b_{i,0} \qquad i\in\left(0,m\right),k\in\left(0,W_i-1\right) \tag{13}$$

Then we can make use of the fact that $\sum_{i=0}^{m}\sum_{k=0}^{W_i-1}b_{i,k}=1$ to obtain $b_{0,0}$. However, note that we need to discuss the expression of $b_{0,0}$ according to the different values of m and $N_{\max}$.

1) $N_{\max}\geq m$

In this situation, the backoff window will remain at the maximum stage m for the last $N_{\max}-m$ transmission attempts. Therefore, according to the above formulas and $W_i=2^iW_0, i\in\left[0,m\right]$, we can derive that:

$$\begin{aligned}1&=\sum_{i=0}^{N_{\max}}\sum_{k=0}^{W_i-1}b_{i,k}\\ 1&=\frac{1}{p_1+p_{ec}}\sum_{i=0}^{N_{\max}}b_{i,0}\sum_{k=0}^{W_i-1}\frac{W_i-k}{W_i}\\ &=\frac{1}{p_1+p_{ec}}\left[\sum_{i=0}^{m-1}p_2^ib_{0,0}+\sum_{i=m}^{N_{\max}}\frac{p_2^m}{1-p_2}b_{0,0}\right]\frac{W_i+1}{2}\\ &=\frac{b_{0,0}}{2\left(p_1+p_{ec}\right)}\left[W_0\sum_{i=0}^{m-1}\left(2p_2\right)^i+\sum_{i=0}^{m-1}p_2^i+\sum_{i=m}^{N_{\max}}\frac{W_0\left(2p_2\right)^m+p_2^m}{1-p_2}\right]\\ &=\frac{b_{0,0}}{2\left(p_1+p_{ec}\right)}\left[\frac{W_0\left(1-\left(2p_2\right)^m\right)}{1-2p_2}+\frac{1-p_2^m}{1-p_2}+\frac{\left(N_{\max}-m\right)\left[W_0\left(2p_2\right)^m+p_2^m\right]}{1-p_2}\right]\end{aligned} \tag{14}$$

and then $b_{0,0}$ is:

$$b_{0,0}=\frac{2\left(p_1+p_{ec}\right)\left(1-2p_2\right)\left(1-p_2\right)}{W_0\left[\left(1-p_2\right)+\left[\left(1-2p_2\right)\left(N_{\max}-m\right)-\left(1-p_2\right)\right]\cdot\left(2p_2\right)^m\right]+\left(1-2p_2\right)\left[1+\left(N_{\max}-m-1\right)p_2^m\right]} \quad (15)$$

2) $N_{\max} < m$

In this circumstance, the maximum backoff stage m is actually unattainable because the predefined maximum retransmission number is only $N_{\max}$ times. So (14) is changed as follows:

$$1=\sum_{i=0}^{N_{\max}}\sum_{k=0}^{W_i-1} b_{i,k}$$

$$1=\frac{1}{p_1+p_{ec}}\sum_{i=0}^{N_{\max}} b_{i,0}\sum_{k=0}^{W_i-1}\frac{W_i-k}{W_i}$$

$$=\frac{b_{0,0}}{2\left(p_1+p_{ec}\right)}\left[\frac{W_0\left[1-\left(2p_2\right)^{N_{\max}+1}\right]}{1-2p_2}+\frac{1-p_2^{N_{\max}+1}}{1-p_2}\right] \quad (16)$$

then we can express $b_{0,0}$ as:

$$b_{0,0}=\frac{2\left(p_1+p_{ec}\right)\left(1-2p_2\right)\left(1-p_2\right)}{W_0\left(1-p_2\right)\left[1-\left(2p_2\right)^{N_{\max}+1}\right]+\left(1-2p_2\right)\left(1-p_2^{N_{\max}+1}\right)} \quad (17)$$

finally, $b_{0,0}$ can be expressed as follows:

$$b_{0,0}=\begin{cases}\dfrac{2\left(p_1+p_{ec}\right)\left(1-2p_2\right)\left(1-p_2\right)}{W_0\left(1-p_2\right)\left[1-\left(2p_2\right)^{N_{\max}+1}\right]+\left(1-2p_2\right)\left(1-p_2^{N_{\max}+1}\right)}, & N_{\max}<m\\ \dfrac{2\left(p_1+p_{ec}\right)\left(1-2p_2\right)\left(1-p_2\right)}{W_0\left[\left(1-p_2\right)+\left[\left(1-2p_2\right)\left(N_{\max}-m\right)-\left(1-p_2\right)\right]\cdot\left(2p_2\right)^m\right]+\left(1-2p_2\right)\left[1+\left(N_{\max}-m-1\right)p_2^m\right]}, & N_{\max}\geq m\end{cases} \quad (18)$$

From (18), we can directly observe that $b_{0,0}^{N_{\max}\geq m} < b_{0,0}^{N_{\max}<m}$, which is consistent with the fact that the smaller the $N_{\max}$ is predefined, the greater the probability that a relay transmits a new data packet will be. Moreover, it also provides a suggestion for predefining parameters that too big $N_{\max}$ is not recommended because it will degrade the network performance.

Now, we can express the probability τ that a relay transmits packet at any time slot. We can rewrite (10) as follows by using $\tau=\sum_{i=0}^{m} b_{i,0}$ and $\sum_{i=0}^{m}\sum_{j=1}^{W_i-1} b_{i,j}=1-\sum_{i=0}^{m} b_{i,0}=1-\tau$:

$$\left(1-p_2\right)\tau+p_{ec}\left(1-\tau\right)=b_{0,0} \quad (19)$$

that is,

$$\tau=\frac{b_{0,0}-p_{ec}}{1-p_2-p_{ec}} \quad (20)$$

by $p_1+p_2+p_{ec}=1$, we have the final expression of τ as follows:

$$\tau = \frac{b_{0,0} - p_{ec}}{p_1} \tag{21}$$

3.2 The Probabilities of System Performance

We can get the expressions of probability that reflect the system performance by using (21), which are important for analyzing system performance in section 4. We suppose that there are n active relays in the network. Therefore, the probability of idle in a given slot is:

$$p_1 = (1-\tau)^{n-1} \tag{22}$$

the probability that at least one of the relays attempts to transmit packet in a given slot, P_{tr}, can be expressed as:

$$P_{tr} = 1-(1-\tau)^{n} \tag{23}$$

and the probability of having a successful slot given that a station transmits, p_s, is given by:

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} \tag{24}$$

so, from the perspective of system, the probabilities of having an idle (P_I), collided (P_C), error (P_E) or right (P_R) slot can be written as:

$$P_I = 1 - P_{tr} = (1-\tau)^{n} \tag{25}$$

$$P_C = P_{tr}\cdot(1-p_s) = 1-(1-\tau)^{n} - n\tau(1-\tau)^{n-1} \tag{26}$$

$$P_E = P_{tr}\cdot p_s \cdot p_e = n\tau(1-\tau)^{n-1}\, p_e \tag{27}$$

$$P_R = P_{tr}\cdot p_s \cdot(1-p_e) = n\tau(1-\tau)^{n-1}(1-p_e) \tag{28}$$

where p_e is the PER. Because the use of HARQ with soft combining can improve the probability of D decoding the original packet correctly, so the probability of system having a successful slot, P_s, can be expressed as:

$$P_S = P_R + \alpha\cdot P_E = n\tau(1-\tau)^{n-1}\left[1+(\alpha-1)\right]p_e \tag{29}$$

where α is a complex parameter associated with the encoding strategy, modulation scheme, etc. To simplicity, α is set as a constant in this paper. Using (29), p_{ec} can be calculated as:

$$p_{ec} = \left(K\cdot E[X]\right)^{-1} = \frac{P_s}{K} \tag{30}$$

where K is the value representing the completion of a cooperation phase, i.e., D can decode the original packet after it receives K packet copies from R successfully, $E[X]$ is the expectation that the relay dose not retransmit successfully until X times:

$$E[X] = \sum_{x=1}^{\infty} x\cdot(1-P_S)^{x-1}\cdot P_S = P_S\left[-\frac{\partial}{\partial P_S}\sum_{x=1}^{\infty}(1-P_S)^{x}\right] = \frac{1}{P_S} \tag{31}$$

and the collision probability p_2 is:

$$p_2 = 1 - p_1 - p_{ec} = 1 - (1-\tau)^{n-1} - \frac{P_s}{K} \tag{32}$$

4. Performance Analysis of The System

4.1 System Throughput

This paper denotes S as the normalized system throughput which is defined as the fraction of time that the channel is used to successfully transmit payload bits, that is:

$$S = \frac{E[\textit{payload information transmitted in a slot time}]}{E[\textit{length of a slot time}]} \tag{33}$$

because the average payload information successfully transmitted in a time slot is $P_S \cdot E[P]$ ($E[P]$ is the average packet payload size). Using (25), (26) and (29), it holds that:

$$S = \frac{P_S \cdot E[P]}{P_I \cdot \sigma + P_S \cdot T_S + P_C \cdot T_{Collision}} \tag{34}$$

where σ is the duration of an empty time slot, T_S is the average time a data packet is transmitted successfully, $T_{Collision}$ is the average time the channel is sensed busy by each station during a collision. It is worth noting that we ignore the decoding time of D and the values of T_S and $T_{Collision}$ all depend on the access mechanism adopted by the relays, i.e., the basic access mechanism (BASIC) or the collision avoidance handshake RTS/CTS (COLAV), and they can be expressed as:

$$\begin{cases} T_{S|BASIC} = T_{DIFS} + T_{DATA} \\ T_{S|COLAV} = T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} \end{cases} \tag{35}$$

$$\begin{cases} T_{Collision|BASIC} = T_{DIFS} + T_{DATA} \\ T_{Collision|COLAV} = T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS\_TIMEOUT} \end{cases} \tag{36}$$

where T_{DIFS} and T_{SIFS} are the duration of DIFS and SIFS silence periods, respectively. T_{RTS} and T_{CTS} are the transmission time of RTS and CTS packets. T_{DATA} is the duration of packet transmission. $T_{CTS\_TIMEOUT}$ is the duration of transmission timer for CTS packet. We assume that it will be seen as a collision if the relays do not receive the corresponding CTS packet of the RTS packet within the specified time in the transmission timer.

4.2 The Average Packet Transmission Delay

In this paper, the average packet transmission delay of SPRCSMA is denoted by $E[T_{COOP}]$, defined as the average duration of the first failed transmission plus the average time required to complete a successful cooperation phase given an average number of retransmission K. $E[T_{COOP}]$ can be expressed as:

$$E[T_{COOP}] = E[T_{min}] + E[T_{cont}] \tag{37}$$

where $E[T_{min}]$ is the expectation of the minimum packet transmission delay, which is unachievable because it is impossible to attain a perfect scheduling among all the active relays operating in DCF, that is, the contention among the active relays which will undoubtedly increase the average packet transmission delay, represented as $E[T_{cont}]$, is unavoidable.

According to the basic rule of IEEE 802.11, the $E[T_{min}]$ can be calculated as follows:

$$E[T_{\min}] = T_0 + T_{AFC} + K \cdot T_{DR} + T_{ACK} + 4T_{SIFS} \tag{38}$$

where T_0 is the duration of the first transmission from S to D. T_{AFC} and T_{ACK} are the transmission time of the AFC and the ACK packet, respectively.

On the other hand, according to the contention time between packets is independent of each other, the value of $E[T_{cont}]$ can be expressed as:

$$E[T_{cont}] = K \cdot E[T_c] \tag{39}$$

where $E[T_c]$ is the average contention time required to transmit a single packet among all relays. Based on (31), the average number of slots before having a successful transmission is $E[X]$, from which we can derive that the average number of non-successful slots before having a successful transmission is $E[X]-1$. Therefore, the total contention time will be:

$$E[T_c] = \left(E[X]-1\right) E[T_{slot} \mid non-successful\ slot] \tag{40}$$

where $E[T_{slot} \mid non-successful\ slot]$ is the average duration of a slot given that the slot is not successful. As discussed in section 3.2, a given slot will be seen as failed with the probability P_I (idle) , $(1-\alpha)P_E$ (receiving an error copy) and P_C (suffering a collision). Applying Bayes' theorem, the average duration of any slot is considered as failed can be expressed as:

$$E[T_{slot} \mid non-successful\ slot] = \left(\frac{P_I}{1-P_S}\right)\sigma + \left(\frac{(1-\alpha)P_E}{1-P_S}\right)T_S + \left(\frac{P_C}{1-P_S}\right)T_{collision} \tag{41}$$

Therefore, the average total contention time can be rewritten as:

$$E[T_{cont}] = K\left(\frac{1}{P_S}-1\right)\left[\left(\frac{P_I}{1-P_S}\right)\sigma + \left(\frac{(1-\alpha)P_E}{1-P_S}\right)T_S + \left(\frac{P_C}{1-P_S}\right)T_{collision}\right] \tag{42}$$

finally, $E[T_{COOP}]$ can be obtained by substituting (42) and (38) into (37).

5. System Performance Evaluation

The configuration parameters of the stations in the network are shown in **Table 1**. Here, we assume that all packets have the same fixed size, i.e., $E[P]=P$. Moreover, to study the effect of transmission rate on network performance, packet transmissions are performed at four transmission rates, referred to as the *source/relay control_rate* and *source/relay data_rate* respectively and are specified in **Table 2**.

Table 1. System parameters

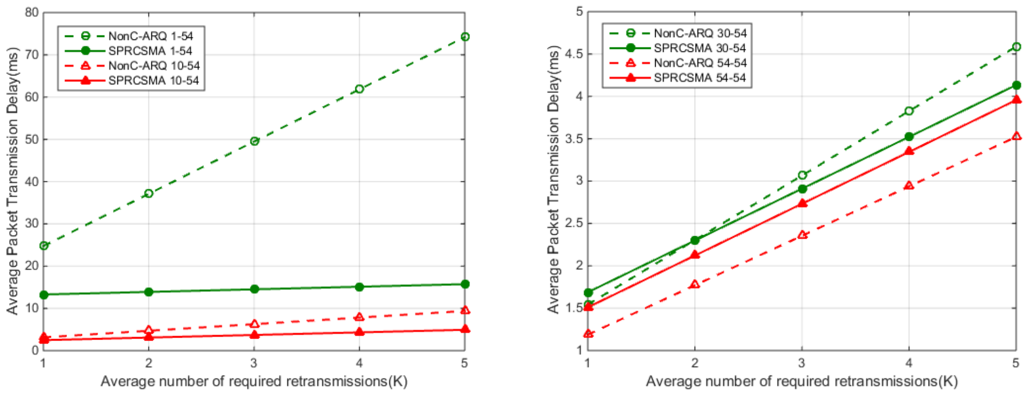
Parameter	**Value**	**Parameter**	**Value**
MAC header	34 bytes	PHY preamble	96 μs
source data_rate	1/10/30/54 Mbps	source control_rate	1/6 Mbps
relay data_rate	54 Mbps	relay control_rate	6 Mbps
ACK/NACK length	14 bytes	P	1500 bytes
RTS length	20 bytes	CTS length	14 bytes
AFC length	14 bytes	W_0	16/32/64
DIFS	50 μs	SIFS and σ	10 μs
CTS_Timeout	90 μs	p_e	0.1

Table 2. Sets of transmission rates (Mbps)

Name	**source control_rate**	**source data_rate**	**relay control_rate**	**relay data_rate**
1-54	1	1	6	54
10-54	6	10	6	54
30-54	6	30	6	54
54-54	6	54	6	54

5.1 Case 1: Delay Comparison under Different Transmission Rates

This case is configured with the following parameters: $W_0=16$, $n=10$, $m=5$, $N_{\max}=3$ and the basic access method. The average packet transmission delay is illustrated in **Fig. 6a** and **Fig. 6b** as a function of K under different sets of transmission rates.



a. Low-rate range **b.** High-rate range

Fig. 6. Average delay vs. transmission rate

As it could be expected, the retransmission of the non-cooperation ARQ is only performed by S because the relays have not been involved in, benefitting the continuous retransmission without contention and making the ratio between the *source data_rate* and the *relay data_rate* determines how efficient the SPRCSMA protocol is in comparison to non-cooperation ARQ. For instance, in the case of using the transmission rate set 1-54 in **Fig. 6a**, the delay of the non-cooperation ARQ is linearly increased with the increase of K because the *source data_rate* is very low (only 1 Mbps), by contrast, a faster *relay data_rate* (54 Mbps) can greatly improve the efficiency of SPRCSMA protocol and make the corresponding average packet transmission delay increases slightly with the increase of K. However, in the case of using the transmission rate set 54-54 in **Fig. 6b**, the delay performance of the SPRCSMA is worse than that of the non-cooperation ARQ because the *source data_rate* is equal to the *relay data_rate*, making the SPRCSMA protocol not only lacks the advantage of high-speed retransmission rates from relays, but also needs some extra time to coordinate the contention between relays.

It could be found that the SPRCSMA protocol will be particularly suitable for some long-distance communication scenarios where the destination locates far away from the transmitting station and the sender has to transmit packets at a low speed, significantly benefitting from the retransmission performed by relays and finally achieving diversity.

5.2 Case 2: Performance Comparison under Different K and n

The parameter configuration is same with case 1 and the transmission rate set is 30-54. The average packet transmission delay and the throughput are represented in **Fig. 7** and **Fig. 8** as a function of the number of active relays n for different values of K, respectively.

From **Fig. 7**, we can clearly observe that, as we expected, the more the retransmissions are required, the longer the average delay will be. This is because that the greater the K is, the longer the contention period among the relays and the larger the MAC overhead will be, which undoubtedly lead to longer delay. As for throughput, it can be observed from **Fig. 8** that the larger the K is, the greater the throughput will be, which is consistent with the truth that the more the retransmissions are required, the more payload the relays will transmit, and the greater the throughput will be. So, we can summarize that K is proportional to both the average packet transmission delay and the throughput.

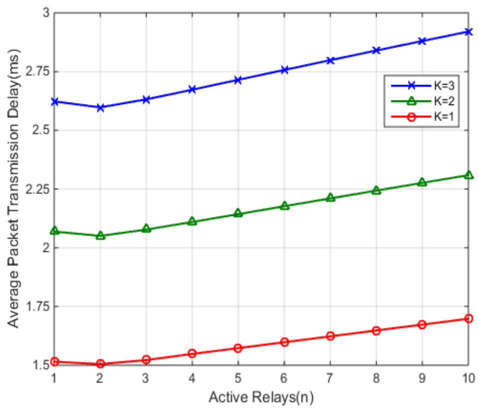


Fig. 7. Average delay vs. active relays(n)

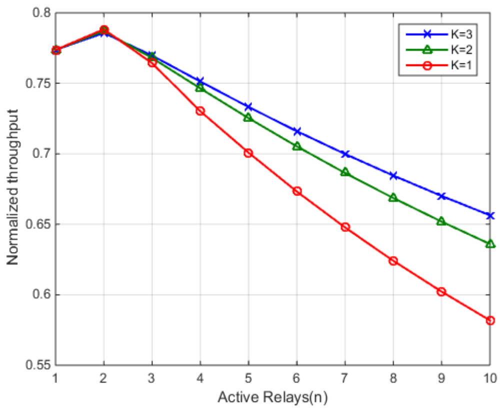


Fig. 8. Throughput vs. active relays(n)

On the other hand, the average delay increases but the throughput decreases with the increase of n. This is because that the more the number of active relays are, the more contention among relays will be, undoubtedly resulting in longer delay and lower throughput. Moreover, irrespectively of the value of K, there always exists an optimum number of active relays $n_{optimal} = 2$ which can minimize the average delay and maximize the throughput, giving advice for network deployment from the perspective of theoretical analysis. Actually, the value of $n_{optimal}$ also depends on the size of the initial backoff window W_0.

5.3 Case 3: Performance Comparison under Different Sizes of W_0

This case is configured with the following parameters: $K=3$, $m=5$, $N_{max}=3$, the transmission rate set 30-54 and the basic access method. For a given W_0, the probability of collision increases as the number of relays. Therefore, if the value of W_0 is too small for the number of relays, the higher probability of collision leads to the increase of the average delay and the decrease of throughput. On the other hand, if the value of W_0 is larger, it will result in an unnecessary waste of time devoted to backoff deferral periods. In order to better demonstrate this assumption, the average packet transmission delay and the throughput for different sizes of W_0 are depicted in **Fig. 9** and **Fig. 10** respectively, which completely confirms the correctness of our assumption that a smaller value of W_0 yields better performance when the number of relays are low while larger values of W_0 perform better as the number of relays increases. For example, both curves of $W_0=16$ in **Fig. 9** and **Fig. 10** can achieve lower average delay and higher throughput in the case of a smaller number of active relays ($n \le 3$), but as n increases, their network performance deteriorates significantly and gradually underperforms that of the curves W_0=64.

Therefore, the optimum design of W_0 becomes one of the key factors influencing system performance and we should choose a proper value of W_0 as a function of n because a higher W_0 wastes too much time devoted to backoff periods but a lower W_0 increases the probability of collision. It is worth mentioning that under the circumstance of not being able to operate at the optimum value of W_0, it would be more recommended to use a higher value of W_0 because the cost of a collision is much higher than that of some extra backoff slots no matter what access method is adopted.

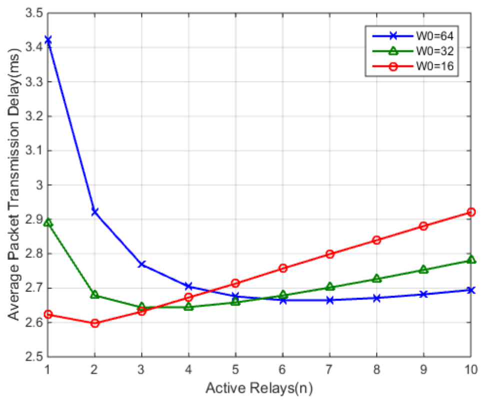


Fig. 9. Average delay vs. W_0

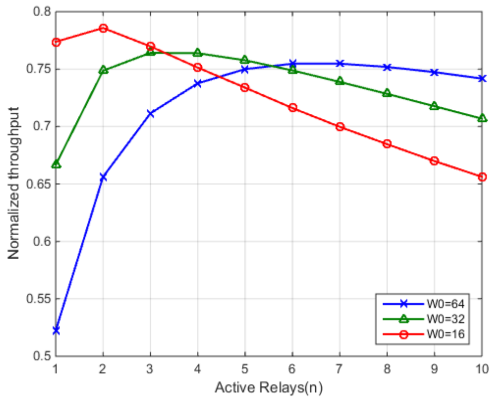


Fig. 10. Throughput vs. W_0

5.4 Case 4: Performance Comparison under Different Access Methods

This case is configured with the following parameters: W_0=16, $m=5$, $N_{max}=3$ and the transmission rate set 30-54. We assume that the relays use either the BASIC method or the COLAV method, and the average packet transmission delay and the throughput are depicted in

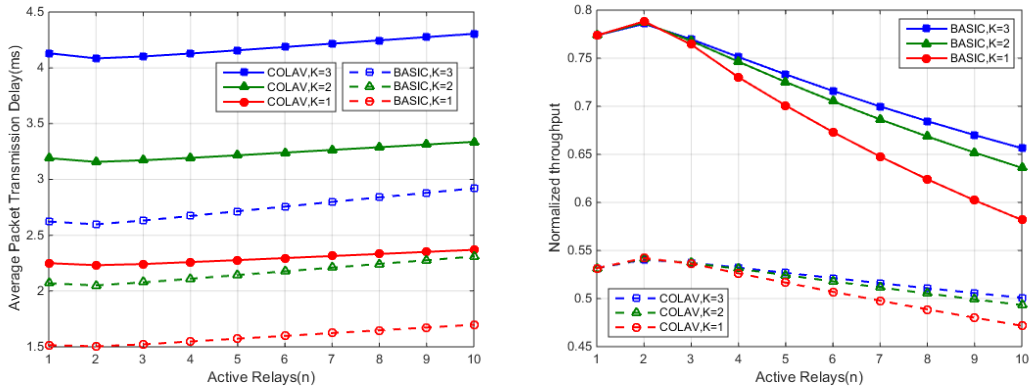
Fig. 11a and **Fig. 11b** as a function of n for different values of K, respectively.

From **Fig. 11a** and **Fig. 11b**, it is clear that the BASIC method has the better performance than the COLAV method both in the case of the average delay and the throughput, which is because that there is no hidden terminal in this considered scenario, but in reality, the COLAV method not only plays a positive role in preventing the hidden terminal, but also can restrict the collision of data packets in the control plane by transmitting the RTS and CTS frame.

So, we can summarize as follows: although the COLAV method degrades the performance gain because it brings an extra control information overhead to the system, it is widely used in various communication scenarios for its unique advantages. In the selection of specific access mechanism, we should make a concrete analysis according to the actual situation.

5.5 Case 5: The Contrast Experiment

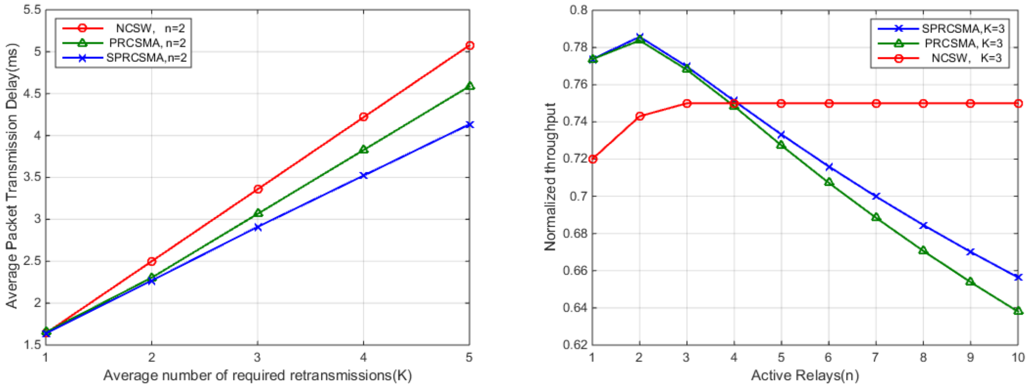
The parameter configuration is same with case 2. For completeness, we compare the SPRCSMA protocol with the NCSW and PRCSMA protocol, the results of the average packet transmission delay and the throughput are plotted in **Fig. 12a** and **Fig. 12b**, respectively. **Fig. 12a** shows that the average packet transmission delay of NCSW protocol is significantly higher than that of the other two protocols, which is because that relays in this protocol perform retransmission according to the IEEE 802.11DCF and do not retransmit their packet copies in a persistent manner, i.e., D in NCSW protocol needs to give feedback to each copy received from R in the cooperation phase, spending time on exchanging control information (ACK, NACK, etc.) and waiting for the corresponding interframe space (SIFS). This performance difference becomes more and more obvious with the increase of K. On the other hand, since HARQ technology with soft combining can effectively improve the probability of D successfully decoding the original data packet, R in SPRCSMA protocol can take less time than PRCSMA protocol, which uses simple ARQ, to transmit K copies in the cooperation phase, i.e., SPRCSMA protocol can complete data retransmission faster, thus effectively reducing the average delay.



a. the average delay **b**. the throughput

Fig. 11. The influence of different access mechanisms on

Similarly, as for throughput shown in **Fig. 12b**, since the use of persistent retransmission which can effectively reduce the transmission times of control information enables PRCSMA and SPRCSMA protocol to transmit more payload in a time slot, making the throughput of them outperforms that of NCSW protocol when the number of active relays is small ($n \le 4$) and achieves the maximum value when the number of optimal relays $n_{optimal} = 2$ is reached.



a. the average delay **b**. the throughput

Fig. 12. The influence of different methods on

It is worth noting that although this advantage no longer exists when $n > 4$, this is because, as mentioned in the introduction, NCSW protocol does not consider the important contention process caused by cooperation between multiple relays, so its throughput remains unchanged after reaching the maximum, it is obviously contrary to the fact that the more the number of relays participating in cooperation phase, the more the collisions of relays accessing channels will be occurred in a distributed wireless network, degrading the system performance. It also fully proved that the contention process among multiple relays is a vital problem which can not be ignored in distributed wireless networks and the number of active relays is not the more the better, an inappropriate and larger n is bad for improving system performance, so the selection of $n_{optimal}$ is very important. On the other hand, although throughput is declining, it in SPRCSMA protocol does not decline as fast as PRCSMA protocol at the same PER ($p_e = 0.1$), which proves that SPRCSMA protocol can combat poor channel conditions better.

6. Conclusions

We have proposed a SPRCSMA protocol for distributed wireless networks, developed a two-dimensional DTMC analytical model for the contention process among multiple relays and calculated its steady-state distribution. The closed expressions of system performance including throughput and average packet transmission delay were obtained and simulation results were shown to validate the analysis model, to evaluate the impact of network parameters on system performance and to verify the superiority over the other two protocols. It can be concluded that the contention process in distributed multi-relay cooperative wireless networks cannot be ignored and there always exists an optimal number of relays in the network which can maximize the performance gain (i.e., the minimum average packet transmission delay and the maximum system throughput). Moreover, the size of the initial backoff window should be properly tuned as a function of the number of active relays for each cooperation phase to avoid either existence of a high probability of collision or wasted time due to deferral periods. Finally, the performance comparison with other two cooperative ARQ schemes (NCSW and PRCSMA) also proves the performance improvement of SPRCSMA, especially in the long-distance communication scenarios.

Therefore, it is still a challenging hot issue for future research to design an efficient cooperative MAC protocol that can optimize the contention problem in distributed multi-relay cooperative wireless network, such as the solution of the optimal relay number and the design of an adaptive backoff window cooperative ARQ scheme, etc.

References

[1] Sadeghi R, J. P. Barraca and R. L. Aguiar, "A survey on cooperative MAC protocols in IEEE 802.11 wireless networks," *Wireless Personal Communications*, vol. 95, no. 2, pp. 1469-1493, July, 2017. Article (CrossRef Link).

[2] Ju Peijian, W. Song and D. Zhou, "Survey on cooperative medium access control protocols," *IET Communications*, vol. 7, no. 9, pp. 893-902, August, 2013. Article (CrossRef Link).

[3] A. Meier and J. S. Thompson, "Cooperative diversity in wireless networks," in *Proc. of 6th IEE Conf. on 3G and Beyond*, pp.35-39, November 7-9, 2005. Article (CrossRef Link).

[4] Cetinkaya C and F. Orsun, "Cooperative medium access protocol for dense wireless networks," in *Proc. of the third annual Mediterranean ad hoc networking workshop-Med Hoc Net*, 2004. Article (CrossRef Link).

[5] Sai Shankar N and C. T. Chou et al., "Cooperative communication MAC (CMAC)-a new MAC protocol for next generation wireless LANs," in *Proc. of International Conference on Wireless Networks, Communication and Mobile Computing, IEEE*, pp. 1-6, December, 2005. Article (CrossRef Link).

[6] Dianati M, Ling X and Naik K et al., "A node-cooperative ARQ scheme for wireless ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 3, pp. 1032-1044, May, 2006. Article (CrossRef Link).

[7] Liu P and Tao Z et al., "CoopMAC: a cooperative MAC for wireless LANs," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, pp. 340-354, February, 2007. Article (CrossRef Link).

[8] Alonso-Zárate J, Kartsakli E and Verikoukis C et al., "Persistent RCSMA: A MAC protocol for a distributed cooperative ARQ scheme in wireless networks," *Eurasip Journal on Advances in Signal Processing*, vol. 2008, no. 1, pp. 1-13, December, 2008. Article (CrossRef Link).

[9] Alonso-Zárate J, Alonso L and Verikoukis C, "Performance analysis of a persistent relay carrier sensing multiple access protocol," *IEEE Transactions on Wireless Communications*, vol. 8, no. 12, pp. 5827-5831, December, 2009. Article (CrossRef Link).

[10] Hu Z and Tham C K, "CCMAC: Coordinated cooperative MAC for wireless LANs," *Computer Networks*, vol. 54, no. 4, pp. 618-630, March, 2010. Article (CrossRef Link).

[11] Nischal S and V. Sharma, "A cooperative ARQ scheme for infrastructure WLANs," in *Proc. of IEEE Wireless Communications & Networking Conference*, pp. 428-433, April, 2013. Article (CrossRef Link).

[12] Lee Jong Kwan, H. J. Noh and J. Lim, "TDMA-based cooperative MAC protocol for multi-hop relaying networks," *IEEE Communications Letters*, vol. 18, no. 3, pp. 435-438, April, 2014. Article (CrossRef Link).

[13] Liu K and Chang X Y et al., "A cooperative MAC protocol with rapid relay selection for wireless ad hoc networks," *Computer Networks*, vol. 91, pp. 262-282, November, 2015. Article (CrossRef Link).

[14] Mahmud Md. Tareq et al., "Distance-aware data rate adaptive cooperative MAC protocol for wireless networks," in *Proc. of International Conference on Electronic Design, IEEE*, pp. 185-190, August, 2016. Article (CrossRef Link).

[15] Zhang X, Guo L and Anpalagan A et al., "Performance of energy-efficient cooperative MAC protocol with power backoff in MANETs," *Wireless Personal Communications*, vol. 92, no. 3, pp. 843-861, February, 2017. Article (CrossRef Link).

[16] AlonsoZárate J, Gómez J and Verikoukis C et al., "Performance evaluation of a cooperative scheme for wireless networks," in *Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1-5, September, 2006. Article (CrossRef Link).

[17] Wu H, Peng Y and Long K et al., "Performance of reliable transport protocol over IEEE 802.11 wireless LAN: analysis and enhancement," in *Proc. of Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol.2, pp. 599-607, 2002. Article (CrossRef Link).

[18] Wu, Peng and N. Jindal, "Performance of hybrid-ARQ in block-fading channels: A fixed outage probability analysis," *IEEE Transactions on Communications*, vol. 58, no. 4, pp. 1129-1141, April, 2010. Article (CrossRef Link).

[19] Chiti Francesco and R. Fantacci, "A soft combining hybrid-ARQ technique applied to throughput maximization within 3G satellite IP networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 2, pp. 594-604, March, 2007. Article (CrossRef Link).

[20] Holland I. D., H. J. Zepernick and M. Caldera, "Soft combining for hybrid ARQ," *Electronics Letters*, vol. 41, no. 22, pp. 1230-1231, October, 2005. Article (CrossRef Link).

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