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Wireless Cooperative Communication and Networking

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WIRELESS COOPERATIVE COMMUNICATION AND NETWORKING

by

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ABSTRACT

WIRELESS COOPERATIVE COMMUNICATION AND NETWORKING

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Cooperative communication can achieve diversity gain and increase the channel capacity This paper proposes a novel cooperative scheme called Cooperative Step-Wise Demodulation, which utilizes low level demodulation to demodulate high level modulated signal cooperatively This paper focuses cooperative scheme in multi-hop wireless networks. The bit error rate probability is analyzed. The comparison among the proposed scheme and the conventional scheme is made through simulation and soft-define radio based experiments. Results show that the proposed scheme has great potential in the performance improvement of cooperative communication.

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure

Chapter 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 [8] In recent years, novel opportunistic technologies of cooperation among wireless mobile terminals, referred as *cooperative relay*, have been considered as a potential scheme to significantly improve the communication system performance by cooperatively relaying the received signals at intermediate nodes to the destination in order to constitute a distributed virtual multiple input multiple output (MIMO) system [2, 3, 9] Because of various gains of cooperative relay over the conventional single-path transmission, it is expected to be an essential technology to the next generation wireless networks. In particular, relay station in cellular system is able to increase energy efficiency and extend cell coverage[20]

In wireless communication, normally, high-order modulations lead to high error propagation and large bit error rate (BER) in wireless communication, especially under low SNR channel conditions. Although low-order modulations can address the problem, they yield low bit rate. 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 error rate of low-order modulations.

In this paper, we propose a novel cooperative strategy called *Cooperative Step-wise Relaying and Combining* (CSRC) for multi-hop wireless networking system that partially demodulates the signal symbol with low-order robust modulations, let us say QPSK, 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 or decode-and-forward relaying schemes, *CSRC* makes a *partial* demodulation decision 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 16-QAM or 64-QAM, for high bit rates over multi-hop wireless networks. The bit error probability of *CSRC* is analyzed theoretically Extensive simulation evaluations are conducted and prove the strengths of the proposed *CSRC* Furthermore, the comparisons of performance between proposed scheme and conventional scheme are conducted on a soft-define radio (SDR) testbed. The results of both simulation results and SDR testbed experiments show the great potentials of *CSRC* in improving the communication performance.

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 Step-Wise Relaying and Combining* . In Section V, the bit error probability of *CSRC* is analyzed. The simulation experiments are demonstrated in Section VI. In Section VII, the results of SDR testbed experiments are demonstrated. Finally, Section VIII concludes this work.

Chapter 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 [13], demodulate-and-forward [7], decode-and-forward [13, 4] and soft decode-and-forward [10] In amplify-and-forward (AF), a relay node amplifies the received signals and forwards the scaled signal 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 is low-complexity and 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 [14] Coding schemes such as distributed Turbo codes [22, 19] have been also studied to exploit the cooperative diversity for DF in relay channels. Recently, Low Density Parity Check (LDPC) codes were investigated for half-duplex relay channels [1, 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* [10, 22] 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 [15] and Decode-Estimate-Forward [18] , which use the minimum mean square error estimation (MMSE) to optimize SNR.

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 [11] 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 [21]

All of the relay protocols that have been discussed above suffer from the problem of low spectrum efficiency Specifically, their spectrum efficiency is half of that of direct transmission. To improve the spectrum efficiency, two-way relaying is proposed [5, 17] The packets from two ends are combined at the relay node. The combined packets are relayed to two ends. Finally, there two can extracts the packets they need by subtracting the packets they have sent. In three terminal and TDMA setting, two-way relaying need two slots instead of four for one-way relay

Chapter III
SYSTEM MODEL

This section describes the system model and assumptions that this paper is based on. Consider the half-duplex multi-hop relay system shown in Figure 1, there are two topologies. The upper one is one branch relay channel, the lower one is two branches cooperative channel. Both of them consist of one source, one destination, and distributed relays that cooperatively support the communication between the source S and destination D In this system, the source encodes the information bits and transmits the modulated signals to the relay The relay demodulates, decodes and re-encodes the received message. The resulting message is modulated and forwarded to its next prospective relay node. Finally, the destination receives the signals from the last relays. It is assumed that every node in this system can only hear the two nodes next to it. In addition, this relay system is an inband setting, namely, transmitting and receiving over the same frequency band in a half-duplex mode, which is achieved with a time division duplex (TDD), where data are transmitted and received 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 facilitate the communications between relays.

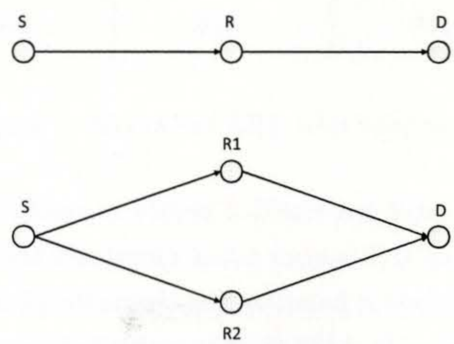

Figure 1 Topologies of channel model

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, $E\left[\left|X^2\right|\right] < P_0$ In the baseband model, for all $i \in \{1, 2, \cdots, n\}$ corresponding to relays and the destination D, the signal is disturbed by Rayleigh frequency-flat fading characterized by fading coefficients h_i, which are constant complex scalars known to the relays. $Z_i \sim N(0, \sigma_i)$ captures the additive white Gaussian noise (AWGN) perceived by nodes, 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 path loss. The overall channel gain is modeled as $G_i = \sqrt{P_i \cdot g_i} \cdot h_i$. 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:

$$Y_i = G_i \cdot X_i + Z_i$$

Chapter IV
COOPERATIVE STEP-WISE RELAYING AND COMBINING

In this section, we explain how the proposed *Cooperative Step-wise Relaying and Combining* (CSRC) works. *CSRC* works on multi-hop relay channels. 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 detection with low-order modulations, e.g. QPSK, 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. To facilitate the explanation, *CSRC* for 16-QAM modulation in one branch relay channel is elaborated as an example to show how it works. Extensively, *CSRC* for 64-QAM in both of one branch relay channel and two branches relay channel are illustrated in the following.

4.1 16-QAM CSRC

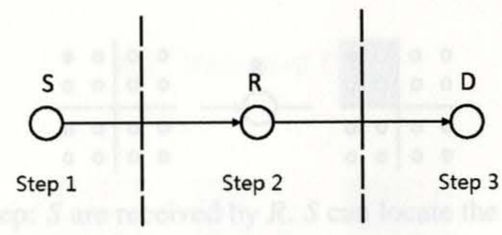

Figure 2· 16-QAM CSRC with three steps

The 16-QAM *CSRC* is shown in Figure 2. There are three steps involved. In the first step, assume that the original 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

$$S_i(t) \quad A_i \ cos(b_i) \ cos(2\pi f_c t) \quad A_i \ sin(b_i) \ sin(2\pi f_c t)$$

,where $i \in \{1,2, \quad 16\}$ The complex lowpass representation of S_i is $S_i(t) \quad Re\{u_i(t)\}$, where $U_i(t) \quad S_I(t) + jS_Q(t)$ is the equivalent lowpass signal of S_i To facilitate the explanation, without loss of generality, we assume the symbol that represents "0000", the constellation point at upper left corner on the 16-QAM's constellation map as in Figure 3, is transmitted from the source in the first step.

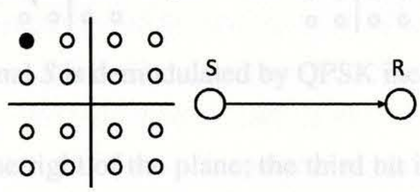

Figure 3: The first step: Symbol "0000" is transmitted from the source, *S*, to the relay node, *R*

The the second step is shown in Figure 4. The relay node, *R*, receives the signal *S*, transmitted by the source *S* Unlike any conventional cooperative communication strategy (for instance, amplify-and-forward [13], demodulate-and-forward [7], and decode-and-forward [13, 4]), *CSRC* does not attempt to demodulate the received 16-QAM signal. Rather, it treats the signal as a QPSK modulated signal, *which is the core of CSRC* *R* demodulates the 16-QAM symbol with QPSK. As is shown in Figure 4, at *R*, the perceived 16-QAM symbol can be detected in the upper left of constellation map via QPSK demodulation. And then, the relay node *R* sends *two* signals to the destination *D* One is the original 16-QAM signal *S* The other one is a QPSK symbol, which is a hint, *H*, which indicates the location of the original symbol in the constellation map. In this example, the hint indicates the symbol is in the upper left.

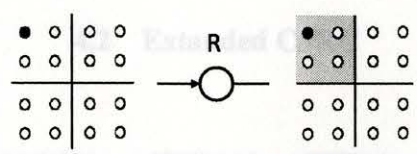

Figure 4 The second step: *S* are received by *R* *S* can locate the symbol on the upper left quadrant.

The the third step is shown in Figure 5 In this step, the destination *D* receives the two signals, *S* and *H*, from the relay node *R* Before the original symbol *S* is demodulated, *H* is demodulated first so that *S* is located in one of the four quadrants of the constellation map. Base on this hint, 16-QAM *S* can be detected by QPSK, (NOT 16-QAM), which is more reliable than the detection of 16-QAM. By this moment, the original signal *S* is fully demodulated with two consecutive QPSK demodulations.

CSRC 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 *CSRC* 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

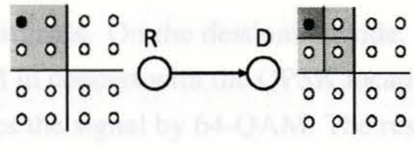

Figure 5 The original signal *S* is demodulated by QPSK incorperating with the hint *H*

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 *CSRC*, the first and second bits are determined by *R*. In the third step, the third and fourth bits are determined by the destination, *D* It is clear that each relay node determines only two bit. Namely, each relay conducted a QPSK demodulation, **which is much more tolerant to channel noise and fading than demodulating a 16-QAM symbol**.

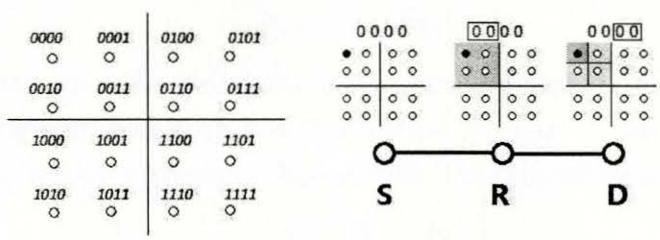

Figure 6· The code mapping on constellation and the overview of CSRC for 16-QAM

4.2 Extanded CSRC

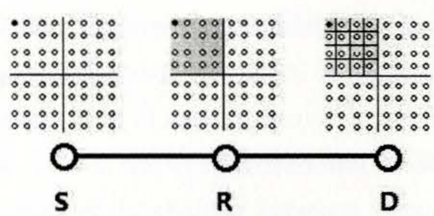

Figure 7 CSRC for 64-QAM

In addition to apply *CSRC* for 16-QAM modulation, it can also be used for 64-QAM and 256-QAM symbols. The entire procedure for *CSRC* with 64-QAM is illustrated in Figure 7 Based on the same three-node model (one source, one relay and one destination), data stream can be modulated by 64-QAM and transmitted by the source. Then, the relay demodulates the received signal with QPSK to locate the symbol in one of the four quadrants of the constellation map. This location is modulated by QPSK and forwarded to the destination with the original 64-QAM signals. On the destination side, the original 64-QAM signal is demodulated by 16-QAM in concert with the QPSK location hint. For *CSRC* with 256-QAM, the relay demodulates the signal by 64-QAM. The resulted, as a hint, is forwarded with the original 256-QAM signal. The destination demodulates the original signal by 64-QAM incorporating the 64-QAM hint. CSRC is also able to adopt to two branches network topology in lower parts of Figure 1 It can be in cooperative manner by transmitting identical signal using CSRC in both branches and combining the received signals from both branches at the destination.

Chapter V
BIT ERROR PROBABILITY OF CSRC

In this section, the bit error probability of CSRC for 16-QAM in AWGN channel is analyzed to show the improvement of performance on detection. *CSRC* achieves low error of detection by partially demodulating the signal symbol with QPSK, which is the more reliable, at each cooperative relay node. Assume that all channels have the same SNR, γ_0 The probability of error of QPSK with coherent detection and perfect recovery of the carrier frequency and phase is

$$P_0 \quad Q\left(\sqrt{2\gamma_0}\right)$$

,where $Q(x)$ is defined as the probability that a Gaussian random variable X with mean 0 and variance 1 is greater than x. $Q(x) \quad P(X > x) \quad \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx$. AWGN channel can be represented by Binary Symmetric Channel [16] The channel transition matrix is

$$T \quad \begin{bmatrix} 1 \quad P_0 & P_0 \\ P_0 & 1 \quad P_0 \end{bmatrix}$$

The element in the first row and the first column is the probability of sending bit 0 and receiving bit 0. The element in the first row and the second column is the probability of sending bit 0 and receiving bit 1. In *CSRC* for 16-QAM, each relay detects two bits. In addition, the transmission error probability for each bit is not always the same, because they are detected at different nodes. The error probabilities for each bit are discussed separately and followed by the bit error probability for *CSRC* in the following.

For the first two bits, denoted as P_1 and P_2, they are detected at *R*, transmitted to *D*, and finally demodulated by *D* Due to the assumption that SNR of all channels are identical, the channel transition matrixes of the channel between *S* and *R* and the channel between *R* and *D* are identical. Therefore, the transition matrix for the transmission of the two bits by *CSRC* strategy, denoted as T_{12}, is

$$\begin{aligned} T_{12} &= T \quad T \\ &= \begin{bmatrix} P_0^2 + (1 \quad P_0)^2 & 2P_0 \quad (1 \quad P_0) \\ 2P_0 \quad (1 \quad P_0) & P_0^2 + (1 \quad P_0)^2 \end{bmatrix} \end{aligned}$$

Thereby, the error probability of the first two bits is

$$P_1 \quad P_2 \quad 2P_0 \, (1 \quad P_0)$$

For the last two bits, denoted as P_3 and P_4, the detection depends on the previous detection of the first two bits. To assure the correction of the detection, the first two bits must be received and demodulated correctly at D in order to locate the region of the signal in the constellation map. In other words, the detection of QPSK hint must be right. The probability of QPSK symbol error is

$$P_s \quad 1 \quad (1 \quad Q\left(\sqrt{2\gamma_0}\right))^2$$

The transition matrix for the transmission of the two bits by *CSRC* strategy, denoted as T_{34}, is

$$T_{34} = \begin{bmatrix} 1 \quad P_s & P_s \\ P_s & 1 \quad P_s \end{bmatrix} \begin{bmatrix} 1 \quad P_0 & P_0 \\ P_0 & 1 \quad P_0 \end{bmatrix}$$

$$\begin{bmatrix} (1 \quad P_s)\ (1 \quad P_0) + P_s\ P_0 & (1 \quad P_s)\ P_0 + P_s\ (1 \quad P_0) \\ (1 \quad P_s)\ P_0 + P_s\ (1 \quad P_0) & (1 \quad P_s)\ (1 \quad P_0) + P_s\ P_0 \end{bmatrix}$$

Thus, the error probability of the last two bits is

$$P_3 = P_4 \quad (1 \quad P_s)\ P_0 + P_s\ (1 \quad P_0)$$

The symbol error probability of CSRC strategy is

$$P_{symbol} = 1 \quad \prod_{i=1}^{4} (1 \quad P_i)$$

The bit error probability can be approximated by

$$P_{bit} \approx P_{symbol} / log_2 M$$

, where M is the order of the modulation. In this example, 16-QAM is used so that M equals to 4.

To consider the bit error probability of CSRC in two branches case in Figure /reff1, the additional effect of combing at the destination must be analyzed. Suppose MRC servers as the combing technique, which maximized the SNR with respect to the weights on each branch. The SNR of the result of MRC equals to the sum of SNR of each branch. In our analysis, γ_d denotes the SNR after MRC at the destination, γ_1 denotes the SNR of the upper branch, γ_2 denotes the SNR of the lower branch. The SNR after MRC at the destination is $\gamma_d \quad \gamma_1 + \gamma_2$ The transition matrix of relay-destination chennal is modified by γ_d To get transition matrix of relay-destination chennal, we define

$$P_0{}' \quad Q\left(\sqrt{2\gamma_d}\right), and$$

$$T' \begin{bmatrix} 1 & P_0' & P_0' \\ P_0' & 1 & -P_0' \end{bmatrix}$$

The transition matrix for the transmission of the first two bits, denoted as T_{12}', is

$$T_{12}' \quad T \quad T'$$

The transition matrix for the transmission of the last two bits, denoted as T_{34}', is

$$T_{34}' \begin{bmatrix} 1 & P_s & P_s \\ P_s & 1 & P_s \end{bmatrix} T'$$

Using these two transition matrixes by the same way as what is formulated for one branch case, we can get the bit error probability for the two branches case.

To compare the bit error performance of CSRC strategy with conventional amplified and forward strategy in both of one branch and two branches cases in Figure 1, the curves of bit error probability are illustrated in Figure 8 against SNR.

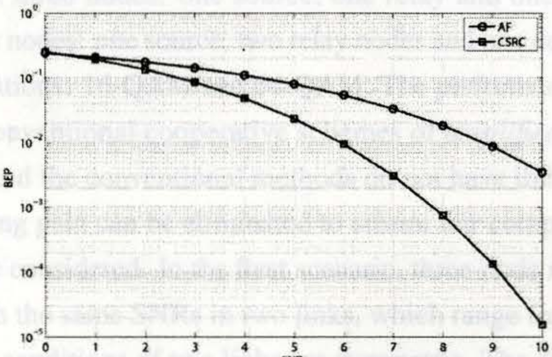

Figure 8: Comparison of theoretical bit error probability of 16-QAM modulated transmission between CSRC and conventional amplified and forward strategy

Chapter VI

PERFORMANCE EVALUATION

In order to evaluate the performance of the proposed *CSRC*, this section presents numerical results obtained with Monte Carlo simulations. The performance is measured in bit error rate (BER) upon SNR. The simulations are based on AWGN channels in different scenarios. The performance with AWGN channels can be considered as the upper bound.

6.1 Experiment Settings

In the simulation experiments, we consider two channel models, as illustrated in Figure 1. One model consist of three nodes: one source, one relay and one destination. The other model consists of four nodes: one source, two relay nodes and one destination. We simulated *CSRC* for two modulations: 16-QAM and 64-QAM. The performance of *CSRC* schemes is compared with the conventional cooperative schemes of *amplified-and-forward relaying*, because both *CSRC* and the conventional methods do not have the error control coding so that the effect of coding gain can be eliminated to ensure fair comparisons.

Four scenarios are considered. In the **first** scenario, three-node model, the upper case in Figure 1, is used, with the same SNRs in two links, which range from 0dB to 10dB. In this scenario, the channel conditions of two links are symmetric. The performance is measured from poor to good channel conditions. In the **second** scenario, the SNR of the link between the destination and the relay varies from 0 dB to 10 dB, but the SNR of the other link is kept constant as low (5 dB is set in experiments). In this scenario, the channel conditions of two links are asymmetric. This scenario particularly evaluates the effect of low SNR source-relay condition on the performance. In the **third** scenario, four-node channel model, the lower case in Figure 1, is considered and all the links in the upper and lower branches have the same SNRs, which range from 0 dB to 10 dB. In this scenario, the channel conditions of two branches are symmetric. The **fourth** scenario is designed for asymmetric links in two branches: all the links of the upper branch have relatively low SNRs (5 dB), but the SNRs of the links in the lower branch vary from 0 dB to 10 dB. In this scenario, the effect of one low SNR branch on the performance is revealed.

6.2 Simulation Results

Figure 9 shows the BER performance of the proposed *CSRC* and the conventional amplified-and-forward (AF) cooperative strategy in the first scenario, 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 9, we observe that *CSRC* outperforms the conventional AF strategy Specifically, it improves the BER around 2 to 3 dB over the conventional AF strategy The performance gap between two strategies for 64-QAM is larger than for 16-QAM, which indicates that the performance gain of *CSRC* 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 space for *CSRC* to improve.

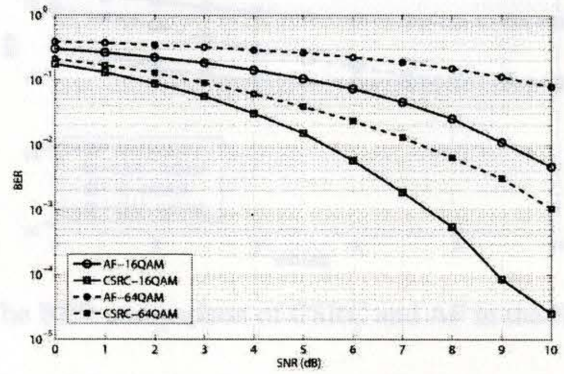

Figure 9· The BER comparison of CSRC and AF in the first scenario.

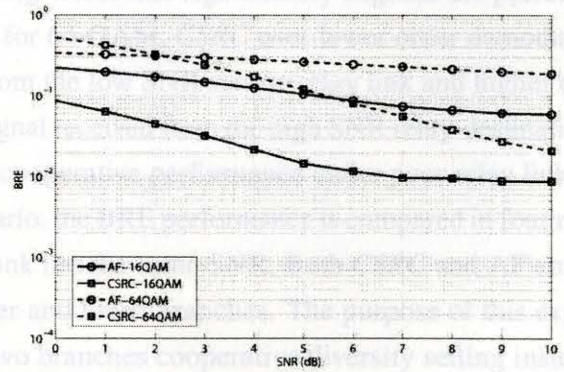

Figure 10· The BER comparison of CSRC and AF in the second scenario.

For the second scenario, Figure 10 compares the performance on low SNR (5 dB) relay links. The *x*-axis represents the SNR of the link between the relay *R* and the destination *D* Unreliable relay links can cause error propagation and highly degrade the performance of cooperative communication. *CSRC* outperforms the conventional strategy when the SNRs

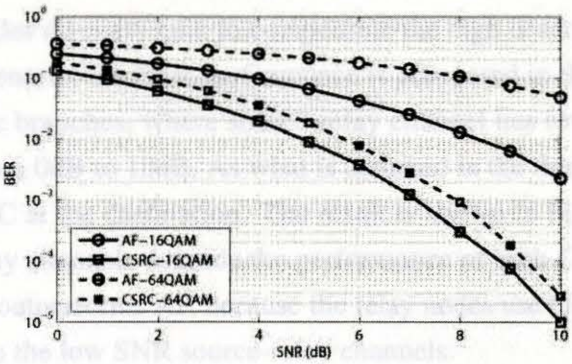

Figure 11 The BER comparison of CSRC and AF in the third scenario.

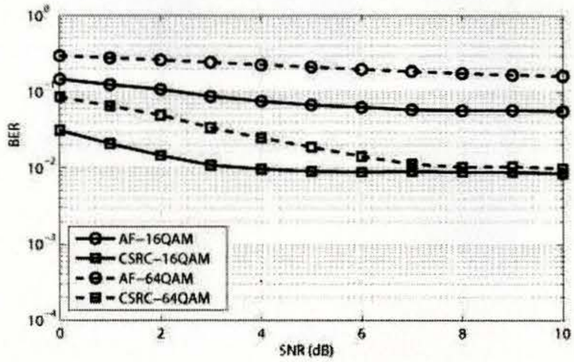

Figure 12 The BER comparison of CSRC and AF in the fourth scenario.

between the relay node and the destination are high. That is because *CSRC* 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. Especially, for 64-QAM, *CSRC* uses lower order demodulation, QPSK, to detect the signal received from the low SNR source-relay link and higher order demodulation, 16-QAM, to detect the signal received from the high SNR relay-destination link. This adaptation greatly improves the cooperative performance under poor relay link circumstance.

For the third scenario, the BRE performance is compared in four nodes over two branches setting, where each link has the same SNR. Both *CSRC* and AF employ MRC to combine the signals from upper and lower branches. The purpose of this experiment is to compare the performance in two branches cooperative diversity setting instead of one branch relay setting in previous two experiment. The result is demonstrated in Figure 11 It can be observed that *CSRC* greatly outperforms the conventional AF, especially when the order of modulation increases. The reason is that the low order demodulation, QPSK, is employed at the relay node to ensure that the destination can safely locate the symbol correctly Although a high order demodulation, 16-QAM, is used to detect the rest part of data, using MRC at the destination provides diversity gain to compensate the high order demodulation loss.

For the fourth scenario, the BER performance is compared in the setting of four-node over two asymmetric branches, where source-relay channel has low SNR, which is 5 dB Other links varies from 0dB to 10dB As what is assumed in the third scenario, both *CSRC* and AF employ MRC at the destination. The result is shown in Figure 12. Although the low SNR source-relay channels degrade the performance of both *CSRC* and AF, It can be observed that *CSRC* outperforms AF, because the relay nodes use QPSK to demodulate the signals received from the low SNR source-relay channels.

Chapter VII
SDR EXPERIMENTS

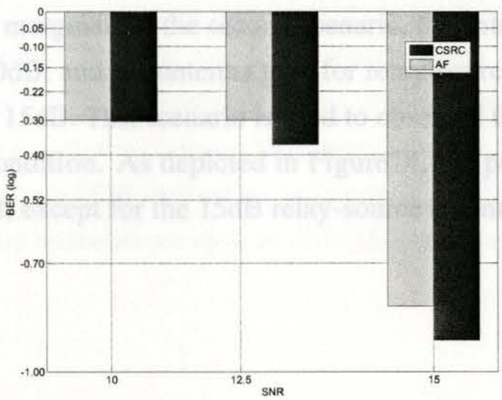

Figure 13: The BER comparison of CSRC and AF in SDR experiment.

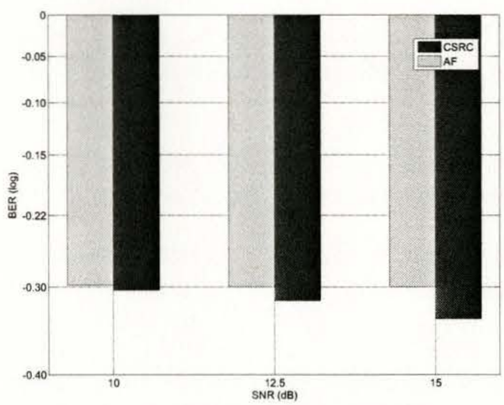

Figure 14 The BER comparison of CSRC and AF in SDR experiment.

In this section, the indoor SDR experiment is presented. The purpose of the experiment on the SDR tested is to validate the feasibility of hardware implementation and to test the performance in real wireless environment sand real hardware pipelines. The SDR tested consists of three USRP 210N nodes as shown in Figure 1 The distance between each two node is set as 5 meters. CSRC with 16-QAM is tested. The transmission is over 5GHz frequency band. To test the performance in different channel conditions, the antenna gains are varied in the tests. Two scenarios are considered. In one scenario, three values are selected, specifically 10 dB, 12.5dB and 15dB with respect to poor, average and good channel conditions. The results obtained from the SDR tested is illustrated in Figure 13 From the results, *CSRC* demonstrates better BER performance than AF in the average antenna gain setting and high antenna gain setting. However, in low antenna gain settings, the performance gain is marginal. In the second scenario, the antenna gain for source-relay transmission is set as 10dB, and the antenna gain for relay-source transmission is selected from 10dB, 12.5dB and 15dB This scenario is used to observed the performance under bad source-relay channel condition. As depicted in Figure14, the performance gain between CSRC and AF are small, except for the 15dB relay-source antenna setting.

Chapter VIII

CONCLUSION

This paper proposes a novel Cooperative Step-Wise Relaying and Combining strategy (CSRC) for cooperative communication with high order modulation. CSRC supports high order modulation to achieve high bit rate transmission while maintaining low bit error rate performance with low order demodulation detections at cooperative relay nodes. The strengths of *CSRC* are confirmed with theoretical analysis of bit error probability, extensive simulations and open source SDR testbed experiments. *CSRC* can be further extended to support other higher-order modulations such as 256-QAM over multi-hop wireless networks.

BIBLIOGRAPHY

[1] A. Chakrabarti, A. de Baynast, A. Sabharwal and B Aazhang. Low density parity check codes for the relay channel. *IEEE Journal on Selected Areas in Communications*, 25(2):280–291, 2007

[2] A. Sendonaris, E. Erkip, and B Aazhang. User cooperation diversity, part I. System descrıption. *IEEE Transaction on Communications*, 51(1)·1927ÍC1938, 2003.

[3] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity, part II. Implementation aspects and performance analysis. *IEEE Transaction On Communications*, 51(1):1939ÍC1948, 2003.

[4] A. Stefanov and E. Erkip. Cooperative coding for wireless networks. *IEEE Transaction On Communications*, 52(9), 2004.

[5] B Rankov and A. Wittneben. Spectral efficient protocols for half-duplex fading relay channels. *IEEE J. Select. Areas Commun.*, 25:379–389, 2007

[6] M. J Berger. Stability of interfaces with mesh refinement. Paper 83-42, ICASE, NASA Langley Research Center, Hampton, August 1983.

[7] D. Chen and J N Laneman. Modulation and demodulation for cooperative diversity in wireless systems. *IEEE Transactions on Wireless Communications*, 2005

[8] D. Tse and P Viswanath. *Fundamentals of Wireless Communication*. Cambridge.

[9] G Kramer, M. Gastpar and P Gupta. Cooperative strategies and capacity the ındependent and ıdentically dıstributed theorems for relay networks. *IEEE Transaction on Information Theory*, 51 3037–3063, 2005

[10] H. H. Sneessens and L. Vandendorpe. Soft decode and forward improves cooperatıve communıcations. *3G 2005ql6th IEE International Conference on 3G and Beyond*, 2005

[11] J Adeane, M. R. D Rodrigues, and I. J Wassell. Characterisation of the performance of cooperative networks in ricean fadıng channels. *12th Int. Conf Telecommun., Cape Town, South Africa*, 2005

[12] J Hu and T M. Duman. Low density parity check codes for the relay channel. *IEEE Transactions on Communications*, 6(9):3384ÍC3394, 2007

[13] J Laneman, D Tse and G Wornell. Cooperative diversity in wireless networks. Efficient protocols and outage behaviour. *IEEE Transactions on Information Theory*, 50(12):3062–3080, 2004.

[14] K. Azarian, H. El Gamal, and P Schniter On the achievable diversıty-multiplexıng tradeoff in half-duplex cooperatıve channels. *IEEE Transactions on Information Theory*, 51(12):552ÍC572, 2005

[15] K. Gomadam and S. A. Jafar Optimal relay functionality for snr maximization in memoryless relay networks. *IEEE Journal on Selected Areas in Communications*, 25(2).390–401, 2007

[16] M.C. Thomas and A.T Joy *Elements of Information Theory (second edition)* WILEY.

[17] P Popovski and H. Yomo. Wireless network coding by amplify-and-forward for bi-directional traffic flows. *IEEE Commun. Lett.*, 11 16–18, 2007

[18] P Weitkemper, D WÍźbben, V KÍźhn and K. D. Kammeyer Soft information relaying for wireless networks with error-prone source-relay link. *Proceedings of 7th International ITG Conference on Source and Channel Coding*, 2008.

[19] R. Thobaben. On distributed codes with noisy relays. *In Proceedings of Asilomar Conference on Signals, Systems and Computers,*, pages 26–29, 2008.

[20] T Tran, Y Shin and O. Shin. Overview of enabling technologies for 3gpp lte-advanced. *EURASIP Journal on Wireless Communications and Networking*, 2012.54.

[21] T Wang, A. Cano, G Giannakis and N Laneman. High performance cooperative demodulation with decode-and-forward relays. *IEEE Transactions on Wireless Communications*, 55(7):1427–1438, 2007

[22] Y Li, B. Vucetic, T.F. Wong, and M. Dohler Distributed turbo coding with soft information relaying in multihop relay networks. *IEEE Journal on Selected Areas in Communications*, 24(11):2040 ÍC 2050, 2006.