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Analysis and determination of cooperative MAC strategies from throughput perspectives

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Abstract In recent years, cooperative communication has been developed as a new communication strategy that incorporates a relay node to assist direct point-to-point transmission. By exploiting cooperative diversity, different types of techniques have been proposed to improve transmission reliability from the physical layer perspective. However, owing to the longer transmission time resulting from the cooperative schemes, there is no guarantee to enhance network throughput in view of the medium access control (MAC) performance. In this paper, system throughput of combined direct/cooperative communication is evaluated by exploiting the proposed analytical model based on the IEEE 802.11 MAC protocol. The feasibility of adopting either cooperative or direct communication is also studied in the analytical model. In terms of network throughput, whether to adopt cooperative schemes depends on the tradeoff between cooperative transmission delay and channel quality of direct communication. Moreover, two cooperative MAC protocols are proposed to determine the circumstances to activate cooperative communication according to the channel quality. The full-channel quality indicator based cooperative (FCC) MAC protocol is introduced to choose both the transmission scheme and the relay node according to the full channel quality information. However, the overhead caused by the FCC scheme can degrade the throughput performance as the number of available relays is significantly increased. Therefore, the bitwise competition based cooperative (BCC) MAC protocol is utilized to efficiently determine a feasible relay node for data transmission. Simulations are performed to validate the effectiveness of proposed analytical models and cooperative MAC protocols. It is observed that the proposed BCC scheme can outperform both the FCC protocol and conventional direct transmission with enhanced system throughput.

Keywords Cooperative communication · Performance analysis · IEEE 802.11 standard · Medium access control · Relay selection

1 Introduction

Due to the unreliable environment for wireless communication, different types of transmission schemes have been developed to maintain the quality of communication. Multi-input multi-output (MIMO) systems are introduced to achieve high capacity by taking advantages of multipath channels and spatial diversity. However, multi-antenna system equipped within mobile devices may not be easily deployed due to the limitation of its physical size. Recently, techniques for cooperative communications are proposed to effectively enhance the diversity gain and robustness based on the broadcast nature of wireless communication. Through the help of relays in the network, the virtual antenna array can be formed in order to increase the transmission reliability. In other words, data communication between the source and the destination is captured by the relay, which duplicates the frame and consequently delivers it to the destination. In order to acquire diversity gain, the duplicated frames are received and combined at

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the destination by exploiting different methods, e.g. the maximum ratio combining (MRC) algorithm. Moreover, the amplify-and-forward (AF) and decode-and-forward (DF) proposed in [1] are the two commonly used schemes in cooperative communications. In the AF scheme, the relay simply amplifies and forwards the frames that are acquired from the source; while the relay forwards the received frames to the destination after decoding them correctly in the DF scheme.

Research works have been conducted to explore the cooperative communications from various aspects. The analysis of cooperative diversity by adopting different cooperative schemes has been investigated in [2–4]; while [5] develops several cooperative strategies and calculates the resulting capacity. The work presented in [6–8] also delivers the cooperative schemes from the physical (PHY) layer perspectives. The symbol-error-rate performance analysis and optimum power allocation are provided in [6, 7] with different modulation types. Variable-rate two-phase collaborative communication scheme is proposed in [8] which also provides performance analysis of outage probability. Moreover, the performance of cooperative communication can further be improved with the utilization of coding strategy as shown in [9, 10]. With the consideration of fading channels, distributed space-time coding schemes and their associated performance analysis are introduced in [11–13]. Furthermore, cooperative automatic repeat request (ARQ) techniques in [14–16] exploit the cooperative diversity to achieve efficient retransmission; while [17] provides the analysis of frame error rate (FER) under various cooperative ARQ protocols. On the other hand, the relaying node selection algorithm (RSA) is proposed in [18] based on maximization of channel capacity in order to lower the computational complexity.

However, it is noticeable that most of the research work focuses on cooperative communications from the viewpoint of information theory and PHY layer design. Although the FER can be ameliorated by means of the cooperative diversity, there is no assurance to result in enhanced network throughput due to the tradeoff between the FER and the longer frame transmission time. In general, the cooperative schemes will lead to prolonged frame transmission time no matter the AF-based or the DF-based protocols are applied. With the adoption of half-duplex channel, two phases are required for relay-based communication in order to complete the data transmission. In other words, data frame must be delivered from the source to both the destination and the relay with duplicated frame transmitted from the relay to the destination.

In order to evaluate the combined system including the conventional direct transmission and the cooperative communication in terms of network throughput, a suitable analytical model from the medium access control (MAC) perspective should be exploited. The IEEE 802.11 [19] has been considered a well-adopted standard for wireless local area networks (LANs). In the IEEE 802.11 MAC protocol, the distributed coordination function (DCF) is utilized as the basic mechanism for channel access. The DCF ensures that each node can acquire a fair opportunity to access the wireless medium according to the carrier sensing multiple access with collision avoidance (CSMA/CA) scheme. A random backoff process is executed in each node for the purpose of decreasing the probability of data collision. Moreover, the request-to-send (RTS)/clear-to-send (CTS) exchange before the data transmission is employed in order to resolve the potential hidden terminal problem. A great amount of existing research [20–22] contributes to the establishment of analytical models for the IEEE 802.11 MAC protocol. The saturation throughput of IEEE 802.11 DCF is obtained via a two-dimensional Markov chain model as proposed in [20]. Work presented in [21, 22] further considers channel error conditions into the design of analytical models.

In this paper, the backoff model of IEEE 802.11 MAC extended from [20, 21] is adopted to analyze the saturation throughput of cooperative techniques. Both cooperative and direct communications are considered in the design of the proposed analytical model. Simulations are also exploited for validating the effectiveness of proposed model. It can be observed from the analytical results that the performance of cooperative communication is affected by various factors, especially the FER and the frame transmission delay. Cooperative schemes in general result in decreased FER; while the rerouting delay incurred by the cooperative process can considerably degrade the network throughput. The feasible circumstances to adopt the cooperative algorithms are suggested in this paper by considering the tradeoff between the FER and the transmission delay for the enhancement of network throughput.

Furthermore, it is important to provide feasible determination mechanisms to choose an appropriate relay for cooperative communication while there are more than one available relay in the network. The CoopMAC protocol proposed in [23] provides cooperation from mobile stations with higher data rate to assist the other stations with lower data rate during data transmission. The relay selection scheme in CoopMAC protocol is merely based on the observations from previous data transmissions. Moreover, the CD-MAC [24] and CMAC [25] protocols are developed to proactively and randomly select the feasible relays respectively. However, the determination schemes within these cooperative MAC protocols can result in degraded performance under fast-changing channel conditions. There are research works such as [26–28] that focused on the topic of relay selection according to the network channel quality. Energy issue is further considered in [29] in order to balance the power consumption of mobile users. Game theory is also exploited in [30] to provide a theoretical infrastructure for relay selection. However, most of these existing techniques for relay selection only considered the channel quality instead of throughput performance, which will result in decreased throughput performance in spite of possible improvement of FER. In other words, a suitable design of MAC protocol by considering both the FER and the transmission time is necessitate for increasing the network throughput in cooperative communication. In [31], the CRBAR scheme is proposed for multi-rate wireless networks, and the stations with low data rate can be assisted by relays with high data rates. However, when the number of relays is increased, the throughput performance will be degraded because of the increasing probability of collision between the frames transmitted by the relays.

Therefore, based on all the issues mentioned above, two MAC protocols are proposed in this paper to provide the determination mechanisms to activate the cooperative communication after acquiring the instantaneous channel quality indicator (CQI), which contains the information of channel quality, e.g. SNR. In the full CQI based cooperative (FCC) MAC protocol, the destination node will select a feasible relay based on the acquisition of all the channel quality information. On the other hand, in order to decrease the excessive exchanges of control frames, the bitwise competition based cooperative (BCC) MAC protocol is proposed to choose an appropriate relay after acquiring the channel quality information between the source and relay nodes. The channel quality information between the potential relay nodes are contended based on bit-by-bit manner in order to select the feasible node to conduct packet forwarding to the destination. Even though only partial CQI information is obtained by the proposed BCC protocol, the resulting throughput performance can still be increased with reduced control overhead. Based on the simulation results, it is discovered that both proposed FCC and BCC protocols can significantly enhance the network throughput, especially in the case that the direct communicating channel is under deep fading environments.

Noted that the benefits acquired by adopting the cooperative scheme were firstly presented in our previous work in [32] based on a simplified analytical model from throughput perspective. In this work, we develop a more comprehensive analytical model for cooperative throughput analysis associated with the design of cooperative MAC protocols in order to further enhance the network throughput. The rest of this paper is organized as follows. The modeling of backoff operations with combined direct/cooperative strategy is presented in Sect. 2. Section 3 describes the analytical modeling and validation for the saturation throughput based on the combined strategy. Section 4 explains the proposed FCC and BCC MAC protocols for relay selection; while numerical evaluation is performed in Sect. 5. Section 6 draws the conclusions.

2 Markovian model with combined direct/cooperative strategy

As shown in Fig. 1, the network scenario considered in the performance analysis consists of one destination, one fixed relay, and N user nodes. In general, the destination node can be regarded as an access point for uplink data transmission. In this paper, instead of assigning mobile devices to serve as the relays for frame transmission, one fixed relay node is considered and exploited. The major reason is primarily owing to the excessive power consumption that will be incurred within the mobile devices while relaying data frames for other network nodes. Moreover, we assume that the user nodes and relay are located within the transmission range of destination node. The major reason is for ease of analysis and is considered practical in most of the wireless networks mentioned in the existing works [23–31] and heterogeneous networks [33–36] nowadays. Both direct and two-hop communications are considered as the network scenario in the analysis.

Furthermore, security issues and potential unknown movements are also concerned to adopt mobile devices for data forwarding. In addition, the users in the network can be adaptively categorized into non-cooperative and cooperative groups depending on the transmission requirements. The users in non-cooperative group transmit data frames based on conventional direct transmissions; while those in cooperative group transmit their data frames via the

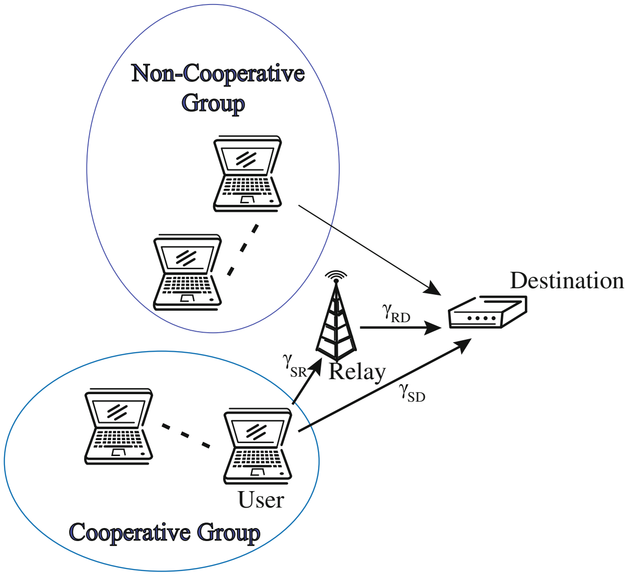

Fig. 1 Network scenario with the combined direct/cooperative transmission scheme

assistance of relay node. The total number of nodes in the non-cooperative and cooperative groups are denoted as N_{dir} and N_{coop}, respectively. It is noted that DF cooperative communication is adopted in the analysis. That is, the source transmits the data frame to both the relay and destination in phase I. In phase II, the relay forwards the received data frame to the destination if the data is correctly decoded by the relay. Finally, the MRC method is utilized by the destination to combine the data frames from both the source and relay. Moreover, the channels between these network nodes are modeled as independent, flat Rayleigh fading, and zero-mean additive white Gaussian noise with unit variance. Each node is equipped with a single antenna where half-duplex transmission is assumed, i.e. simultaneously transmitting and receiving data frames is not considered. The parameters γ_{SD}, γ_{SR}, and γ_{RD} as illustrated in Fig. 1 denote the instantaneous received signal-to-noise ratio (SNR) of the source-destination link, the source-relay link, and the relay-destination link respectively. Their corresponding average received SNR values are represented as σ_{SD}, σ_{SR}, and σ_{RD}.

In order to evaluate the throughput performance of the system which adopts both the direct and cooperative strategies, the conventional model for backoff mechanism is adjusted to incorporate both the direct and cooperative schemes. The Markov chain model of the backoff mechanism is shown in Fig. 2. The backoff operation $(s(t), b(t))$ consists of two stochastic processes, where $s(t) \in [0, m+r]$ indicates the backoff stage with the maximum $m+r$ times of retransmission opportunities, and $b(t) \in [0, W_i]$ denotes the backoff timer whose maximum value at the ith stage can be represented as

$$W_i = \begin{cases} 2^i \cdot W & 0 \le i \le m \\ 2^m \cdot W & m < i \le m+r \end{cases} \quad (1)$$

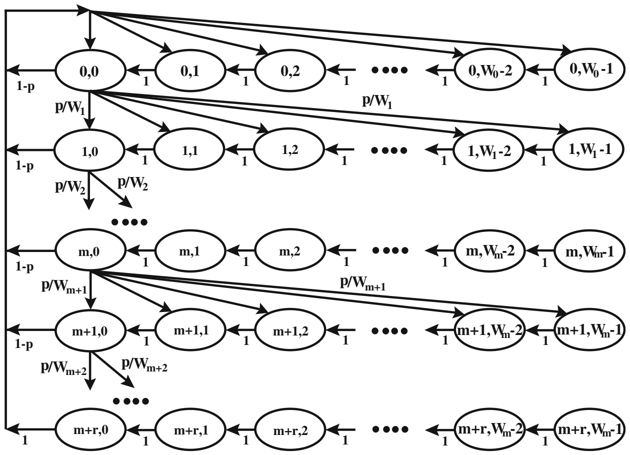

Fig. 2 Markov chain model for the backoff mechanism with the combined direct/cooperative strategy

where W denotes the minimum contention window size, m represents the maximum backoff stage, and $m+r$ is the retry limit. Note that the contention window size will become W_{max} after m times of retransmission opportunities, i.e. $W_{max} = 2^m \cdot W$. The contention window size will remain at the value of W_{max} until the packet is either successfully transmitted or discarded if the number of failed retransmission reaches the maximum retry limit, i.e. $m+r$. Therefore, the window size $W_i = 2^m \cdot W$ for $m < i \le m+r$ as presented in (1). The parameter p as shown in Fig. 2 represents the probability of receiving an inaccurate frame at the destination. The unsuccessful reception of data frames at the destination is resulted from either the frame collision or transmission error. It is noticed that the meaning of parameter p within the Markov chain model can be different in each node depending on which group it belongs to. The parameters p_{dir} and p_{coop} are introduced as the probabilities of receiving an inaccurate frame at the destination via the direct and cooperative transmission, respectively. Specifically, owing to different FER values caused by different transmission schemes, the parameter p will be replaced by p_{dir} in the Markov chain model for nodes in the non-cooperative group. On the other hand, p_{coop} will substitute the parameter p with nodes in the cooperative group. For simplicity, the parameter p will still be utilized in some of the following derivations in the case that both groups share the same equations.

Furthermore, the transition probabilities, which are defined as $P_t(i_1, k_1 | i_0, k_0) \triangleq P_t(s(t+1) = i_1, b(t+1) = k_1 | s(t) = i_0, b(t) = k_0)$, can be obtained as

$$\begin{cases} P_t(i,k|i,k+1) = 1 & k \in [0, W_i - 2],\ i \in [0, m+r] \\ P_t(i,k|i-1,0) = \frac{p}{W_i} & k \in [0, W_i - 1],\ i \in [1, m+r] \\ P_t(0,k|i,0) = \frac{1-p}{W_0} & k \in [0, W_0 - 1],\ i \in [0, m+r-1] \\ P_t(0,k|m+r,0) = \frac{1}{W_0} & k \in [0, W_0 - 1] \end{cases} \quad (2)$$

Let $\pi_{i,k} \triangleq \lim_{t \to \infty} P_t(s(t) = i, b(t) = k)$ be defined as the stationary probability with $i \in [0, m+r]$ and $k \in [0, W_i - 1]$, the stationary probabilities can be correlated to $\pi_{0,0}$ as follows:

$$\begin{cases} \pi_{i,k} = \frac{W_i - k}{W_i} \cdot \pi_{i,0} & k \in [0, W_i - 1],\ i \in [0, m+r] \\ \pi_{i,0} = p^i \cdot \pi_{0,0} & i \in [0, m+r] \end{cases} \quad (3)$$

Consequently, based on $\sum_{i=0}^{m+r} \sum_{k=0}^{W_i - 1} \pi_{i,k} = 1$, the stationary probability $\pi_{0,0}$ can be obtained as

$$\pi_{0,0} = \left[\sum_{i=0}^{m} p^i w_i + \sum_{i=m+1}^{m+r} p^i w_m \right]^{-1} \quad (4)$$

where $w_i = (W_i + 1)/2$ and $w_m = (W_m + 1)/2$. The characteristics of proposed Markov chain model with combined strategy can be illustrated via (2)–(4) after p, i.e. p_{dir} and p_{coop}, can be obtained. The determination of these two probabilities is explained as follows.

The probabilities that a node in the non-cooperative and cooperative group transmit within a randomly selected time slot, i.e. the conditional transmission probabilities τ_{dir} and τ_{coop}, can be respectively expressed as

$$\tau_{dir} = \sum_{i=0}^{m+r} \pi_{i,0} = \pi_{0,0}\left(\frac{1-p_{dir}^{m+r+1}}{1-p_{dir}}\right) \tag{5}$$

$$\tau_{coop} = \sum_{i=0}^{m+r} \pi_{i,0} = \pi_{0,0}\left(\frac{1-p_{coop}^{m+r+1}}{1-p_{coop}}\right) \tag{6}$$

Note that the probability for a node to transmit a packet can be obtained based on the stationary probability of each state in the Markov chain. Since a node will transmit a packet only when its backoff counter is equal to zero, the packet will be transmitted in state $\pi_{i,0}$ where $i \in [0; m+r]$. After deriving the stationary probability of the chain $\pi_{i,k}$ as shown in (3) and (4), the probability that a node transmits a packet, i.e. either τ_{dir} or τ_{coop}, can therefore be obtained from (5) and (6). Let $\overline{P}_{f(dir)}$ and $\overline{P}_{f(coop)}$ denote the average FER resulted from transmission error through the direct and the cooperative transmission respectively. The following relationships can be obtained:

$$p_{dir} = 1 - (1 - \overline{P}_{f(dir)})(1 - p_c) \tag{7}$$

$$p_{coop} = 1 - (1 - \overline{P}_{f(coop)})(1 - p_c) \tag{8}$$

where the collision probability p_c in (7) and (8) is derived as the probabilities that the destination receives an inaccurate frame. The collision probability pc can be acquired as

$$p_c = 1 - \Big[\mathcal{R}_{cg}(1-\tau_{coop})^{N_{coop}-1}(1-\tau_{dir})^{N_{dir}} + (1-\mathcal{R}_{cg})(1-\tau_{coop})^{N_{coop}}(1-\tau_{dir})^{N_{dir}-1}\Big] \tag{9}$$

with $\mathcal{R}_{cg}$ denoting the ratio of node number in cooperative group to the total number of network nodes, i.e. $\mathcal{R}_{cg} = N_{coop}/N$. The second term in pc represents that only one node in the cooperative group can successfully transmit its packet; while all the other $(N_{coop} - 1)$ nodes in the cooperative group and N_{dir} nodes in the non-cooperative group did not transmit their packets. The third term can also be explained in similar manner. Note that (9) considers the assumption of saturation traffic that there is always a packet waiting to be transmitted for each node.

Therefore, it can be observed that both p_{dir} and p_{coop} are functions of the conditional transmission probabilities τ_{dir} and τ_{coop}. On the other hand, by substituting (4) into (5) and (6), the probabilities τ_{dir} and τ_{coop} can be represented as a function of p_{dir} and p_{coop} respectively. As a result, the values of p_{dir}, p_{coop}, τ_{dir}, and τ_{coop} can be acquired through numerically solving the nonlinear equations from (5) to (8). Note that one of the major contributions for the proposed analytical model is to jointly consider the parameters τ_{dir} and τ_{coop} for the derivation of collision probability p_c in (9), and further obtain the probabilities of receiving an inaccurate frame at the destination via different transmission schemes, i.e. p_{dir} and p_{coop}. On the other hand, conventional models for IEEE 802.11 throughput analysis [20] can only be utilized to obtain τ_{dir}/τ_{coop} and p_{dir}/p_{coop} independently. In other words, it is only feasible to describe the contention-based network with only either direction or cooperative communication between the network nodes. Based on the proposed model, the throughput performance for the networks with both direct and cooperative communications can be acquired.

3 Throughput analysis for direct/cooperative schemes

The saturation throughput based on the Markovian model as proposed in Sect. 2 will be analyzed and compared. The feasible occasion to adopt either the direct or the cooperative scheme will be explored under different channel quality. Note that the main purpose of this work is to develop and observe the throughput performance of a contention-based network with the existence of both cooperative and non-cooperative nodes. Therefore, we develop the analytical model that includes both direct and two-hop communications within the network under saturation traffic consideration. Based on the throughput analysis, two relay-assisted MAC protocols will be proposed in the next section. In the first subsection, the FER values are calculated for both direct and cooperative strategies. The saturation throughput analysis is described in the second subsection; while the performance comparisons are conducted in the third subsection. In order to effectively enhance the system performance, the results obtained from throughput analysis will be utilized in the design of feasible cooperative MAC protocols, which will be described in Sect. 4.

3.1 FER calculation for direct/cooperative transmissions

In this subsection, the average FER values through both the direct and cooperative links, i.e. $\overline{P}_{f(dir)}$ and $\overline{P}_{f(coop)}$, will be obtained from the average SNR values via their corresponding channel quality. The derivation from instantaneous SNR to its resulting FER value has been studied in [6, 37, 38]. Several influential factors are considered within their formulation, including the modulation type, coding strategy, channel quality, and frame sizes. In order to facilitate the derivation of throughput performance in the next subsection, an efficient model as proposed in [38] is utilized by adopting an exponential relationship between the instantaneous FER $P_{f,ij}$ and SNR value γ_{ij} as

$$P_{f,ij} = \begin{cases} \alpha \cdot e^{-g\gamma_{ij}}, & \gamma_{ij} > \gamma_t \\ 1, & \gamma_{ij} \leq \gamma_t \end{cases} \tag{10}$$

where the subscript *ij* within the parameters represents the channel from node *i* to node *j*. For example, as shown in Fig. 1, γ_{SD} indicates the instantaneous received SNR of the source-destination link associated with its corresponding instantaneous FER value $P_{f,SD}$. Depending on different modulation and coding schemes, the parameters α, g, and the threshold γ_t within (10) can be obtained from the least-square fitting method as shown in [38] based on the tolerable bit error rate threshold. Simply stated, the instantaneous FER $P_{f,ij}$ can be derived from the exponential function if the received SNR γ_{ij} exceeds the threshold γ_t. Moreover, due to the exponential distribution of received SNR for Rayleigh fading channel, the probability distribution function (pdf) of received SNR γ_{ij} can be acquired as

$$f_{\Gamma_{ij}}(\gamma_{ij}) = \frac{1}{\sigma_{ij}} e^{-\gamma_{ij}/\sigma_{ij}} \tag{11}$$

where σ_{ij} corresponds to the average received SNR of the channel from node *i* to node *j*, i.e. $\sigma_{ij} \triangleq E[\gamma_{ij}]$.

The average FER via conventional direct transmission, i.e. $\overline{P}_{f(dir)}$, can be derived by calculating the average FER of the source-destination channel $\overline{P}_{f,SD}$. By considering the relationship between instantaneous and average FER values over the channel realizations, the average FER $\overline{P}_{f(dir)}$ from direct link can be obtained as

$$\begin{aligned} \overline{P}_{f(dir)} = \overline{P}_{f,SD} &= \int_0^\infty P_{f,SD} \cdot f_{\Gamma_{SD}}(\gamma_{SD}) d\gamma_{SD} \\ &= \int_0^{\gamma_t} 1 \cdot \frac{1}{\sigma_{SD}} e^{-\gamma_{SD}/\sigma_{SD}} d\gamma_{SD} \\ &\quad + \int_{\gamma_t}^\infty \alpha e^{-g\gamma_{SD}} \cdot \frac{1}{\sigma_{SD}} e^{-\gamma_{SD}/\sigma_{SD}} d\gamma_{SD} \\ &= 1 - \frac{g\sigma_{SD}}{1 + g\sigma_{SD}} e^{-\gamma_t/\sigma_{SD}} \end{aligned} \tag{12}$$

where $f_{\Gamma_{SD}}(\gamma_{SD})$ and σ_{SD} are obtained as defined in (11). On the other hand, due to the utilization of DF scheme in cooperative communication, whether the relay can correctly decode the received data frame or not is required to be considered in the derivation of $\overline{P}_{f(coop)}$. In other words, if the relay correctly decodes the received data frame, the destination can combine two copies of data frame from both the source and relay nodes. Otherwise, only one copy of the data frame will be received at the destination. Therefore, the FER value $\overline{P}_{f(coop)}$ by adopting the cooperative scheme is obtained as

$$\overline{P}_{f(coop)} = (1 - \overline{P}_{f,SR}) \cdot \overline{P}_{f,(SR)D} + \overline{P}_{f,SR} \cdot \overline{P}_{f,SD} \tag{13}$$

where $\overline{P}_{f,SD}$ can be acquired from (12). $\overline{P}_{f,SR}$ represents the average FER from the source to the relay and is obtained similar to $\overline{P}_{f,SD}$ as

$$\overline{P}_{f,SR} = 1 - \frac{g\sigma_{SR}}{1 + g\sigma_{SR}} e^{-\gamma_t/\sigma_{SR}} \tag{14}$$

Furthermore, $\overline{P}_{f,(SR)D}$ in (13) represents the average FER at the destination after combining data frames from both the source and relay. The calculation of $\overline{P}_{f,(SR)D}$ can be acquired with the consideration of both source-destination and relay-destination channels as

$$\begin{aligned} \overline{P}_{f,(SR)D} &= \int_0^\infty \int_0^\infty P_{f,(SR)D} \cdot f_{\Gamma_{SD}}(\gamma_{SD}) f_{\Gamma_{RD}}(\gamma_{RD}) d\gamma_{SD} d\gamma_{RD} \\ &= 1 - \left[\frac{\sigma_{RD}}{\sigma_{RD} - \sigma_{SD}} \frac{g\sigma_{RD}}{1 + g\sigma_{RD}} e^{-\gamma_t/\sigma_{RD}} \right. \\ &\quad \left. - \frac{\sigma_{SD}}{\sigma_{RD} - \sigma_{SD}} \frac{g\sigma_{SD}}{1 + g\sigma_{SD}} e^{-\gamma_t/\sigma_{SD}} \right] \end{aligned} \tag{15}$$

where $P_{f,(SR)D}$ is the instantaneous FER at the destination after DF combination. It is noted that the benefit of adopting exponential relationship between the FER and its corresponding SNR as in [38] can be observed. With the knowledge of both channel quality and estimated parameters α, g, and γ_t, the average FER $\overline{P}_{f(coop)}$ through cooperative communication can therefore be derived as in (13). The results obtained above will be utilized to measure the suitability of cooperative communication compared to the direct transmission under different channel qualities.

3.2 Saturation throughput analysis

The purpose of this subsection is to obtain the relationship between the SNR values and the corresponding network throughput based on the results obtained from the previous subsection. For the derivation of throughput performance, a contention-based MAC protocol with cooperative communications is adopted. It is designed based on the IEEE 802.11 CSMA/CA scheme [20] associated with the usage of RTS/CTS exchanges. For the purpose of informing network nodes regarding the activation of cooperative communication, two new control frames named cooperative ready-to-send (cRTS) and cooperative clear-to-send (cCTS) are created. It is noted that the cRTS and cCTS fames have the same structures as the RTS and CTS frames respectively except for the subtype field of MAC header. In other words, several reserved values of the subtype field in IEEE 802.11 standard can be utilized to create these new control frames for representing different control messages. Moreover, the channel will be secured to be collision-free after the exchanges of either the RTS/CTS frames or the cRTS/cCTS frames. Specifically, nodes in the cooperative group first initiate the cRTS frame in order to notify the other nodes for data delivery via cooperative communication. The cooperative communication will therefore be activated if the cCTS frame is issued by the corresponding destination. Subsequently, the source will transmit the data frame in the first phase to both the relay and the destination. The relay will forward the received data frame to the destination after a short interframe space (SIFS) duration, which completes the second phase of the cooperative scheme. On the other hand, nodes in the non-cooperative group will transmit their data frame based on the conventional RTS/CTS exchange for channel reservation. Due to the comparably smaller size to the data frames, the frame error of non-data frames is considered neglected. It is noticed that the scheme mentioned above will be utilized as a preliminary evaluation of saturated network throughput in the next subsection. Other contention-based MAC protocol with cooperative diversity can also be designed and analyzed in similar manner.

The saturation throughput is defined as the fraction of time utilized to successfully transmit the payloads. In order to facilitate the computation of network throughput, two associated probabilities p_{tr} and p_{wc} are introduced as follows. The parameter p_{tr} denotes the probability that at least one transmission occurs in the considered time slot, i.e.

$$p_{tr} = 1 - (1 - \tau_{coop})^{N_{coop}} (1 - \tau_{dir})^{N_{dir}} \tag{16}$$

Moreover, p_{wc} indicates the probability of a non-collided transmission on the condition that at least one node is transmitting. It is composed by two probabilities $p_{wc(cg)}$ and $p_{wc(ncg)}$, i.e. $p_{wc} = p_{wc(cg)} + p_{wc(ncg)}$. The parameter $p_{wc(cg)}$ represents one node in the cooperative group reserves the channel while the other nodes remain silent during the time slot, i.e. no collision occurs. On the other hand, $p_{wc(ncg)}$ represents that one node in the non-cooperative group successfully reserves the channel and transmits its data frames. These two probabilities can be obtained as

$$p_{wc(cg)} = \frac{N}{p_{tr}} \left[\mathcal{R}_{cg} \tau_{coop} (1 - \tau_{coop})^{N_{coop}-1} (1 - \tau_{dir})^{N_{dir}} \right] \tag{17}$$

$$p_{wc(ncg)} = \frac{N}{p_{tr}} \left[(1 - \mathcal{R}_{cg}) \tau_{dir} (1 - \tau_{dir})^{N_{dir}-1} (1 - \tau_{coop})^{N_{coop}} \right] \tag{18}$$

Furthermore, the saturation throughput S, which is defined as a function of $\mathcal{R}_{cg}, \overline{P}_{f(dir)}$, and $\overline{P}_{f(coop)}$, can be expressed as

$$S(\mathcal{R}_{cg}, \overline{P}_{f(dir)}, \overline{P}_{f(coop)}) = \frac{E[L_P]}{E[T_B] + E[T_S] + E[T_C] + E[T_E]} \tag{19}$$

The expected values within (19) are obtained as follows. $E[T_B] = (1 - p_{tr})\delta$ indicates the average duration of non-frozen backoff time in a virtual time slot. It is noted that the virtual time slot represents the time duration between two consecutive backoff timers. The parameter δ is defined as the size of one slot time specified in the physical layer of IEEE 802.11 standard. The average duration of successful transmission in a virtual time slot is acquired as

$$\begin{aligned} E[T_S] = {} & p_{tr} \big[p_{wc(cg)} (1 - \overline{P}_{f(coop)}) T_{s(coop)} \\ & + p_{wc(ncg)} (1 - \overline{P}_{f(dir)}) T_{s(dir)} \big] \end{aligned} \tag{20}$$

where $T_{s(dir)}$ and $T_{s(coop)}$ are the required time intervals for a successful transmission via the direct and the cooperative communications respectively. These two parameters are obtained as

$$\begin{aligned} T_{s(dir)} = {} & T_{RTS} + T_{CTS} + T_{Header} + T_{Payload} + T_{ACK} \\ & + 3T_{SIFS} + 4\rho + T_{DIFS} \end{aligned} \tag{21}$$

$$\begin{aligned} T_{s(coop)} = {} & T_{cRTS} + T_{cCTS} + 2T_{Header} + 2T_{Payload} + T_{ACK} \\ & + 4T_{SIFS} + 5\rho + T_{DIFS} \end{aligned} \tag{22}$$

where ρ is denoted as the propagation delay. It is noted that the meanings of the other parameters are revealed by their corresponding subscripts, e.g. T_{Header} and $T_{Payload}$ indicate the time interval for transmitting the header and payload in a frame respectively and are related to the transmission rate, and T_{DIFS} corresponds to the time duration of a distributed inter-frame space (DIFS). Moreover, $E[T_C]$ represents the average time duration for transmissions with collisions in a virtual time slot. The mean duration of a failure transmission caused by the channel fading and noises is denoted as $E[T_E]$. Both $E[T_C]$ and $E[T_E]$ are obtained as

$$E[T_C] = p_{tr} (1 - p_{wc}) T_c \tag{23}$$

$$E[T_E] = p_{tr} [p_{wc(cg)} \overline{P}_{f(coop)} T_{e(coop)} + p_{wc(ncg)} \overline{P}_{f(dir)} T_{e(dir)}] \tag{24}$$

where T_c denotes the time interval for the transmissions with the occurrence of frame collisions, i.e. $T_c = T_{RTS} + \rho + T_{DIFS}$. On the other hand, the parameters $T_{e(dir)}$ and $T_{e(coop)}$ are the required time durations to receive and detect the error frame caused from the channel fading and noises. Both values are considered the same as that for successful transmissions, i.e. $T_{e(dir)} = T_{s(dir)}$ and $T_{e(coop)} = T_{s(coop)}$.

Finally, the parameter $E[L_P]$ represents the average payload bits that are successfully transmitted in a virtual time slot, which can be acquired as

$$E[L_P] = p_{tr}\{p_{wc(cg)}(1 - \overline{P}_{f(coop)})E[L_{Payload}] + p_{wc(ncg)}(1 - \overline{P}_{f(dir)})E[L_{Payload}]\} \tag{25}$$

where $E[L_{Payload}]$ indicates the average number of payload bits in a data frame. The saturation throughput S as defined in (19) can therefore be obtained. Moreover, two special cases for the saturation throughput S are considered as follows. S_{dir} represents the saturation throughput if all the nodes are in the non-cooperative group; while S_{coop} indicates that with the exploitation of cooperative schemes for the entire system, i.e. all the nodes are in the cooperative group. These two special cases can be defined as

$$S_{dir} \triangleq S(\mathcal{R}_{cg} = 0, \overline{P}_{f(dir)}, \overline{P}_{f(coop)} = 0) \tag{26}$$

$$S_{coop} \triangleq S(\mathcal{R}_{cg} = 1, \overline{P}_{f(dir)} = 0, \overline{P}_{f(coop)}) \tag{27}$$

Whether it is suitable to adopt the cooperative schemes can be intuitively observed from the two extreme cases as described in (26) and (27). In general, cooperative protocols can improve the FER with the cooperation of the relay node, i.e. $\overline{P}_{f(coop)} < \overline{P}_{f(dir)}$. However, successful transmission time via the cooperative link is inherently longer than that from the original direct communication, i.e. $T_{s(coop)} > T_{s(dir)}$. Due to the tradeoff between the FER and the required transmission time, there is no guarantee that the saturation throughput from the cooperative communication (S_{coop}) will be higher than that from the direct link (S_{dir}). The analytical models derived in this subsection will be utilized to determine the suitable occasions to exploit the cooperative communication, as will be presented in the next subsection.

3.3 Throughput comparison between direct and cooperative communications

Before describing the details of proposed cooperative MAC protocols in Sect. 4, preliminary analytical results will be observed and validated via simulations in this subsection. As mentioned before, existing techniques only consider channel conditions for FER improvement which may result in decreased throughput performance. Moreover, these works assume fixed transmission rate and is expected to reduce the FER and to enhance the transmission reliability. However, the transmission rate should be assigned with different modulation and coding schemes based on different levels of SNR values. The transmission rate will be limited in a specific range if only the FER reduction is taken into consideration in existing works.

In this work, the relationship between the instantaneous FER and SNR can be acquired according to (10), i.e. the parameters α, g, and the threshold γ_t can be obtained from the least-square fitting method based on a given BER threshold. The average FER can further be obtained according to (12) and (13). The data transmission rate will be adaptively determined according to the modulation and coding scheme, which is decided based on the instantaneous SNR and SNR threshold γ_t. The saturation throughput $S(\mathcal{R}_{cg}, \overline{P}_{f(dir)}, \overline{P}_{f(coop)})$ as defined in (19) can be obtained according to both transmission duration and average FER values computed via respective direct link from (12) and cooperative link from (13). Therefore, throughput is considered a more feasible performance metric to determine whether the cooperative communication should be adopted. From the throughput perspective, the feasible situations to adopt either the cooperative or the conventional direct communication will be discussed in this subsection. In order to validate the analytical model, the network scenario adopted in the simulations includes 30 user nodes with a fixed relay and a destination node. Table 1 illustrates the relevant parameters that are utilized in the analysis and simulations. By adopting the adaptive modulation and code (AMC) scheme, the parameters utilized in (10) within instantaneous FER $P_{f,ij}$ for different transmission modes, i.e. α, g, and γ_t, can be obtained based on the least-square fitting method in [38] under various SNR values. The other parameters are acquired from the IEEE 802.11a standard.

Figure 3 shows the throughput performance and validation under different values of average SNR σ_{SD} from the source-destination link and the ratio $\mathcal{R}_{cg}$. It is noted that the saturation throughput S is obtained from (19) under predefined channel qualities of the source-relay and relay-destination links, i.e. $\sigma_{SR} = \sigma_{RD} = 40$ dB. Within the total of $N = 30$ network nodes, the numbers of nodes in the cooperative group are selected as 0, 15, and 30 which result in $\mathcal{R}_{cg} = 0, 0.5$, and 1. In other words, there is $\mathcal{R}_{cg}$ ratio of nodes in the network conducting their packet transmission based on cooperative manner. Note that the $\mathcal{R}_{cg} \cdot N$ nodes in the cooperative group are randomly selected from the network nodes. As shown in Fig. 3. there exists a crossing point around 36.5 dB of σ_{SD} that illustrates the decision point regarding the feasible situation to activate the cooperative communication. With a larger number of nodes in the cooperative group, e.g. the curve with $\mathcal{R}_{cg} = 1$, degraded throughput performance is observed as the average SNR of source-destination link σ_{SD} is larger than 36.5 dB. Therefore, direct transmission should be adopted under comparably better channel qualities between the source and destination since the exploration of cooperative communication will result in prolonged transmission time,

Table 1 System parameters

Number of nodes (N)	30
Minimum window size (W)	32
Maximum backoff stage (m)	5
Maximum retry limit ($m + r$)	7
MAC header	224 bits
PHY header	192 bits
cRTS/RTS	(160 + PHY header) bits
cCTS/CTS	(112 + PHY header) bits
ACK	(112 + PHY header) bits
Payload	8,184 bits
Basic rate	6 Mbps
Slot time	9 µs
SIFS	16 µs
DIFS	34 µs
Propagation delay	1 µs
Tolerable BER threshold	10^{-4}

which causes degraded effect on the throughput performance. Nevertheless, under a worse channel quality for direct link, i.e. below 36.5 dB in this case, the usage of cooperative communication will significantly improve the resulting throughput performance.

In addition, since coding schemes are not exploited in the derived analytical model, the average SNR σ_{SD} shown in Fig. 3 will be in general overestimated. In other words, the required SNR σ_{SD} for achieving the same throughput will be reduced while a specific coding strategy is adopted. Therefore, similar trend as in Fig. 3 can also be derived with the exploitation of a specific coding scheme. Furthermore, it can be observed from Fig. 3 that the results obtained from both simulations and analytical model coincide with each other under different SNR values of σ_{SD}. Noted that the slight discrepancies at higher σ_{SD} values are mainly contributed to the usage of approximated FER calculation presented in Subsection 3.1. Since the exponential function as in (10) results in faster decay in FER than that in realistic cases as the SNR values are increased, the throughput acquired from analytical model will possess slightly larger value than that from simulations under higher values of σ_{SD} as shown in Fig. 3. However, this negligible modeling difference does not deteriorate the advantage of exploiting the exponential FER approximation due to its simplicity and efficiency.

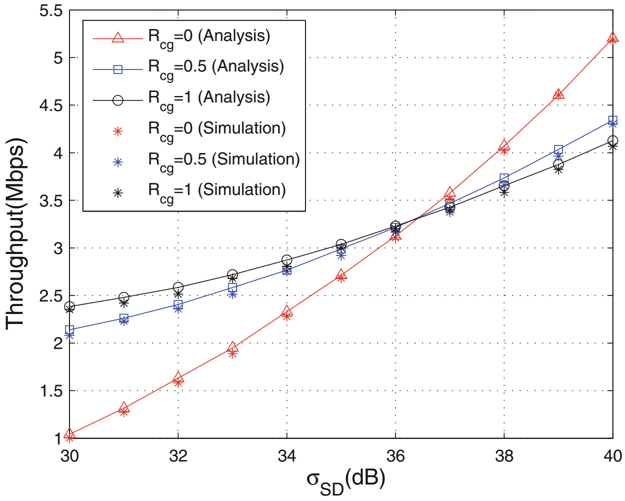

Fig. 3 Throughput performance versus the channel quality of direct link σ_{SD} under various values of $\mathcal{R}_{cg}$

A closer examination on the dependency between the ratio $\mathcal{R}_{cg}$ and the throughput performance is provided in Fig. 4. It illustrates the saturation throughput achieved by the combined direct/cooperative communication system, which includes several nodes conducting direct transmission while others transmit their packets via cooperative communication. The left plot shows the case with worse direct channel quality, i.e. $\sigma_{SD} = 35$ dB; while the case with better channel quality is illustrated in the right plot, i.e. $\sigma_{SD} = 40$ dB. As shown in the left plot of Fig. 4, it can be observed that more nodes in the cooperative group, i.e. with larger $\mathcal{R}_{cg}$ value, will increase the throughput performance under worse direct channel qualities. Conversely, the throughput performance will be significantly degraded as the ratio $\mathcal{R}_{cg}$ is increased when the quality of source-destination channel improves as can be seen from the right plot of Fig. 4. Specifically, as the channel quality of direct link is good enough, transmissions from the source directly to the destination is considered a better choice since the decreased FER resulted from cooperative communication may not be significant. On the other hand, the prolonged transmission time induced by the cooperative communication can cause negative effect on the throughput performance. Therefore, whether a node should join the cooperative group depends on the channel qualities of both the direct and cooperative links.

It is also noted that more throughput improvement can be achieved with better source-relay link compared to the relay-destination link. As shown in the left plot in Fig. 4, the combination of $\sigma_{SR} = 45$ and $\sigma_{RD} = 40$ dB results in higher throughput performance comparing with the case with $\sigma_{SR} = 40$ and $\sigma_{RD} = 45$ dB. These results can be explained by the adoption of DF scheme within cooperative communication. The source-relay link should provide good enough channel quality such that the relay can correctly decode the corresponding frame. Otherwise, full diversity gain will not be achieved with the exploration of cooperative communication. Therefore, the source-relay channel plays a more important role than the relay-destination channel for throughput enhancement, especially under poor channel quality of the direct link. In other words, as the source is suffering from severe fading

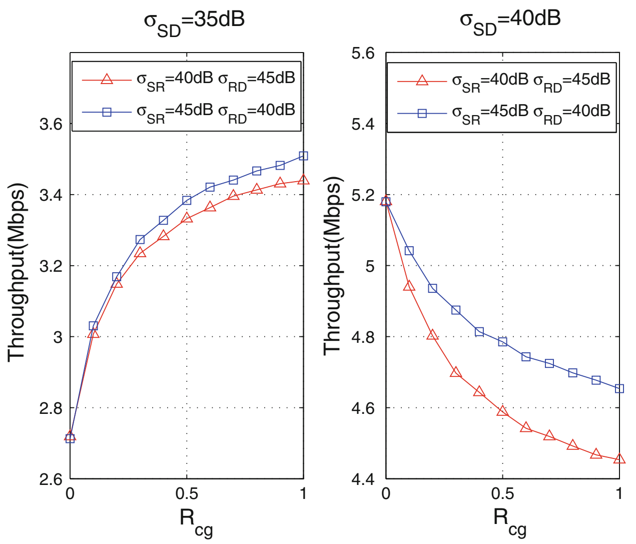

Fig. 4 Throughput performance versus different values of the ratio $\mathcal{R}_{cg}$ (*left plot*: worse direct channel quality $\sigma_{SD} = 35$ dB; *right plot*: better direct channel quality $\sigma_{SD} = 40$ dB)

channel and noises to the destination, a better source-relay channel is considered more important compared to the relay-destination channel in order to allow the destination to acquire another copy of data frames. This results will further be explored in the design of proposed cooperative MAC protocol to provide efficient channel acquisition process, which will be explained in Sect. 4.

Figure 5 shows the occasions for cooperative mechanism to have a better performance than the direct communication under different SNR values. With pre-defined average SNR values of the source-destination and the source-relay channels, the theoretically required average SNR of the relay-destination channel is obtained through the cooperative communication in order to have the same throughput as that via the direct transmission, i.e. $S_{dir} = S_{coop}$ where S_{dir} and S_{coop} are acquired from (26) and (27) respectively. For every specific σ_{SD} and σ_{SR}, each point on the curves represents the value of σ_{RD} that satisfies the following condition:

$$\sup\{\sigma_{RD} : S_{coop}(\sigma_{SD}, \sigma_{SR}, \sigma_{RD}) \geq S_{dir}(\sigma_{SD})\} \tag{28}$$

For example, as $\sigma_{SD} = 30$ dB and $\sigma_{SR} = 40$ dB, the cooperative scheme with $\sigma_{RD} > 30$ dB can outperform the conventional direct communication in network throughput. Each curve in Fig. 5 can also be explained as the case while $S_{coop} = S_{dir}$ for a specific average SNR of the direct link. The region above the curve represents the situations of $S_{coop} > S_{dir}$. Moreover, it is especially noticed that Fig. 5 can be utilized as a reference plot to determine the suitability for adopting the cooperative schemes as opposed to the direct communication, which will further be explored in the design of cooperative MAC protocols in next section.

4 Proposed cooperative MAC protocols

According to analytical study as described in the previous section, whether to adopt either the direct transmission or cooperative communication depends on the variations of channel qualities. In order to improve the throughput performance, cooperative communication should be activated when the channel quality of direct link is comparably worse than that of the cooperative links, i.e. based on the criterion as illustrated in Fig. 5. In other words, all the nodes belong to the cooperative communication group at the beginning, and the proposed schemes are utilized to determine whether cooperative communication should be carried out for each node based on the instantaneous channel quality. Furthermore, a pre-specified single relay node is assumed to be available in the previous analysis. In realistic situation, how to select an appropriate relay node among the available network nodes is considered crucial for the improvement of network throughput. Based on the reasons mentioned in the previous section, fixed relays are also exploited in the design of proposed cooperative MAC protocols. For instance, several relay nodes can be pre-assigned and placed within the transmission range of an access point in order to assist for data transmission. The total number of required fixed relays can be determined based on the total numbers of users, the transmission range of access point, and the required system performance. The feasible locations and numbers of relays within the network is considered pre-determined information, which is not within the scope of this paper. Therefore, for the enhancement of throughput performance, the objectives for the design of proposed cooperative MAC protocols consist of the following: (a) to determine if cooperative

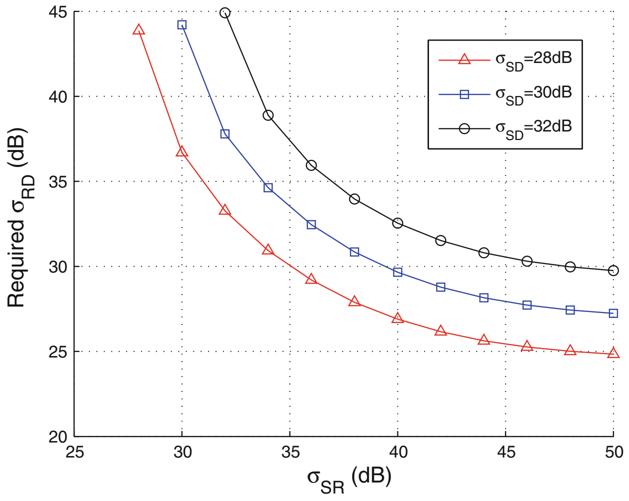

Fig. 5 Required average SNR σ_{RD} via cooperative communication for achieving the same throughput as that with direct transmission under specific σ_{SD} and σ_{SR} values

communication should be employed, and (b) to select a feasible relay node based on available relays within the network.

The schematic diagrams for the design of proposed MAC protocols are depicted in Fig. 6. It shows the transmission sequences including both the handshake and data transmission processes based on the combined direct/cooperative strategy. Noted that frames transmitted by either the source, relay, or destination are denoted with different colors, e.g. frames with blue color are transmitted from the source. Moreover, the channel access method adopted in the proposed protocols is modified from the distributed coordination function (DCF) in IEEE 802.11 standard, which requires the source to contend for the channel usage before transmitting data frames to the destination. As shown in Fig. 6, the three different types of transmission processes in the proposed protocols are explained as follows.

(a) *Direct transmission in non-cooperative group:* Conventional DCF mechanism is exploited for the nodes in non-cooperative group. The source will initiate the transmission of RTS frame after the channel has been sensed in the idle state for the time durations of both a DIFS and the backoff timer. After receiving the RTS frame, the other nodes within the network will set their corresponding network allocation vectors (NAVs) in order not to interfere with the on-going transmission between the source and destination. Data transmission will be started by the source after receiving the CTS frame delivered by the destination. Successful reception of the acknowledgement (ACK) frame by the source will complete the data transmission process.

(b) *Direct transmission in cooperative group:* Instead of initiating conventional RTS frame, the source within the cooperative group will issue the cRTS frame in order to notify the request of cooperative communication. However, the source does not possess enough information to determine whether to activate the cooperative communication or not. The decision to transmit via either the direct or cooperative communication is made by the destination after considering the instantaneous channel qualities. In order to conduct appropriate decision, it is required for the destination to acquire the channel quality indicator (CQI) from the relays, which is implemented within the CQI-acquiring period as shown in Fig. 6. In other words, the relays will utilize this time period to transmit the channel quality information between the source and relays by adopting a specific mechanism, i.e. either the proposed FCC or BCC protocol, which will be described later in this section. It is noted that the destination can also obtain the channel quality information of source-destination and relay-destination links by measuring the received control frames from the source and relays respectively. After obtaining the required channel quality information, the destination will make the decision to transmit data frames either through the direct transmission or via the help from relay. In the case that direct transmission scheme is notified by the decision metrics, the conventional CTS control frame will be forwarded from the destination to both the source and relays. It indicates that only direct communication between the source and destination should be utilized for data transmission.

(c) *Cooperative transmission in cooperative group:* Similar to the process as described in (b), this case also happens as the network nodes belong to the cooperative group. If the direct link suffers from deep fading channel condition, cooperative communication will be chosen by the destination via either the FCC or BCC scheme after the CQI-acquiring period. The cCTS frame which will fill in the identifier of a relay that should participate in this cooperative communication will be transmitted by the destination in order to inform both the source and the chosen relay. Sequentially, cooperative communication for the two-phase data transmission will be activated, i.e. the source first transmits the data frame to both the destination and selected relay, and followed by the data forwarding process from the relay to destination. It is noted that the time gap between two frame transmissions is designed as an SIFS as shown in Fig. 6. After

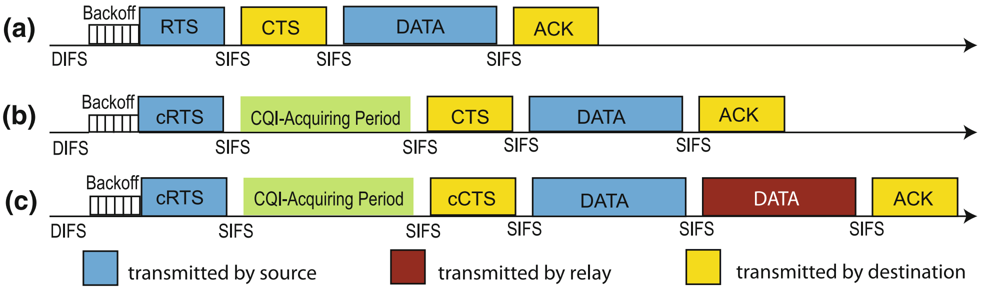

Fig. 6 The schematic diagrams of both the handshake process and data transmission for **a** direct transmission in non-cooperative group, **b** direct transmission in cooperative group, and **c** cooperative transmission in cooperative group

> the cooperative combining process is conducted by the destination, an ACK frame will be delivered to the source to complete the entire transmission procedure.

As described in both processes (b) and (c), it is required for the destination to determine whether the cooperative communication should be adopted. Based on the saturation throughput as derived in Sect. 3, the instantaneous throughput $S_{I(\zeta)}$ is utilized as the decision metrics for the destination node, where the subscript ζ in $S_{I(\zeta)}$ denotes the different transmission schemes, i.e. $S_{I(\zeta)} = \{S_{I(coop)}, S_{I(dir)}\}$. Since the decision metrics adopted at the destination should be implemented based on real-time manner, the instantaneous throughput for the direct and cooperative communication is simplified from the average throughput as derived in (26) and (27) respectively. The average successfully transmitted payload bits $E[L_P]$ in (25) will become $(1 - P_{f(\zeta)})E[L_{Payload}]$, where the average length of payload bits in a data frame $E[L_{Payload}]$ is defined as in (25). The instantaneous FER $P_{f(\zeta)}$ can be obtained from each instantaneous FER of communication link $P_{f,SD}$, $P_{f,SR}$, and $P_{f,(SR)D}$, i.e. $P_{f(dir)} = P_{f,SD}$ and $P_{f(coop)} = (1 - P_{f,SR})P_{f,(SR)D} + P_{f,SR}P_{f,SD}$. Noted that the probability for at least one transmission occurs in a time slot p_{tr} and the probability of a non-collided transmission $p_{wc(cg)}$ and $p_{wc(ncg)}$ in (25) are equal to 1 since the throughput $S_{I(\zeta)}$ is considered at each instantaneous time slot after one node has already reserved the channel. Moreover, instead of obtaining the average time durations $E[T_B]$, $E[T_S]$, $E[T_C]$, and $E[T_E]$ in (19), the required instantaneous transmission time $T_{I(\zeta)}$ is obtained for the considered communication scheme. The parameter $T_{I(\zeta)}$, which includes the handshake and data transmission processes, can be estimated according to the ratio of the frame length to the data rate for the corresponding scheme. Therefore, the instantaneous throughput $S_{I(\zeta)}$ can be obtained as

$$S_{I(\zeta)} = \frac{E[L_{Payload}]}{T_{I(\zeta)}}(1 - P_{f(\zeta)}) \tag{29}$$

It is noted that the instantaneous throughput $S_{I(dir)}$ and $S_{I(coop)}$ will be computed directly within the destination by gathering the channel quality information during the CQI-acquiring period. After acquiring the instantaneous throughput $S_{I(dir)}$ and $S_{I(coop)}$ with different relays, the destination will determine if cooperative communication should be adopted. In the case that cooperative scheme is exploited, the destination will further select the most feasible relay for data forwarding based on either the proposed FCC or BCC MAC protocol, which are described as follows.

4.1 Full CQI based cooperative (FCC) MAC protocol

The design concept of the proposed FCC protocol is to provide full channel quality information of the potential relays such that the destination node can obtain sufficient information to select a feasible relay node for data forwarding. As shown in Fig. 7, a control frame named relay ready-to-send (rRTS) is created to carry the channel quality information of source-relay link from the relays to destination. It is designed to have the same structure as the CTS frame except that additional one-byte is added to store the channel quality information between source and relay. Moreover, since the relays are assumed to be deployed in advance, each relay can be assigned with a specific number representing its sequence to transmit the corresponding rRTS frame. According to the design of FCC scheme, the relays will transmit their rRTS frames sequentially within the CQI-acquiring period as depicted in Fig. 7. The channel quality between the source and the corresponding relay can consequently be delivered from the relay to destination. The SIFS durations are assigned between the rRTS frames from different relays. On the reception of rRTS frames, the destination will also measure the channel qualities of relay-destination links from the corresponding relays. After receiving all the channel quality information through the rRTS frames sending from the neighboring relays, the destination can therefore select a feasible relay node if cooperative communication is to be exploited.

4.2 Bitwise competition based cooperative (BCC) MAC protocol

Based on the design of FCC scheme as mentioned above, it is beneficial to provide available channel quality information via all different relays for the destination to conduct relay selection scheme. However, due to the elongated CQI-acquiring period, the throughput performance can be severely degraded if the total number of relay nodes are increased, i.e. excessive rRTS frames are to be sequentially delivered to the destination node. On the other hand, small

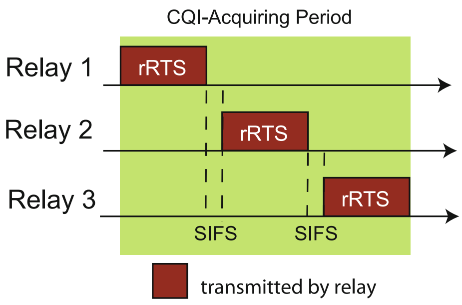

Fig. 7 The schematic diagram of process in CQI-acquiring period with FCC protocol

CQI-acquiring period can result in the incompleteness of delivering channel quality information from the relays to destination. Therefore, the design concept of proposed BCC scheme is to compromise between the overhead caused by the exchange of channel quality information and sufficient information for the destination to conduct suitable decisions. A pre-specified length of CQI-acquiring period is provided for all the relays in the network to conduct *relay contention process*. The winner after the contention period will be the only relay to transmit its rRTS frame to the destination for reporting the channel quality of source-relay link.

As was discovered in the left plot of Fig. 4 that the channel quality of source-relay link is more important than the link between the relay and destination by adopting the DF scheme. Noted that similar results and observations can also be obtained in [6]. Therefore, without considering the relay-destination link, only the channel quality of source-relay link is considered for the selection of a feasible relay. As shown in Fig. 8, the bitwise competition in the CQI-acquiring period is designed to choose the appropriate relay, including 8 bits of channel quality information sequence and 2 bits of relay identifier. It is noted that every bit occupies one time slot which is defined in the IEEE 802.11 PHY layer standard. After receiving the cRTS frame transmitted from the source, the relays estimate their corresponding channel qualities for source-relay links. The relays will transform the channel qualities into 8-bit channel quality information sequences, where better channel quality will be represented by a larger value of channel quality information sequence. For example, an all ones 8-bit sequence indicates the best channel quality for the source-relay link. In addition to the sequence obtained from channel quality, the relays also transform their specific identification number into the 2-bit relay identifier in order to avoid potential collision under the situations that two relays may have the same channel quality information sequence. Therefore, based on the channel quality and identification number, all the neighboring relays will initiate the relay contention process within the CQI-acquiring period. Noted that each bit value with one denotes that the corresponding relay will issue an active signal; while the zero value in a bit represents that the relay will remain silent and continue listening to the channel state.

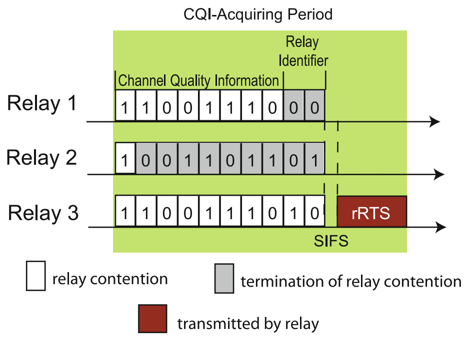

Fig. 8 The schematic diagram of process in CQI-acquiring period with BCC protocol

For example, a three-relay scenario is considered to explain the relay contention process of proposed BCC protocol. Both channel information and identification number are available for each relay as depicted in Fig. 8. All the three relays will transmit signals during the first slot; while only Relay 2 will become silent in the second slot due to the zero value in its 8-bits channel information sequence. Relay 2 keeps monitoring the channel state in the second slot and detects that it is in the busy state. Consequently, Relay 2 will quit from the relay contention process since it realizes that there is at least one relay that has better channel quality of source-relay link. The remaining two relays will continue the relay contention process in order to become the winner in the following slots. However, both relays possess the same channel quality which results in the same channel quality information sequence as indicated in Fig. 8. The purpose of the last two bits, i.e. the relay identifier, come into play for resolving the contention between Relays 1 and 3. According to the identification numbers, Relay 3 will become the final winner within the relay contention process. An rRTS frame will be transmitted from Relay 3 to the destination in order to deliver the channel quality information of source-relay link. Based on the decision metrics within the destination, either a CTS or cCTS frame will be transmitted by the destination in order to notify if either the direct or the cooperative transmission should be activated. The performance evaluation and comparison between the proposed FCC and BCC protocols will be conducted in the next section.

5 Performance evaluation

Numerical results are performed to evaluate the throughput performance of conventional direct transmission and proposed FCC and BCC protocols. The network scenario for performance evaluation and comparison is described as follows. Similar to Fig. 1, a single destination is assumed to locate at the center of the considered network, which confines a circular region with radius equal to 50 m. The source nodes, which denotes the users, are randomly located within the area between 30 and 50 m from the destination. Based on the observation from [39], suitable relay deployment is to place the relays around the intermediate location between the users and destination in order to appropriately enhance the network throughput. Therefore, stationary relays are uniformly distributed around the circle which is 20 m from the destination. Various numbers of sources and relays will be considered under different simulation cases. In the case that either the FCC or BCC scheme is adopted, the destination is the node to determine whether the direct or cooperative communication should be adopted for each data transmission. It is also noted that the pathloss exponent is set to 4 in the following simulations. The other parameters utilized in the simulations is selected the same as in Table 1.

Figures 9 and 10 illustrate the throughput performance for proposed FCC and BCC protocols respectively under different SNR values σ_{DB}. The parameter σ_{DB} is defined as the average received SNR between the destination and a source located on the transmission boundary of destination, i.e. the circle with radius 50 m. Noted that the average received SNRs of other links can also be computed according to the distances of the links compared to that located on the boundary with σ_{DB}. The total number of relays are selected as 4, 6, and 8 in both cases; while that for the sources is chosen as 30. It is intuitive to observe in both figures that the throughput performance is increased under both schemes as the value of σ_{DB} is augmented. However, in the proposed FCC protocol, the increased number of relays will degrade the throughput performance as shown in Fig. 9. The main reason is due to the requirement to transmit additional rRTS frames by adopting the FCC scheme as the number of relays is increased. Throughput performance will consequently be decreased since excessive overheads are introduced by the elongated CQI-acquiring period. On the other hand, the throughput performance is enhanced as the number of relays is increased by applying the proposed BCC protocol. The reason is that additional relays can provide data forwarding services for more users within the fixed CQI-acquiring period. Even though only partial channel quality information is available by adopting the BCC scheme's relay contention process, the resulting throughput performance can still be improved with augmented number of relays. Furthermore, as shown in Fig. 10, the throughput enhancement due to the increased number of relays becomes insignificant as σ_{DB} is augmented, i.e. all three lines converge as σ_{DB} is around 40 dB. This is attributed to the situation with sufficiently good channel quality, i.e. with larger σ_{DB} values, where direct transmission will mostly be activated by the destination. Consequently, the number of relays will result in less impact on the throughput performance.

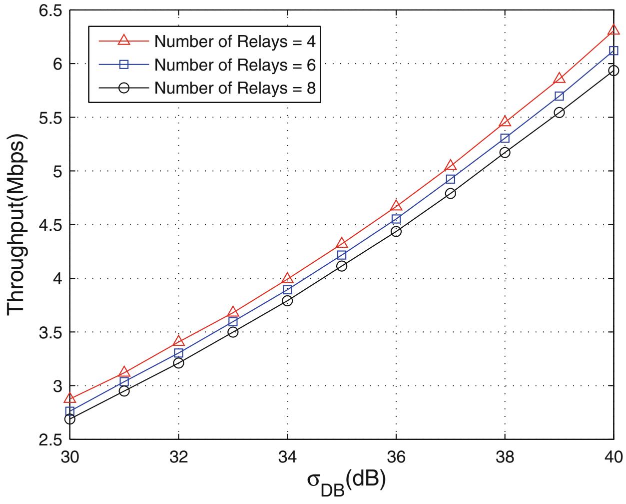

Fig. 9 Throughput performance versus average SNR value of boundary node σ_{DB} using FCC protocol (number of sources = 30)

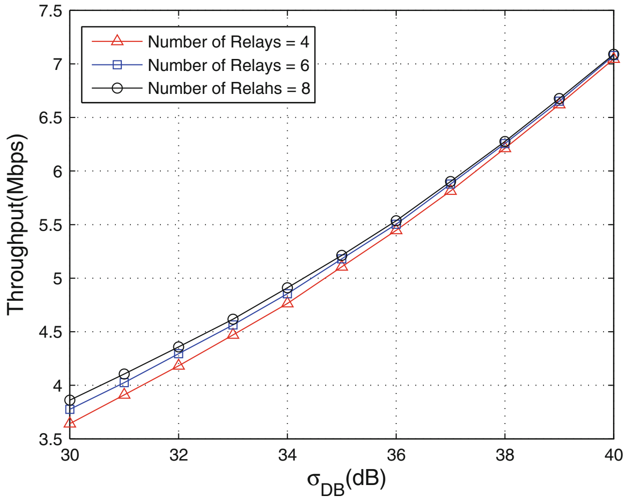

Fig. 10 Throughput performance versus average SNR value of boundary node σ_{DB} using BCC protocol (number of sources = 30)

Figures 11 and 12 are illustrated to compare the throughput performance of proposed protocols with various number of relays. The total numbers of sources are selected as 20, 30, and 40 for both cases. It is noted that the SNR value σ_{DB} is chosen as 30 dB for observing the effectiveness of proposed schemes under relatively poor channel quality. It can be discovered that the throughput obtained from the FCC scheme decreases as the number of relay is augmented. The BCC protocol, on the other hand, can still result in enhanced throughput performance as the number of relays is increased as in Fig. 12. Similar to the reasons as mentioned in the previous paragraph, the FCC protocol introduces additional overheads by sending excessive rRTS frames as the number of relays is increased. A harmful effect will occur when the control overheads cannot be compensated by the enhancement of throughput resulted from the cooperative communication. In contrary, the BCC protocol will still be beneficial from the additional relays due to the limited CQI-acquiring period. Furthermore, similar trend can be obtained in both figures as the number of users is increased. The network throughput will be

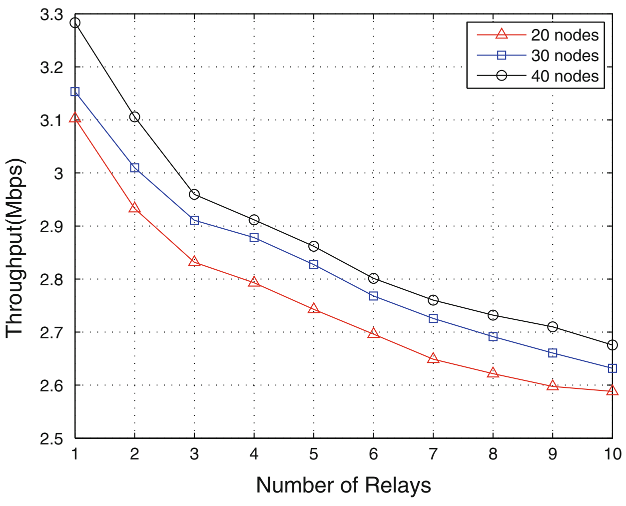

Fig. 11 Throughput performance versus number of relays using FCC protocol with different number of sources ($\sigma_{DB} = 30$ dB)

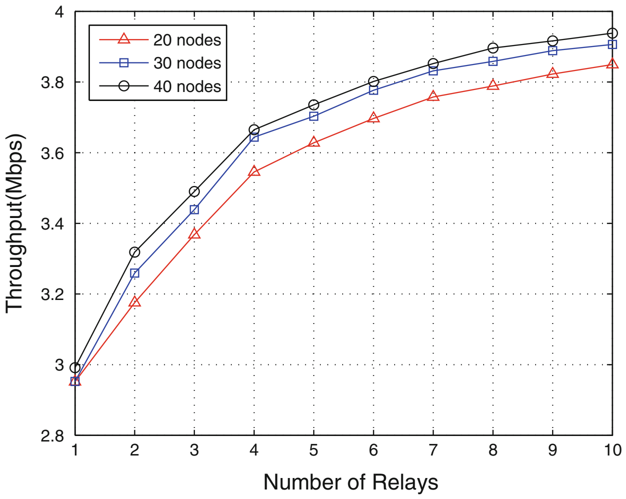

Fig. 12 Throughput performance versus number of relays using BCC protocol with different number of sources ($\sigma_{DB} = 30$ dB)

enhanced with increasing number of sources; however, the amount of improvement becomes smaller as the number of sources continues to grow.

After observing the properties of FCC and BCC schemes under different circumstances, both protocols will be compared with direct transmission and the RSA and CRBAR protocols as proposed in [18, 31], respectively. Instead of targeting at maximizing system throughput in both FCC and BCC schemes, the RSA method is developed based on the maximization of channel capacity. However, the decision of relay selection delivered from relay to source has not been considered in the RSA scheme. Therefore, the FCC and BCC protocols are respectively incorporated within the RSA scheme to become the RSA-FCC and RSA-BCC protocols for performance comparison. On the other hand, by adopting the CRBAR scheme, the relay nodes determine the transmission rates based on the instantaneous channel measurements. After monitoring the RTS and CTS frames from the source and destination respectively, the relays in the network will contend with each other for channel access. The relay with minimal backoff counter will transmit a ready-to-relay (RTR) frame to inform the source that it is ready to transmit data. After correctly decoding the data from the source, the confirmed relay node will forward data to the corresponding destination. The main difference between proposed BCC and CRBAR schemes is the relay contention process. In BCC scheme, a fixed CQI-acquiring period (chosen to be 10 time slots) is utilized to determine the relay that will win the channel access. On the other hand, the contention period of CRBAR scheme is decided based on the minimal backoff counters selected by the relays. The contention period of CRBAR scheme is easily to become much longer than that of the BCC scheme if the backoff counters of all relays are chosen to be larger than the CQI-acquiring period.

Figures 13 and 14 show the throughput improvement of proposed protocols compared to direct transmission under different numbers of relays and numbers of users, respectively. The SNR value σ_{DB} is also chosen as 30 dB in both figures. The total number of users is set to be 30 in Fig. 13; while the number of relays is selected as 3 in Fig. 14. As shown in Fig. 13, it can be seen that the FCC scheme can provide slightly better performance than BCC protocol as the number of relays is equal to 1. The reason is that FCC protocol collects full channel quality information and makes the best decision on relay selection. However, BCC scheme chooses the feasible relay only based on the channel quality of source-relay links, which may not result in the best relay considering both source-relay and relay-destination channels in the cooperative communication. Nevertheless, as the number of relays is increased, the

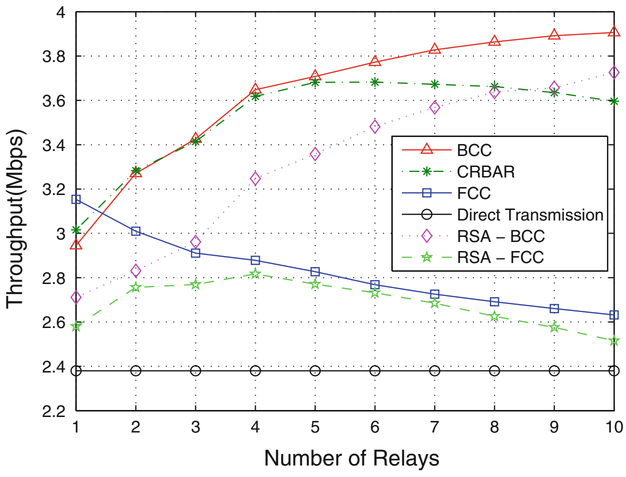

Fig. 13 Throughput comparison versus number of relays with direct transmission and relay-assisted protocols ($\sigma_{DB} = 30$ dB)

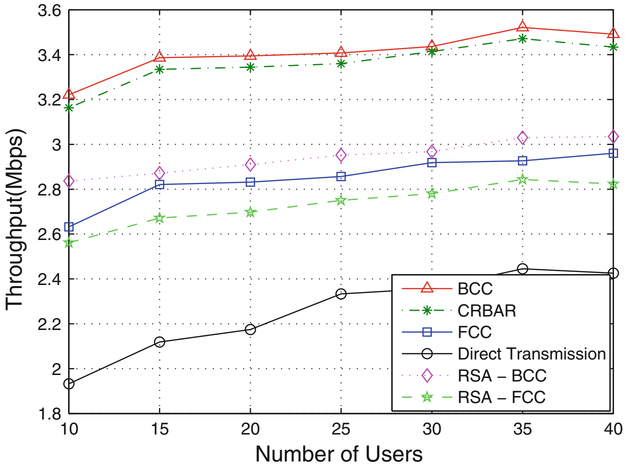

Fig. 14 Throughput comparison versus number of users with direct transmission and relay-assisted protocols ($\sigma_{DB} = 30$ dB)

performance from FCC protocol degrades due to excessive overhead caused by transmitting channel quality information via the rRTS frames. BCC protocol can outperform FCC scheme in throughput performance owing to its efficient design of relay contention process.

Furthermore, both proposed protocols can still provide better performance than that from direct transmission under different numbers of relays. Noticed that this figure can also be utilized as a reference plot to determine the number of relays to be deployed in order to achieve the required throughput performance. It can also be observed that proposed FCC and BCC schemes outperform their respective RSA-based protocols, e.g. the performance of RSA-FCC scheme is worse than that of FCC protocol if the number of relays is less than 4. The reason is that the RSA-based schemes do not provide the option to conduct direction transmission, which can become an feasible choice under smaller numbers of relays. On the other hand, RSA-BCC protocol can provide better performance than that from RSA-FCC scheme owing to the design superiority of BCC scheme compared to the FCC method. Moreover, the CRBAR scheme outperforms the BCC mechanism under small number of relays owing to its smaller relay selection period than that of the BCC scheme. The contention period of CRBAR scheme will be shorter than the CQI-acquiring period of BCC method if at least one of the relays' backoff counter is chosen smaller than 10, and CRBAR scheme will provide better performance because of its shorter transmission period. However, when the number of relay is increased, the performance of CRBAR scheme becomes worse than that of BCC algorithm if the relay in CRBAR method that cannot provide the minimal transmission period has the smallest backoff counter and wins the contention process. Furthermore, in the CRBAR scheme, the collision between RTR frames transmitted by the relays will happen more frequently when the number of relays is larger. If all the RTR frames collide with each other, the data frame can only be transmitted through direct transmission and the throughput performance will be significantly degraded.

The impact from the number of users on throughput performance is illustrated in Fig. 14. It is intuitive that total network throughput will be increased with augmented number of users. However, owing to potential frame collision, the resulting throughput performance may reach its saturation point or even decreases as the number of users is increased. Nevertheless, the proposed BCC scheme can provide much better throughput performance compared to FCC protocol, RSA-based schemes, and conventional direct communication. On the other hand, as mentioned before, the CRBAR scheme will result in comparably worse performance than the BCC method if its relay that wins the channel contention possesses larger backoff counter than the fixed CQI-acquiring period. The collision between RTR frames also makes the inferior performance of CRBAR scheme.

Figure 15 shows the performance comparison for average number of retransmissions under different channel qualities. Noted that the number of relays is selected as 3 in FCC, BCC, and RSA-based schemes. It can be discovered that both proposed FCC and BCC protocols can effectively reduce the number of retransmissions especially under relatively poor channel quality. The average numbers of retransmissions from the RSA-based protocols are respectively higher than their corresponding FCC and BCC schemes. On the other hand, although the acquisition of full channel quality information can be beneficial to reduce the number of retransmissions, the prolonged transmission time resulting from the FCC protocol will degrade the throughput performance as shown in Fig. 16. This figure illustrates the dependency of throughput performance with the conventional direct transmission and relay-enhanced protocols under different channel qualities. Both the FCC and BCC protocols can provide better performance than the RSA-based schemes and direct transmission under poor channel qualities. It is also noted that the BCC protocol can further improve the throughput performance compared to the FCC scheme due to its limited transmission time for relay contention. The throughput performance of CRBAR scheme is slightly worse than the proposed BCC method under different channel qualities. As the channel quality improves, the transmission overhead introduced by proposed protocols will result in relatively lower throughput performance comparing with direct transmission. Nevertheless, the proposed cooperative MAC protocols will still be advantageous especially under the environments with comparably poor channel qualities.

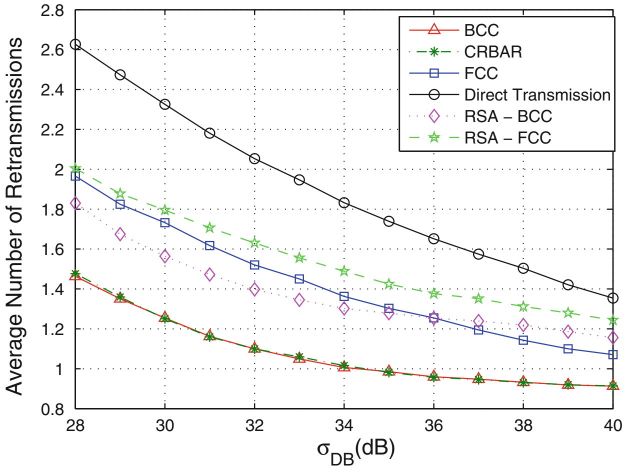

Fig. 15 Average number of retransmissions versus average SNR value of boundary node σ_{DB} via direct transmission and relay-assisted protocols

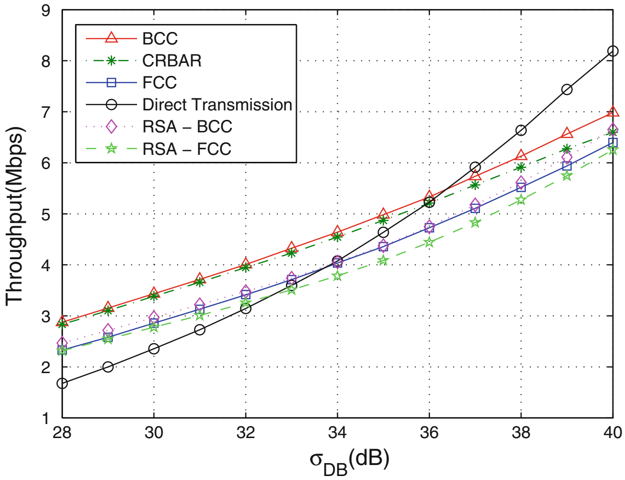

Fig. 16 Throughput performance versus average SNR value of boundary node σ_{DB} via direct transmission and relay-assisted protocols

Moreover, according to the simulation results from Fig. 16, it can be observed that direct transmission can provide better performance compared to the proposed schemes under higher received SNR values, e.g. under $\sigma_{DB} = 38$ dB. However, the results from all previous plots including Fig. 16 assume the channel noise to be AWGN with zero-mean and unit variance. With different variances of Gaussian noise, the direct transmission may not be able to provide better performance than the proposed protocols even though σ_{DB} is good enough. Figure 17 shows the throughput comparison under different variances of channel noise with the cases of $\sigma_{DB} = 38$ and 38 dB. It can be observed that both the BCC and FCC schemes can provide better throughput performance compared to the direct transmission, especially under larger variances of channel noise. The major reason is that the proposed schemes can select a feasible relay for data transmission based on the channel quality. Even though the performance evaluation shows that the BCC scheme outperforms FCC method under most of the circumstances, it is still worthwhile to evaluate the FCC protocol due to its ease of implementation compared to the BCC algorithm. Perfect time synchronization between the relays is required for BCC protocol in order to realize the bitwise competition. On the other hand, time synchronization is not strictly required by the relays adopting the FCC scheme since the relays only have to transmit their rRTS packets consecutively after receiving the cRTS packets from the source node. From practical considerations, the FCC scheme is still valuable to be adopted even though its performance is slightly inferior compared to the BCC scheme. Therefore, the merits of both proposed FCC and BCC schemes can be observed.

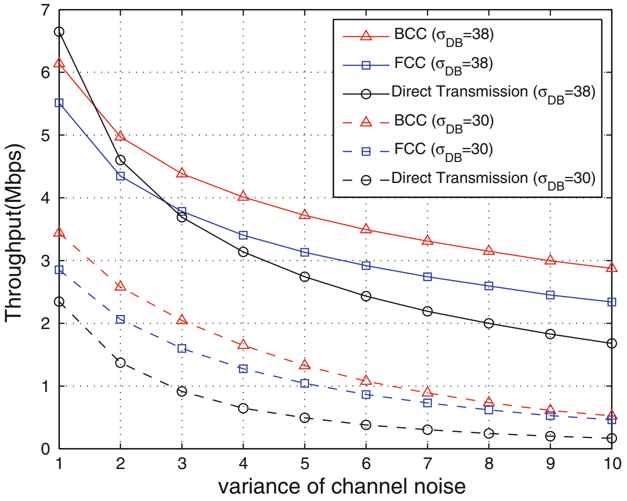

Fig. 17 Throughput performance versus channel variance of boundary node via direct transmission and proposed relay-assisted protocols

6 Conclusion

This paper presents performance analysis and protocol designs of cooperative communication from the medium access control (MAC) perspectives. An analytical model which consists of both the conventional direct communication and the cooperative mechanism is proposed to evaluate the suitability for adopting the cooperative scheme. In order to enhance the network throughput, it is suggested in this paper that not only the cooperative diversity but also the transmission delay should be considered in the design of cooperative communications. Moreover, both the full-CQI based cooperative (FCC) MAC protocol and bitwise competition based cooperative (BCC) MAC protocol are proposed to adaptively choose the appropriate relay for data forwarding against the variation of channel qualities. Although the FCC protocol is designed based on full channel quality information, the overhead introduced by the exchange of control frames can result in degraded throughput performance. On the other hand, the BCC protocol adopts the relay contention process to limit the time period for acquiring channel quality information, which effectively reduces the communication overhead. Simulation results show that both the proposed MAC protocols can provide enhanced throughput performance compared to direct communication, especially under poor channel qualities.

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