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Cooperative MAC Design in Multi-hop Wireless Networks: Part I: When Source and Destination are within the Transmission Range of Each Other

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Abstract Cooperative communication is regarded as a promising technology in future 5G wireless networks to enhance network performance by exploiting time and/or space diversity via distributed terminals. In this paper, we propose a cooperative medium access protocol which addresses three key aspects of cooperative communications from MAC layer perspective, namely, when to cooperate, whom to cooperate with and how to protect ongoing cooperative transmissions. To further improve the protocol performance in dense networks, three techniques are investigated to avoid potential collision among multiple contending relays. Both analysis and simulation results demonstrate that significant improvement in terms of throughput and packet delivery ratio can be achieved by the proposed cooperative protocol.

Keywords 5G · One-hop cooperative MAC · Relay selection · Collision avoidance

1 Introduction

In future 5G networks which are characterized by ubiquitous computing and communication, cooperative communication via distributed wireless devices is foreseen as an eminent feature. The theory behind cooperative diversity has been studied in depth, and significant improvement of network performance has been demonstrated in terms of throughput, outage prabability, network coverage and energy efficiency [1].

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While most existing work on cooperative communications focuses on physical layer issues, more and more attention has recently been paid to cooperative Medium Access Control (MAC) design in distributed wireless networks. From this perspective, three key issues need to be addressed, i.e., when to cooperate, whom to cooperate with and how to protect cooperative transmissions. Our study aims at cooperative MAC design to deal with the aforementioned issues with a minimum cost of network resources.

Within such a context, a Cooperative Automatic Repeat reQuest protocol (C-ARQ) is proposed in this paper. Firstly, cooperative transmission is initiated only when the direct transmission fails. In this way, unnecessary occupation of channels by relay nodes and waste of system resources are avoided. Secondly, the relay nodes are sorted by different backoff time before data retransmission, and the relay node with best relay channel quality will be selected to forward the data packet first. Lastly, the cooperative transmission sequences are specifically designed to give cooperative retransmissions higher priority for channel access and to protect ongoing packet forwarding by relay nodes. Furthermore, to avoid collisions among multiple contending relay nodes for packet retransmission in a dense network, we introduce three enhanced techniques based on C-ARQ, referred to as *the p-persistent access scheme*, *the increased threshold scheme* and *the extended backoff scheme*. Both analytical and simulation studies are conducted to evaluate the performance of the proposed schemes, in terms of network throughput and packet delivery ratio.

The rest of the paper is organized as follows. The related work is briefly summarized in Sect. 2 before the system model is described in Sect. 3. After that, the proposed protocol is explained in details in Sect. 4. Throughput and packet delivery ratio analysis of different protocols is given in Sect. 5, and the performance is evaluated through simulations in Sect. 6. Finally, the paper is concluded in Sect. 7.

2 Related Work on Cooperative Networking

Most cooperative schemes in the literature have traditionally focused on physical layer issues based on a three-node scenario [2]. However, little attention has been paid to cooperative networking, and cooperative MAC design remains to large extent an unchartered area. For instance, the assumption of simultaneous transmission of source and relay in many publications [3–5] needs to be re-visited. In the following, we classify existing cooperative MAC mechanisms into two categories.

2.1 Distributed On-Demand Cooperative ARQ

The concept of distributed cooperative ARQ have been proposed and studied in a few recent publications. We refer to this type of cooperation as *on-demand cooperative ARQ* since it is activated only if the initial source-to-destination transmission fails. The gain of a cooperative ARQ scheme in terms of transmission reliability is derived in [6].

Persistent Relay Carrier Sensing Multiple Access (PRCSMA) [7] is claimed to be the first cooperative ARQ MAC, in which all relay nodes contend for channel access according to the Distributed Coordination Function (DCF) protocol if the direct transmission is not successful. However, the resulted long defer time and random backoff interval at each relay lead to its low bandwidth efficiency.

2.2 Proactive Multi-Rate Cooperative MAC

This group of cooperative MAC protocols deal with the tradeoff on whether one-hop direct transmission at a lower data rate or two-hop communication at a higher data rate should be used to achieve maximal end-to-end throughput. These MAC protocols are operated in a *proactive* manner, since which alternative to use is pre-decided before each packet transmission.

The most representative proactive multi-rate cooperative protocol is CoopMAC [8]. In CoopMAC, a helper is is selected from a CoopTable which is established and maintained based on the observations of historical transmissions. Similar to [8], Efficient Multi-rate Relaying (EMR) MAC [9] is another example of MAC design which deals with the multi-rate issues in ad hoc networks. In EMR MAC, a relay link is selected if it can provide higher effective throughput. The effective throughput is obtained based on an assumption of ideal physical channel condition in both the direct source-destination link and the combined source-relay-destination link.

Another important aspect in cooperative MAC design is relay selection. There exist many approaches for relay selection. Some of them are based on the geographic locations of the nodes, provided that such information is available through hardware support. Other schemes introduce additional signaling to select relays and to synchronize data transmission. Recently, a simple distributed method has been proposed in [10] to select the best path without any topology information or any explicit communications among relay nodes.

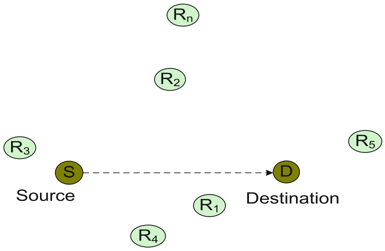
To summarize our discussions on related work, although more attention has recently been drawn to cooperative MAC design, further efforts are still needed for solutions of the three key issues we mentioned above, especially when the compatibility with CSMA with Collision Avoidance (CSMA/CA) is taken into consideration. In what follows, we present our C-ARQ protocol, as an effort towards this direction.

3 System Model and Assumptions

The network shown in Fig. 1 is taken as an example to illustrate the network topology and cooperation scenario. The network consists of a source node, S, a destination node, D, and several randomly distributed potential relay nodes, $R_1, R_2, \ldots, R_n$.

In this model, S and D are within the transmission range of each other. The channels between every transmission pair, i.e., between S and D, S and each relay node R_i, as well as R_i and D, are assumed to be independent of each other, hence full spatial diversity can be achieved by data retransmission over another/other channel(s). Moreover, we assume that consecutive packets on the same channel are subjected to the same channel fading condition and hence identical packet error rate.

Fig. 1 System model for cooperative transmission



4 Cooperative MAC Protocol Design: C-ARQ

In this section, we first present the relay selection scheme proposed in C-ARQ, and then how the C-ARQ protocol works is illustrated. Lastly, three techniques to further avoid collisions among relay transmissions are introduced.

4.1 Relay Selection Criterion

Similar to our previous work in [11], the relay nodes in C-ARQ are selected in a distributed manner by using the instantaneous channel condition obtained through a Call For Relay (CFR) packet sent from D. After the cooperative phase starts, each relay candidate starts its timer with an initial value of:

$$T_i = \left\lfloor \frac{SNR_{low}}{SNR_i} \frac{T_{up}}{slottime} \right\rfloor, \quad i = 1, 2, \ldots, n \tag{1}$$

where T_i is the backoff time at relay node R_i, defined as an integer in number of microseconds; SNR_i is the SNR value in dB of the CFR packet received at R_i; SNR_{low} is the threshold of SNR_i for R_i to participate in cooperative retransmission; and n is the number of the relay nodes in the network. The value of SNR_{low} can be determined according to the specified Modulation and Coding Schemes (MCSs) at the physical layer. T_{up} in Eq. 1 is the upper bound of the backoff time for relay candidates. T_{up} in the basic C-ARQ scheme is set to be $DIFS - SIFS$ in order to guarantee that the cooperative retransmission will not be interrupted by other nodes in the network. Different from [11], the granularity of T_i is specified to be *slottime* of the system in order to cover the propagation delay in the network.

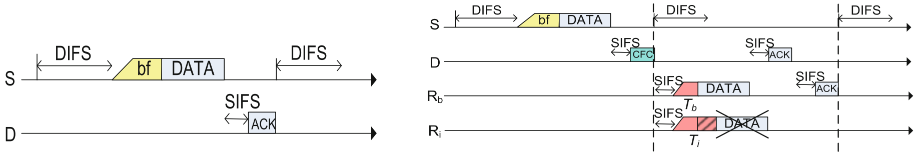
4.2 Cooperative Automatic Repeat Request Scheme

The message exchange sequence of the C-ARQ scheme is illustrated in Fig. 2. It has four operation cases: (I) direct transmission succeeds; (II) best-relay-channel retransmission succeeds; (III) multi-relay retransmission succeeds; and (IV) the whole cooperative retransmission fails. The C-ARQ protocol procedure is briefly presented in the following. More details about how the cooperative protocol works can be found in [11].

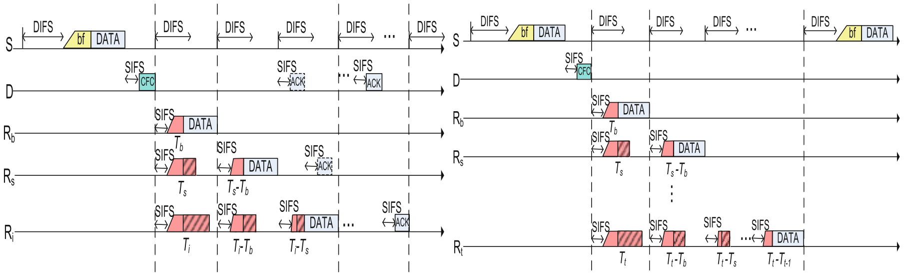
(a) As the first step, S sends out a data packet to its destination D following the original DCF basic access scheme. (b) If and only if the data packet is received erroneously at D, D will broadcast a CFR packet to invite other nodes in the network to operate as relay nodes and at the same time to provide them the opportunity of measuring their respective relay channel quality. According to Eq. 1, the relay node with the best relay channel quality $\mathrm{R_b}$, will first get channel access and forward its received packet to the destination. If D decodes the packet correctly after the best-relay-channel retransmission, D will return an ACK packet, which is relayed afterwards by $\mathrm{R_b}$ to S. (c) Otherwise, the other relay nodes will participate in data retransmission consecutively one after another until D decodes the packet successfully. (d) Finally, if cooperations of all relay nodes still can not lead to successful data reception at D, or if the number of retransmission attempts reaches the retry limit, the cooperative transmission fails.

4.3 Techniques to Avoid Collision among Relay Transmissions

In Eq. 1, T_{up} is set as $DIFS - SIFS$, which indicates that the scheme can only distinguish at most $\lfloor \frac{DIFS-SIFS}{slottime} \rfloor$ relays, resulting in potential collisions among relays in a dense network. In order to solve this problem, three techniques are proposed:



(a) *Case I* **(b)** *Case II*



(c) *Case III* **(d)** *Case IV*

Fig. 2 C-ARQ basic access scheme

- *P-persistent Cooperative Automatic Repeat ReQuest (P.C-ARQ)*
  With P.C-ARQ, after the timer expires at R, R will forward the packet with a given probability, p, with $0 < p < 1$. It is obvious that the probability of collision can be decreased with a smaller value of p. However, the probability of cooperative retransmissions is also decreased at the same time. Therefore, the parameter p should be tuned properly according to network conditions to maximize overall system performance.
- *Increased Threshold Cooperative Automatic Repeat ReQuest (IT.C-ARQ)*
  The SNR threshold of the received signal (SNR_{low}) in Eq. 1 can be adjusted according to IT.C-ARQ. SNR_{low} not only determines whether a relay node is qualified to cooperate but also influences the distribution of the backoff time at all relay candidates and therefore affects collision probability. With a higher SNR_{low} value, the probability of having a qualified relay node for retransmission will decrease accordingly. Meanwhile, fewer relay nodes will be allowed to participate in cooperation, leading to less collision probability. Indeed, the tradeoff needs to be studied with an optimal value of SNR_{low} to maximize throughput performance according to different network conditions.
- *Extended Back-off Cooperative Automatic Repeat ReQuest (EB.C-ARQ)*
  Using EB.C-ARQ, the upper bound of the backoff time T_{up} is extended to be $DIFS - SIFS + CW_{min} slottime$. In this way, the relay nodes can be distinguished and sorted more accurately using this larger range of backoff time. However, the cooperative transmission is only given a higher priority to access the channel by using the minimum contention window CW_{min} in the upper bound, and it is not guaranteed any more that the cooperative retransmission will not be interrupted by other contending nodes in the network.

5 Performance Analysis

The performance of the different MAC protocols is analyzed in terms of saturation throughput and Packet Delivery Ratio (PDR) at the MAC layer in this section.

The normalized system saturation throughput, denoted by η, is defined as the successfully transmitted payload bits per time unit. According to [12], η can be calculated as $E[G]/E[D]$, where $E[G]$ is the number of payload information bits successfully transmitted in a virtual time slot, and $E[D]$ is the expected length of the virtual time slot. The virtual time slot here means the time interval between two consecutive packet transmissions initiated by S. The general expressions of $E[G]$ and $E[D]$ for all the three protocols discussed in this paper are given as follows:

$$E[G] = \left(1 - \prod_{i=1}^{m} p_{e,i}\right) L \tag{2}$$

$$E[D] = \begin{cases} E[D_1]; & \text{for } m = 1 \\ (1-p_{e,1})E[D_1]+p_{e,1}E[D_2]; & \text{for } m = 2 \\ \\ (1-p_{e,1})E[D_1]+\sum_{i=2}^{m-1}\prod_{j=1}^{i-1} p_{e,j}(1-p_{e,i})E[D_i]+\prod_{i=1}^{m-1} p_{e,i}E[D_m]; & \text{for } m \geq 3 \end{cases} \tag{3}$$

In the above expressions, m is the maximal number of possible transmission attempts, *including* the original direct data frame transmission by the source node; $p_{e,i}$ is the error probability of data packets at the ith transmission attempt; L is the packet length in bits and D_i is the virtual time slot with i performed transmission attempts.

The PDR is the ratio between the number of successfully transmitted packets at the MAC layer and the number of total packets delivered from its upper layer. The general expression is given as follows:

$$PDR = 1 - \prod_{i=1}^{m} p_{e,i} \tag{4}$$

In the following, we take the proposed C-ARQ protocol as an example to illustrate the performance analysis approach. The performance of non-cooperative DCF and PRCSMA can be calculated in the same way and the analysis results can be found in [11].

With regard to the C-ARQ scheme, m is the minimal value between the retry limit and the number of relay candidates available in the network, plus 1 for the initial direct transmission; $p_{e,1}$ is the packet error rate on the direct channel and $p_{e,i}, i = 2, 3, \ldots, m$ is the packet error rate on the $(i-1)$th relay channel in the descending order of relay channel quality. $p_{e,i}$ becomes 1 if a collision happens among multiple active relays at the $(i-1)$th transmission attempt. In our analysis, it is assumed that the MAC header is always decoded correctly at the destination.

The virtual time slot duration in the case when i transmission attempts are executed in the C-ARQ scheme is denoted as D_i^c and can be expressed as follows:

$$D_i^c = \begin{cases} DIFS + \delta_1 + T_{DATA} + SIFS + T_{ACK}, & \text{if } i=1 \\ \\ DIFS + \delta_1 + (i+3)SIFS + 2T_{ACK} + iT_{DATA} + T_{CFR} + T_i, & \text{otherwise;} \end{cases} \tag{5}$$

where T_{DATA} and T_{ACK} represent the time used for transmitting the DATA and ACK frames respectively; T_i is the backoff time consumed at the ith retransmitting relay node; and δ_1 is the average backoff time of the first transmission. Since it is assumed that there are no other contending nodes in the network, δ_1 is half of the minimal contention window duration.

The throughput and PDR performance for the C-ARQ scheme can be obtained by substituting the above parameters into Eqs. 2, 3 and 4, respectively. The three enhanced versions of the C-ARQ scheme introduced in the preceding section, namely P.C-ARQ, IT.C-ARQ and EB.C-ARQ, can still use the above formulas for the C-ARQ protocol to calculate their throughput and PDR performance. The only difference is that different schemes result in different backoff time for relay nodes, T_i, and correspondingly different error probabilities at the ith transmission attempt, $p_{e,i}$.

6 Simulations and Numerical Results

To evaluate the performance of the proposed MAC protocol, we have implemented the DCF, PRCSMA and C-ARQ protocols in MATLAB for the purpose of performance comparison. The relay nodes are randomly distributed in a square area of 50 m × 50 m. The source node and the destination node are placed symmetrically along the center line and 25 meters apart from each other. The path loss coefficient is set to be 4 to emulate the indoor environment. The transmitting and receiving antenna gains are set to be 1. The channels between each transmission pair are implemented as independent Rayleigh fading channels.

For both C-ARQ and PRCSMA, the cooperation SNR threshold is set to be 2.0 dB for QPSK with convolutional code rate 1/2 and 9.0 dB for 64QAM with 3/4 rate, respectively. The packet size is set to be 500 bytes. Furthermore, the retry limit is set to be 7 for all the investigated cases. Other simulation parameters are listed in Table 1.

In the first part of this section, the performance of C-ARQ is evaluated in a sparse network with only 4 or 8 relay nodes in comparison with that of DCF and PRCSMA. In the second part, the performance of the enhanced versions, P.C-ARQ, IT.C-ARQ and EB.C-ARQ, is evaluated in a dense network scenario where collision may become serious. Note that the number of relays listed in all the figures shown below means the number of *potential relays* in the simulated network. The actual number of relays that participate in each cooperative transmission cycle depends on channel conditions and system parameter configuration.

6.1 Sparse Relay Network

Figure 3a illustrates the throughput comparison of the investigated three protocols under different channel conditions with few potential relays in the network. The simulation results generally coincide with the theoretical analysis, both showing that throughput is enhanced by the cooperative schemes when channel condition is poor (E_t/N_0 in the range of 125∼145 dB). Moreover, we can also observe that C-ARQ outperforms PRCSMA generally over all ranges of the investigated channel conditions. In Fig. 3b, both the analytical and simulation results demonstrate that the PDR performance is enhanced significantly by C-ARQ. More

Table 1 Simulation parameters

MCS Scheme	QPSK 1/2 / 64 QAM 3/4	Basic datarate	6 Mbps
Payload length	500 bytes	CFR	14 bytes
MPDU header	24 bytes	DIFS	34 μs
PHY header	20 μs	SIFS	16 μs
Datarate	12 Mbps / 54 Mbps	Slottime	9 μs

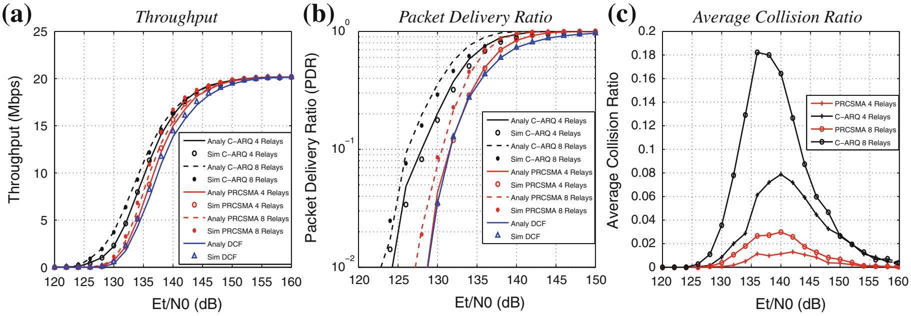


Fig. 3 Performance comparison in sparse networks

significant improvement is observed when the relay nodes are more densely distributed in the network [11].

The average number of collisions among all transmissions for C-ARQ and PRCSMA is illustrated in Fig. 3c. From this figure, one may notice that PRCSMA is to a large degree capable of avoiding collisions among relay nodes thanks to the DCF scheme. In contrast, C-ARQ which uses different backoff time at different contending relay nodes, turns out to be less efficient for collision avoidance. For example, the collision ratio in C-ARQ is 0.08 when there are 4 potential relays, but it increases sharply when the number of potential relays reaches 8. In a denser network with even more contending relays, the collision probability may become noticeably high.

6.2 Dense Relay Network

To evaluate and compare the performance of the three collision avoidance techniques, we configure a densely distributed network with 50 potential relays nodes and set the date rate to be 12 Mbps. In this way, the collision problem could be observed in more details. The other parameters are configured the same as in the previous subsection.

6.2.1 The P.C-ARQ Scheme

Figure 4 depicts the performance of P.C-ARQ with different values of p under different channel conditions. It is evident from these figures that parameter p is critical for the performance of P.C-ARQ. When channel condition is poor (E_t/N_0 between 110 dB and 120 dB), there are few qualified relay nodes in the network, a large value of p can give relay nodes better chance to participate cooperative retransmission. As channel condition becomes better (E_t/N_0 between 120 dB and 130 dB), more relays will contend for channel access, and the throughput impairment by packet collisions becomes more significant, which indicates that a smaller p value will provide better performance. However, p cannot be set to be too small, since it results in too few relay participants, leading to deteriorated throughput and PDR performance. When channels are in very good condition (E_t/N_0 is above 140 dB), cooperative retransmissions rarely happen. Therefore, p has smaller or even negligible influence on throughput performance.

In summary, different values of p should be used to maximize network performance under different channel conditions. The optimal values of p as well as the corresponding

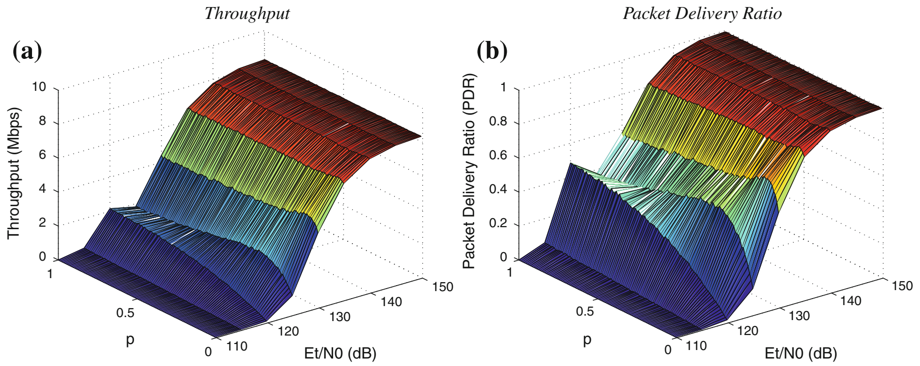


Fig. 4 Performance of P.C-ARQ in dense networks as a function of E_t/N_0 and p

Table 2 Optimal p in P.C-ARQ scheme

Et/N_0 (dB)	110	115	120	125	130	135	140	145	150
Optimal p	0.95	1.00	0.99	0.31	0.10	0.05	0.03	0.73	0.42
Throughput (Mbps)	0	0.27	2.21	2.78	5.12	7.05	7.91	8.22	8.32
PDR	0	0.06	0.50	0.54	0.72	0.89	0.96	0.99	1.00
Average collision ratio	0	0	0.20	0.31	0.15	0.07	0.02	0.01	0
Average num cooperations	0	0.07	0.78	0.87	0.45	0.17	0.05	0.02	0.01

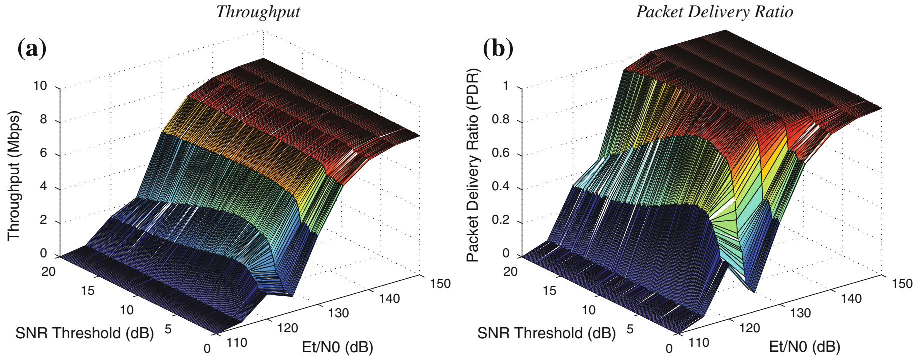


Fig. 5 Performance of IT.C-ARQ in dense networks as a function of E_t/N_0 and SNR threshold

performance in terms of throughput, PDR, average collision ratio and average number of retransmissions are listed in Table 2.

6.2.2 The IT.C-ARQ Scheme

Figure 5 depicts the performance of IT.C-ARQ with different SNR threshold values for relay selection (SNR_{low}) under different channel conditions. It is shown in both figures that

Table 3 Optimal SNR_{low} in IT.C-ARQ scheme

Et/N_0 (dB)	110	115	120	125	130	135	140	145	150
Optimal SNR_{low} (dB)	16.4	2.7	3.5	6.7	8.1	11.0	11.7	17.4	15.1
Throughput (Mbps)	0	0.28	2.62	4.13	6.18	7.56	8.09	8.28	8.33
PDR	0	0.06	0.59	0.89	1.00	1.00	1.00	1.00	1.00
Average collision ratio	0	0	0.14	0.63	0.05	0	0	0	0
Average num cooperations	0	0.07	0.78	1.20	0.73	0.28	0.09	0.03	0.01

SNR_{low} has significant impact on the performance of C-ARQ, especially where E_t/N_0 is between 115 dB and 140 dB.

As illustrated in Fig. 5, a determined optimal value of SNR_{low} that maximizes system throughput exists under each specific channel condition. When channel condition is poor and few relay nodes are qualified in the network, SNR_{low} should be small in order to allow more relay nodes to participate in cooperation. However, when there are more contending relays in the network and collisions may happen more often, SNR_{low} should be set to be a higher value to mitigate collision. The obtained optimal values of SNR_{low} and the corresponding performance are summarized in Table 3.

6.2.3 The EB.C-ARQ Scheme

Finally, we illustrate in Fig. 6 the performance of EB.C-ARQ in comparison with the optimal P.C-ARQ, optimal IT.C-ARQ , PRCSMA and DCF schemes under diverse channel conditions. The optimal values of p and SNR_{low} have been selected according to Table 2 and Table 3 respectively to maximize throughput performance. It can be observed from these two figures that EB.C-ARQ provides best throughput and PDR performance among all these schemes. P.C-ARQ is inferior to PRCSMA when E_t/N_0 is between 125 dB and 140 dB due to its relatively inefficient p-persistent channel access scheme for multiple relays.

The average collision ratios for these schemes are shown in Fig. 6c. Again, the EB.C-ARQ scheme appears as the most efficient scheme for collision avoidance. More specifically, in a dense network with 50 potential relays, the peak value of the average collision ratio is

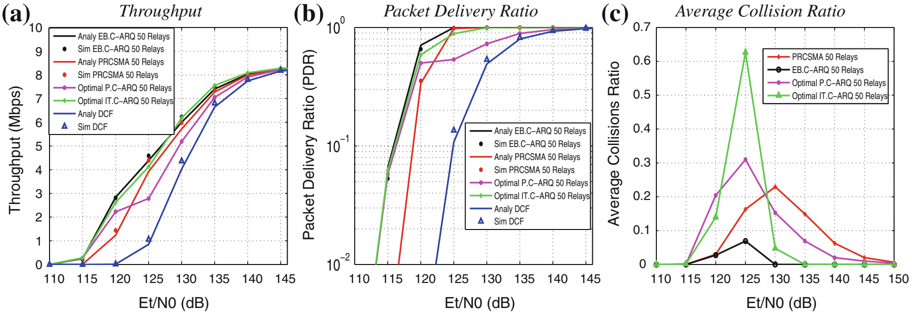


Fig. 6 Performance comparison in dense networks

still below 0.07 for EB.C-ARQ, which is much lower than 0.24 for PRCSMA and 0.27 for P.C-ARQ. The high value of collision ratio in P.C-ARQ in Fig. 6c also explains the reason of its inferior throughput and PDR performance.

In addition to the superior throughput and PDR performance over its counterparts, P.C-ARQ and IT.C-ARQ, another advantage of EB.C-ARQ is its simplicity in implementation, since no parameters need to be adjusted even though channel conditions may vary.

7 Conclusions

Cooperative communication becomes a characteristic of future 5G wireless networks due to the ubiquity of wireless devices. As a baseline segment in a multi-hop communication chain, we target the scenario of one-hop direct cooperation communication between source and destination in this study. A cooperative MAC protocol, C-ARQ, has been proposed, addressing all the three key issues concerning cooperative communications from the perspective of MAC design. Through analysis and simulations, we demonstrate that C-ARQ generally outperforms the original DCF and PRCSMA protocols, in terms of both throughput and packet delivery ratio performance. Moreover, P.C-ARQ, IT.C-ARQ and EB.C-ARQ are proposed and studied in depth in order to further avoid collisions in a dense network. EB.C-ARQ outperforms the other two schemes with low implementation complexity as well as low collision rate due to its high accuracy of distinguishing relay nodes.

References

1. Laneman, J. N., Tse, D. N. C., & Wornell, G. W. (2004). Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory, 50*(12), 3062–3080.
2. Valentin, S., Lichte, H. S., Karl, H., Vivier, G., Simoens, S., Vidal, J., & Agustin, A. (2009). Cooperative wireless networking beyond store-and-forward: Perspectives in PHY and MAC design. *Wireless Personal Communication, 48*, 49–68.
3. Levorato, M., Tomasin, S., & Zorzi, M. (2008). Cooperative spatial multiplexing for ad hoc networks with hybrid ARQ: System design and performance analysis. *IEEE Transactions on Communications, 56*(9), 1545–1555.
4. Azgin, A., Altunbasak, Y., & AlRegib, G. (2005). Cooperative MAC and routing protocols for wireless ad hoc networks. *Proceedings of IEEE GLOBECOM, 5*, 2854–2859.
5. Moh, S., Yu, C., Park, S., & Kim, H. (2007). CD-MAC: Cooperative diversity MAC for robust communication in wireless ad hoc networks. *Proceedings of IEEE ICC, 1*, 3636–3641.
6. Dianati, M., Ling, X., Naik, K., & Shen, X. (2006). A node-cooperative ARQ scheme for wireless ad hoc networks. *IEEE Transactions on Communications, 55*, 1032–1044.
7. Alonso-Zarate, J., Kartsakli, E., Verikoukis, C., & Alonso, L. (2008). Persistent RCSMA: A MAC protocol for a distributed cooperative ARQ scheme in wireless networks. *EURASIP Journal on Advances in Signal Processing, 2008*, 13.
8. Liu, P., Tao, Z., Narayanan, S., Korakis, T., & Panwar, S. (2007). CoopMAC: A cooperative MAC for wireless LANs. *IEEE JSAC, 25*, 340–354.
9. Pathmasuritharam, J. S., Das, A., & Gupta, A. K. (2005). Efficient multirate relaying (EMR) MAC protocol for ad hoc networks. *Proceedings of IEEE ICC, 5*, 2947–2951.
10. Bletsas, A., Khisti, A., Reed, D. P., & Lippman, A. (2006). A simple cooperative diversity method based on network path selection. *IEEE JSAC, 24*(3), 672–695.
11. He, X., & Li, F. Y. (2010). A multi-relay cooperative automatic repeat request protocol in wireless networks. *Proceedings of IEEE ICC*.
12. Bianchi, G. (2000). Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE JSAC, 18*(1), 535–547.

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