Cooperative Binary Relaying and Combining for Multi-hop Wireless Communication

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***Abstract*—Cooperative communication can achieve diversity gain and increase the channel capacity. This paper proposes a novel cooperative scheme called Cooperative Binary Relaying and Combining (CBRC) for multi-hop wireless networking systems where the nodes cooperatively demodulate high-order modulated signal symbols with low-order robust modulations. Low-order demodulation schemes make partial decision at each relay node and avoid propagating the errors that can result from high-order demodulation schemes in conventional cooperative relaying. Therefore, CBRC supports high bit rate transmission at high-order modulations over low SNR links. Extensive simulations are conducted to evaluate the bit error rate performance of CBRC and conventional cooperative strategies. The results show that CBRC can significantly improve the performance.**

I. Introduction

Wireless communication suffers signal variation and degradation from various causes such as multi-path fading, path loss and mobility. The signal variation and degradation can be mitigated by exploiting user diversity unique in wireless networking where users may experience different link conditions because of their locations and speeds [1]. The cooperation among wireless mobile terminals, called *cooperative relay*, has been appreciated as a novel approach to exploit user diversity by cooperatively relaying the received signals to the destination, which constitutes a virtual antenna array [2], [3]. Cooperative relay significantly improves the communication performance with reduced bit error rate (BER).

In wireless communication, normally, high-order modulations lead to high error propagation and large bit error rate in wireless communication, especially under low SNR channel conditions. Although low-order modulations can address the problem, they yield low bit rate as well. The **motivation** of this work is to design a cooperative approach that is capable of maintaining the high bit rate of high-order modulations while keeping the low detection error of low-order modulations.

In this paper, we propose a novel cooperative strategy called *Cooperative Binary Relaying and Combining* (CBRC) for multi-hop wireless networking systems that partially demodulates the signal symbol with low-order robust modulations, let us say BPSK, at each cooperative relay node. A destination node combines all the partial demodulated outcomes to correctly decode the symbol. Unlike conventional cooperative communication strategies that are generally based on amplify-and-forward and decode-and-forward relaying schemes, *CBRC* makes a binary demodulation decision like BPSK at each relay node, and relays the signal *and decision* to the next node(s). In particular, this strategy supports high-order modulations, such as 256-QAM or 64-QAM, for high bit rates over multi-hop wireless networks. Extensive simulation evaluations validate the strengths of the proposed CBRC.

In the rest of this paper, the related cooperative relay work is reviewed in Section II and the system is modeled in Section III. Then, Section IV presents the proposed *cooperative Binary Relaying and Combining*. The extensive evaluations are discussed in Section V. Section VI presents the discussion of this work. Finally, Section VII concludes this work.

II. Related Work

There are two fundamental components in cooperative communication: relaying and combining. The typical approach for cooperative communication is to relay the received signal at intermediate nodes and finally combine the received signals at the destination node. Different in how the information is processed in the relaying, various schemes have been proposed in the literature, including amplify-and-forward [4], demodulate-and-forward [5], decode-and-forward [4], [6] and soft decode-and-forward [7]. In amplify-and-forward (AF), a relay node amplifies the received signals and forwards them to the destination. In demodulate-and-forward, a relay node demodulates the received signals and forwards regenerated signals to the destination. In decode-and-forward (DF), a relay node decodes the received signals, re-encodes and forwards the regenerated signals to the destination. It has been remarked that AF significantly saves transmission power. However, compared to DF, AF has two main drawbacks. One is that it does not have coding gains and the other is that it will also amplify and forward noises. DF has the advantages of regenerating the signal, and correcting errors at the relay. Nevertheless, when the capability of error correcting in the decoding is not strong enough to correct all errors, the errors will be propagated throughout communication network.

Azarian, Gamal and Schniter investigated the diversity-multiplexing tradeoff of relay protocols [8]. Coding schemes such as distributed Turbo codes [9], [10] have been also studied to exploit the cooperative diversity for DF in relay

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channels. Recently, Low Density Parity Check (LDPC) codes were investigated for half-duplex relay channels [11], [12]. In the case that the channel between the source and relay is not reliable enough to guarantee error free decoded bits at the relay, avoiding error propagation at the relay becomes challenging. To address this challenge, relay schemes that attempt to combine the benefit of DF and AF were proposed, such as the *soft decode-and-forward protocols* [7], [9]. In*soft decode-and-forward*, the soft information in decoding the source signal is used to form a *soft* signal at the relay based on the log-likelihood ratios. Then, the soft signal is transmitted to the destination node with relaying schemes of AF, Estimate-and-Forward [13], or Decode-Estimate-Forward [14].

In cooperative communication, the source and relay signals are finally combined at the destination. A possible combining technique is the well-known Maximum-ratio-combining (MRC). However, it is suboptimal and does not achieve full diversity [15]. Serious performance degradation of MRC can be caused by the error propagation at the relays. Another important challenge is that MRC incurs high computational complexity at the destination, especially when high-order modulations are employed. Wang, *et al.* proposed *Cooperative-Maximum Ratio Combining* (C-MRC) to achieve full diversity with DF relaying schemes by exploiting the knowledge of the instantaneous bit-error probability of the source-relay link at the destination [16].

III. System Model

This section describes the system model and assumptions that this paper is based on. Consider the multi-hop relay system shown in Figure 1, consisting of one source, one destination, and multiple distributed relays that cooperatively support the communication between the source S and destination D. In this system, the source encodes the information bit and broadcasts the modulated signals to the relays. The relay demodulates, decodes and re-encodes the received message. The resulting message is modulated and forwarded to its next prospective relay node(s). Finally, the destination receives the signals from last relays. It is assumed that there is no direct link between the source and the destination and each relay has only one antenna. In practice, terminals cannot transmit and receive simultaneously over the same frequency band. The half-duplex mode is assumed with a time division duplex (TDD) mode, for which data signal transmitting and receiving in separate time slots. We suppose the channels are quasi-static and independent over time slots and all receiving nodes have instantaneous channel state information (CSI). In order to avoid the interference between links, time division multiple access (TDMA) is used for providing orthogonal channels to facility communication between relays.

At the source node S, information bits W are encoded and modulated into the signals $X \in \{S_1, S_2, \cdots, S_k\}$, where S_i denotes a symbol, with power constraint, $E\left[\left|X^2\right|\right] \le P_0$. In the baseband model, for all $i \in \{1, 2, \cdots, n\}$ corresponding to relays and the destination D, the signal is disturbed by frequency-flat fading characterized by fading coefficient

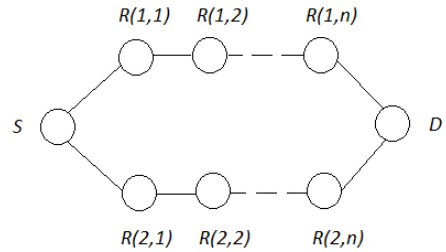

Fig. 1. Multi-hop relay system with one source, S, one destination, D, and two branches of relays, $R(1,1)$, $R(2,1)$ and so on.

h_i, which is constant complex scalars known to the relays. $Z_i \sim N(0, \sigma_i)$ captures the effects of additive white Gaussian noise (AWGN), where $N(0, \sigma_i)$ denotes symmetric complex Gaussian distribution with zero mean and variance σ_i. P_i denotes the transmit power and g_i denotes the pass loss. The overall gain is modeled as $G_i = P_i \cdot g_i$ The signals forwarded by relays are denoted by X_i for all $i \in \{1, 2, \cdots, n\}$. The received signals at relays and the destination D can be written as:

$$Y_i = \sqrt{G_i} \cdot h_i \cdot X_i + Z_i$$

IV. Cooperative Binary Relaying and Combining

In this section, we explain how the proposed *Cooperative Binary Relaying and Combining* (CBRC) works. CBRC works on multi-hop relay channels with two parallel branches, each of which has the same number of relay nodes. High data rate transmission achieved by high order modulation, such as 16-QAM or 64-QAM, can result in performance degradation in the case of low channel SNR. Our approach solves this problem by making binary detection similar to BPSK at each relay node, and forwarding the detection to the next relay. The detection results are gathered on the destination to make the final demodulation and decode the information bits. Without loss of generality, in the following, we use 16-QAM modulation as an example to describe how CBRC works in detail, but it can be easily extended to general cases.

A. 16-QAM CBRC

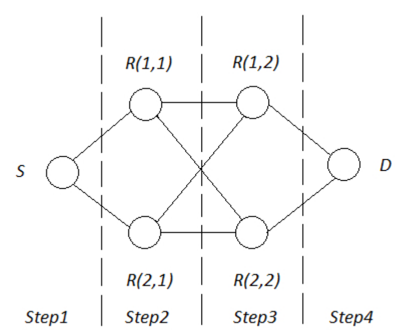

Fig. 2. 16-QAM CBRC with four steps

The 16-QAM CBRC is shown as Figure 2. In the figure, there are four steps. In the first step, the bit stream at the source S, is modulated with 16-QAM of square constellation, where the information is encoded in both amplitude and phase of the transmitted signal. The transmitted signal of 16-QAM is given by

$$S_i\left(t\right) = A_i \cdot cos(b_i) \cdot cos(2\pi f_c t) - A_i \cdot sin(b_i) \cdot sin(2\pi f_c t)$$

,where $i \in \{1, 2, \cdots 16\}$. The complex lowpass representation of S_i is $S_i\left(t\right) = Re\left\{u_i\left(t\right)\right\}$, where $U_i\left(t\right) = S_I\left(t\right) + jS_Q\left(t\right)$ is the equivalent lowpass signal of S_i. To facilitate the explanation, with loss of generalityy, we assume the symbol that represents "0000", the constellation point at upper left corner of the 16-QAM's constellation map as in Figure 3, is transmitted from the source.

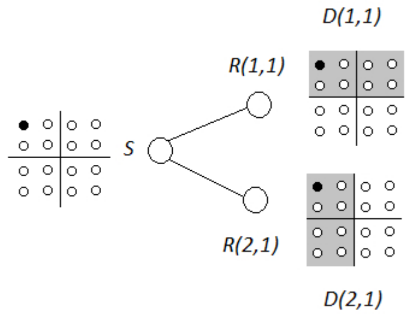

Fig. 3. The second step: Symbol "0000"" is transmitted from the source, $S\left(0,0\right)$. $R\left(1,1\right)$ makes decision $D\left(1,1\right)$;$R\left(2,1\right)$ makes decision $D\left(2,1\right)$.

The overview of the second step is shown in Figure 3. In the second step, the relay nodes, $R\left(1,1\right)$ and $R\left(2,1\right)$, receive the signal transmitted by the source S. Unlike any conventional cooperative communication strategy (for instance, amplify-and-forward [4], demodulate-and-forward [5], and decode-and-forward [4], [6]), CBRC does not attempt to demodulate the received 16-QAM signal. Rather, it treats the signal as a binary modulated signal, which is the core of CBRC. $R\left(1,1\right)$ makes a binary detection that decides the received signal is on the upper half or the lower half of the constellation map. $R\left(2,1\right)$ makes a similar binary detection. But it decides the received signal is on right half or on left half of the constellation map. The decision rules, $D\left(1,1\right)$ for $R\left(1,1\right)$ and $D\left(2,1\right)$, for $R\left(2,1\right)$, can be summarized as:

$$D\left(1,1\right) = \begin{cases} 0 & if\ S_Q \geq 0 \\ 1 & if\ S_Q < 0 \end{cases}$$

$$D\left(2,1\right) = \begin{cases} 0 & if\ S_I \geq 0 \\ 1 & if\ S_I < 0 \end{cases}$$

,where S_Q and S_I are quadrature component and in-phase component of the equivalent lowpass signal $U\left(t\right)$. $D\left(1,1\right)$ and $D\left(2,1\right)$ are modulated by BPSK at relay $R\left(1,1\right)$ and $R\left(2,1\right)$; and they are transmitted to $R\left(1,2\right)$ and $R\left(2,2\right)$ respectively. The original signal is amplified and forwarded from $R\left(1,1\right)$ and $R\left(2,1\right)$ to $R\left(1,2\right)$ and $R\left(2,2\right)$ respectively.

The overview of the third step is shown in Figure 4. In this step, the relay $R\left(1,2\right)$ receives a copy of original signal S, denoted $S\left(1,1\right)$, and the partial binary decision $D\left(1,1\right)$ from the preceding relay node $R(1,1)$, and the partial decision $D\left(2,1\right)$ from $R(2,1)$. Similarly, $R(2,2)$ receives $S\left(2,1\right)$ and $D\left(2,1\right)$ from $R(2,1)$, and $D\left(1,1\right)$ from $R(1,1)$. Based on the prior decisions, $D\left(1,1\right)$ and $D\left(2,1\right)$, and the

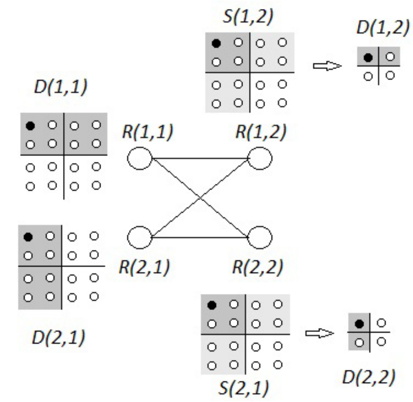

Fig. 4. The scheme of the third step. Both of $D\left(1,1\right)$ and $D\left(2,1\right)$ are received by $R\left(1,2\right)$ and $R\left(2,2\right)$. Combining $D\left(1,1\right)$ and $D\left(2,1\right)$, $R\left(1,2\right)$ and $R\left(2,2\right)$ can locate the symbol on the upper left quadrant. The decisions $D\left(1,2\right)$ and $D\left(2,2\right)$,are made by $R\left(1,2\right)$ and $R\left(2,2\right)$.

forwarded original signal, $R\left(1,2\right)$ and $R\left(2,2\right)$ are able to locate the original signal (,$S\left(1,1\right)$ or $S\left(2,1\right)$) in one of the four quadrants of the constellation map. Because, from $D\left(1,1\right)$, a node can deduce the symbol is on the upper or lower plane. From $D\left(2,2\right)$, the node can deduce the symbol is on the left or right plane. Combining these two decisions, it can locate the received signal, S_1, on one of the four quadrants as shown in Figure 4. Before any detection is made, the located 1/4 region is moved to the center of the constellation map by a linear transformation, as shown in the upper plot of Figure 5. This transformation can be simply done by subtracting the coordinate of received signal, $S\left(1,1\right)$ and $S\left(2,1\right)$, by the coordinate of the center of the $1/4$ region. After the transformation, $R\left(1,2\right)$ makes a binary detection $D\left(1,2\right)$ that decides the symbol is on the upper half part or on the lower half part of the $1/4$ region. Similarly, $R\left(2,2\right)$ makes a binary detection $D\left(2,2\right)$. But it decides the symbol is on the right half part or on the left half part of the $1/4$ region. $D\left(1,2\right)$ and $D\left(2,2\right)$ are illustrated in the lower part of Figure 5.

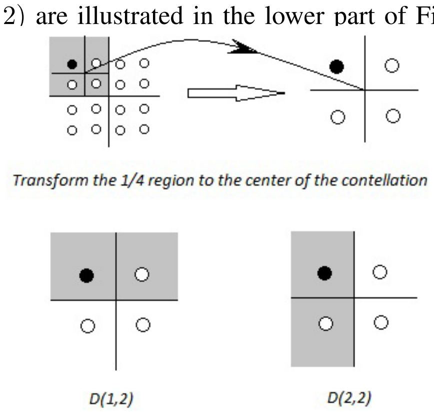

Fig. 5. The upper one is the transformation. The lower one is the binary detections $D_1\left(1,2\right)$ and $D_1\left(2,2\right)$.

The decision rules of $D\left(1,2\right)$ and $D\left(2,2\right)$ are formulated as follows:

$$D\left(1,2\right) = \begin{cases} 0 & if\ S_Q \geq 0 \\ 1 & if\ S_Q < 0 \end{cases}$$

$$D\left(2,2\right) = \begin{cases} 0 & if\ S_I \geq 0 \\ 1 & if\ S_I < 0 \end{cases}$$

Next, the current detections, $D\left(1,2\right)$ and $D\left(2,2\right)$, and the

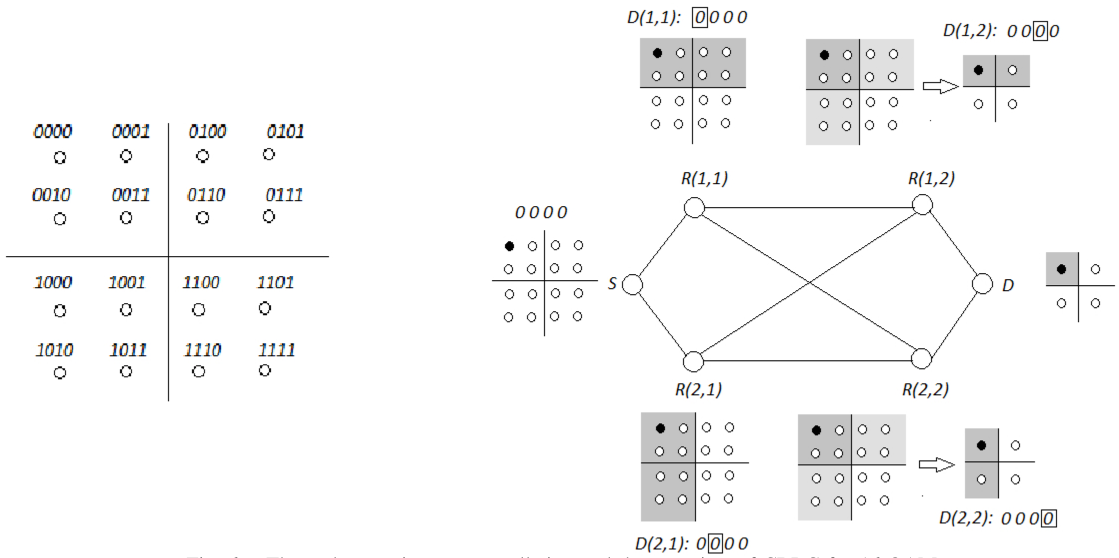

Fig. 6. The code mapping on constellation and the overview of CBRC for 16-QAM

previous detections $D\left(1,1\right)$ and $D\left(2,1\right)$ are forwarded to the destination, D.

Finally, in the fourth step, the destination, D, receives $D\left(1,1\right)$ and $D\left(1,2\right)$ from $R\left(1,2\right)$ and $D\left(2,1\right)$ and $D\left(2,2\right)$ from $R\left(2,2\right)$. All of the four detections are BPSK signals. They are demodulated into four binary bits that are exactly the bits contained in the symbol that is modulated by 16-QAM from the source, S. The symbol is thus fully demodulated.

CBRC can also be explained from the perspective of the code mapping on the constellation. Assume symbols are modulated with 16-QAM of square constellation shape as shown in the left part of Figure 6, which is designed for CBRC. In this code mapping, the first bit indicates that the symbol is on the upper or lower of the plane; the second bit indicates that a symbol is on the left or the right of the plane; the third bit indicates that a symbol is on the upper or lower of a 1/4 quadrant; the fourth bit indicates that the symbol is on the left or right of a 1/4 quadrant. As plotted on the right of Figure 6, in the second step of CBRC, the first bit is determined by $R\left(1,1\right)$ and the second bit is determined by $R\left(2,1\right)$. In the third step, the third bit is determined by $R\left(1,2\right)$ and the fourth bit is determined by $R\left(2,2\right)$. It is clear that each relay node determines only one bit. Namely, each relay made a binary detection as in BPSK demodulation, **which is much more tolerant to channel noise and fading than demodulating a16-QAM symbol**.

V. Performance Evaluation

In order to verify the performance of the proposed CBRC, this section presents numerical results obtained with Monte Carlo simulations. The performance is illustrated in bit error rate (BER) against the practical average SNR per bit in decibel (dB), $\gamma_0 = P_0/N_0$ for various simulation setups. The simulations are based on AWGN channels at different scenarios. The performance over AWGN can be consiered as the upper bound on the performance.

A. Experiment Settings

In the evaluation, we consider two parallel relay branches with multiple chained hops as shown in Figure 2. AWGN channel model is assumed. We implemented CBRC for two modulations: 16-QAM and 64-QAM. The performance of CBRC schemes is compared with the conventional cooperative schemes of *demodulate-and-forward relaying*, because both CBRC and the conventional method do not have the error control coding so that the effect of coding gain can be eliminated to ensure fair comparisons. In such comparison, the performance difference between demodulating the signal directly in every relay node and partially demodulating using the proposed CBRC can be clearly observed. Three scenarios are considered. In the **first** scenario, all the links in the upper and lower branches have the same SNRs, which range from 1dB to 15dB. In this scenario, the channel conditions of two branches are symmetric. The performance is measured from poor to good channel conditions. The **second** scenario is that the SNRs of the links between the destination, D, and the last relays, $R\left(1,2\right)$ and $R\left(2,2\right)$, vary from 1dB to 15dB. The SNRs of all other links, which are relay channels, are low (5dB is set in experiments). In this scenario, the channel conditions of two branches are also symmetric. This scenario particularly evaluates the effect of low SNR inner-relay condition on the performance. The **third** scenario is designed for asymmetric links in two branches: all the links of the upper branch have relatively low SNRs (5dB), but the SNRs of the links in the lower branch vary from 1dB to 15dB. In this scenario, the effect of one low SNR branch on the performance is revealed.

B. Simulation Results

In the first scenario, we consider two relay branches in Figure 2 with the same SNR. Figure 7 shows the BER performance of the proposed CBRC and the conventional demodulate-and-forward cooperative strategy, where x-axis refers to the SNR on each link. The simulation result shows the strengths of the proposed strategy in improving the performance. In Figure 7, we observe that CBRC outperforms the conventional strategy at low SNR link conditions. The proposed strategy improves the BER around 1 to 2 dB over the conventional strategy. The performance of two strategies becomes close as the SNR increases. This is because high SNR does not incur large errors in demodulation, even for high order modulations. Thus, there is limited margin for CBRC to improve because both schemes have almost best performance. The performance gap between two strategies for 64-QAM is larger than for 16-QAM, which indicates that the performance gain of CBRC becomes greater when higher order modulation is employed to achieve high data rate. This is because higher order modulation leads to larger errors and gives more room for CBRC to improve.

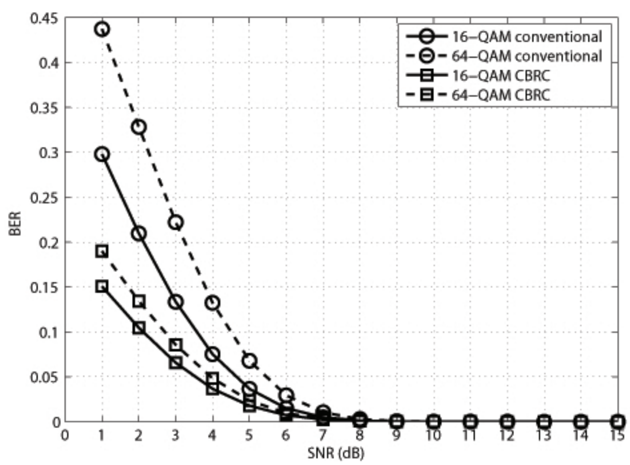

Fig. 7. The BER comparison of CBRC in the case that the SNRs of two branches are identical.

For the second scenario, Figure 8 compares the performance on low SNR (5dB) relay links. The x-axis represents the SNR of the link at the last hop (between the last relay nodes and the destination D). Unreliable relay links can cause error propagation and highly degrade the performance of cooperative communication. CBRC greatly outperforms the conventional strategy when the SNRs between the last relay nodes and destination are high. Also, the comparison between 16-QAM and 64-QAM CBRCs implies that even if a higher order modulation is used, CBRC is still able to maintain the good performance. That is because CBRC decomposes the high order demodulation into binary demodulation under the cooperation of the relay nodes and avoids the decoding errors that significantly degrade the performance of conventional schemes.

For the third scenario where one branch has links of constantly low SNR (5dB). Figures 9 plots the performance where the x-axis refers to the SNR of the other branch that varies from 1dB to 15dB. The observation from the figure is that CBRC still yields better performance than *demodulate-and-forward* solutions. However, the improvement is marginal. The reason is that the low SNR branch links significantly hurt the performance, even in the binary detection.

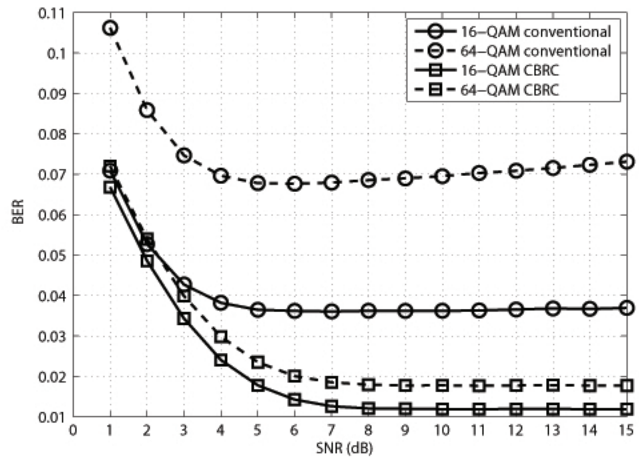

Fig. 8. The BER comparison in the case that the SNRs of relay channels are identical but low.

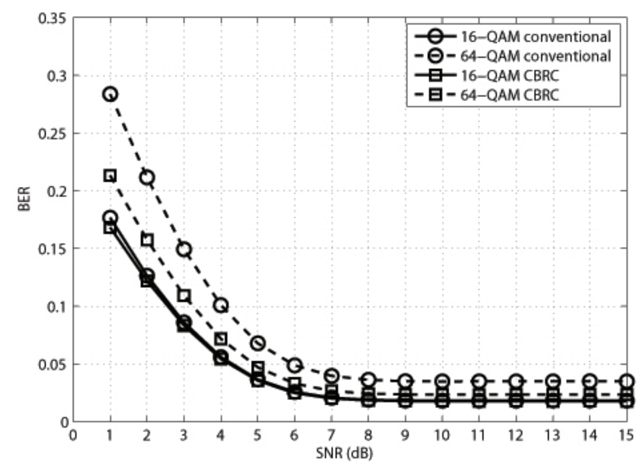

Fig. 9. The BER comparison in the case that e the SNR of one branch is constantly low.

VI. Discussion

In this section, the problems and further works of CBRC are discussed as followings. There are two problems that must be pointed out in this strategy. First, the order of modulation determines the number of hops. The higher-order modulation it employed the more hops it required. For example, 16-QAM requires 4 hops; and 64-QAM requires 6 hops. The reason is that CBRC tries to distribute the pressure of demodulation equally over hops, where each hop demodulates one bit. The higher-order symbol contains more bits. Therefore, higher-order modulation asks for more hops. Secondly, in the third scenario, where the SNR of one of the two branches is low, the simulation shows that CBRC does not provide significantly better improvement. Each node demodulates one bit so that half of total transmitted bits are demodulated under adverse channel condition. In addition, those bits will also affect the demodulation of other bits. Consequently, one low SNR branch highly degrades the performance of CBRC. In the further, the bit error rate of CBRC will be analyzed. And new techniques will be sought to alleviate the first problem discussed above.

VII. Conclusion

This paper proposes a novel Cooperative Binary Relaying and Combining strategy (CBRC) for multi-hop cooperative communication with high order modulation. CBRC supports high order modulation to achieve high bit rate transmission while maintaining low bit error rate performance by making binary detections at cooperative relay nodes. With cooperative binary detection distributed over relay nodes, CBRC is much more reliable than simple relaying-and-combining of the high order modulated signal. Especially, for multi-hop cooperative communication over low SNR relays links, CBRC achieves a significant performance gain, which is investigated and validated through extensive simulation. CBRC can be further extended to support other higher-order modulations such as 64-QAM or 256-QAM for higher bit rate transmission, especially over poor links.

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