Soft Decode and Forward of MQAM Modulations for Cooperative Relay Channels

Reza Hoshyar, and Rahim Tafazolli
Centre for Communication Systems Research (CCSR), Department of Electronic Engineering,
University Of Surrey, Guildford, GU2 7XH, Surrey, UK

***Abstract*—A novel approach for extension of soft decode and forward strategy into higher order MQAM modulation is proposed. A new soft mapping function is introduced to map soft bits onto a point in the complex plane. It is shown that the proposed soft decode and forward (SDF) scheme attains the same level of diversity as amplify and forward (AF) scheme while improves the overall system spectrum efficiency through forwarding with higher order modulations. Simulation results show that new scheme outperforms DF for different links conditions.**

***Index Terms*—Relay Channels, coding, higher order modulation**

I. Introduction

In cooperative relay channel a number of relay nodes participate in a communication between a source and destination node. The main objective of this involvement is improvement of the overall communication performance in terms of bit or packet error rate, and throughput. Pioneering works on cooperative relaying could be traced back to 1968 on the study of three node channels by Van Der Meulen [1], and later on the work carried out by Sato on relay transmission [2], and Cover and El-Gamal on capacity theorems of relay channels [3]. Besides information theoretic treatment of the relay channel, Cover and El-Gamal also introduced several relaying strategies based on cooperation, facilitation, and observation concepts. Recently their proposed relaying strategies are further extended and applied to practical wireless fading channel [4]-[7]. The two basic strategies are ''decode and forward'' (DF) and ''amplify and forward'' (AF). In DF scheme relay first decodes the source signal and then re-encodes and forwards it to destination, while in AF it amplifies the received analogue signal and without any attempt to decode, forwards the amplified signal. As rightly elaborated in [8] and [9] each scheme has got some merits and of course some deficiencies. DF benefits from error correction capability and can correct some or all of the errors happened in source-relay transmission. However this requires reliable enough source-relay link otherwise it will lead to serious error propagation as relay will forward erroneous data and will mislead the destination receiver. In contrast AF keeps itself from any premature decision and in fact preserves the soft information content of the received signal. However this scheme fails to benefit from error correction possibility at relay and also amplifies and forwards relay receiver front end noise. Compared to DF, AF is much less complex. Inspired by soft information preservation property of AF, [8] and [9] propose a modified DF scheme that maintains the soft information content throughout the whole decoding and re-encoding process. The forwarded signal in their proposed scheme is constructed from soft values of the encoded bits. Though they gave different names for their proposed approach here we call their approach as ''soft decode and forward'' (SDF). They demonstrated that SDF outperforms both AF and DF schemes and inherits merits of both schemes. Li et al. use a different version of SDF in their proposed distributed turbo code architecture [11]. An important advantage of DF over AF is that it allows for change of modulation and coding scheme in relay transmission to destination. This enables the system to properly exploit the link capacity of the relay-destination link, especially when this link is highly reliable relay can increase its modulation order and forward its signal in much shorter time. Consequently the overall spectrum efficiency of the system will be boosted. The proposed SDF schemes so far are only proposed for simple binary phase shift keying (BPSK) modulation, extension of their approach to quadrature phase shift keying (QPSK) with Gray labelling is straight forward. However the extension of the approach to any generic higher order modulation scheme is rather an involved process. Here we address the extension of the SDF scheme for multiple quadrature amplitude modulations (MQAM). A new soft mapping function is proposed. Simulation results show that the extended SDF scheme with the proposed new soft mapping overcomes the weaknesses of DF scheme and exhibits satisfactory performance for different configurations of source, relay, and destination links condition.

The rest of the paper is organized as follows. The system model is presented in Section II. Section III discusses the extension of SDF scheme to higher order MQAM modulations and elaborates on soft bit de-mapping and soft mapping concepts. Simulation results for different links' condition and modulation configuration are shown in Section IV and Section V concludes the paper.

II. System Model

Let's assume a simple cooperative communication system composed of three nodes: source node S, relay node R, and destination node D. Let's further assume that nodes transmission-reception is based on a simple protocol composed of two phases. In the first phase of this protocol S broadcasts its signal to R and D, and in the second phase only R transmits to D. Even though more efficient approach is to allow S and R jointly transmit in the second phase, for the convenience of introduction of the proposed approach we adhere to this simple protocol. The Cooperative communication model using this protocol is depicted in Figure 1. The links S-R, S-D, and R-D are enumerated with 0, 1, and 2, respectively. Phases I and II are composed of N_1, and N_2 transmissions, respectively. In phase I S broadcasts signal

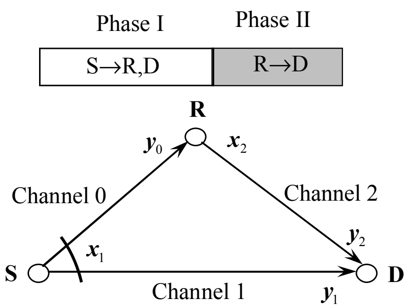

Figure 1 A Cooperative communication model composed of a source, destination, and single relay.

sequence $\boldsymbol{x}_1 = \left(x_{1,1},\ldots,x_{1,N_1}\right)$, and in the phase II R transmits D the signal sequence $\boldsymbol{x}_2 = \left(x_{2,1},\ldots,x_{2,N_2}\right)$. Frequency-flat fading channels are assumed between any pair of the transmitting-receiving nodes. S performs, FEC encoding, bit interleaving, and modulation to generate signal sequence $\boldsymbol{x}_1$, whose components belong to finite signal alphabet $\mathcal{X}_1 \subset \mathbb{C}$ ($\mathbb{C}$ represents the complex plane). For DF scheme components of signal sequence $\boldsymbol{x}_2$, also belongs to a finite signal alphabet $\mathcal{X}_2 \subset \mathbb{C}$ that is not necessarily identical to $\mathcal{X}_1$. Signal alphabets $\mathcal{X}_j$ j=1,2 have associated one-to-one binary labeling maps $\mu_j:\{0,1\}^{m_j} \to \mathcal{X}_j$, where $m_j = \log_2\left|\mathcal{X}_j\right|$. For AF and SDF schemes $\boldsymbol{x}_2$ components could be any complex variable. $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ are subject to power constraints related to S and R. Both receivers at R and D are assumed to have perfect channel knowledge on their corresponding connected channels. No channel knowledge is assumed to be available at the corresponding transmitters.

Upon reception of the source signal, R will use one of the AF, DF, and SDF schemes for processing of the received signal and forwarding it to D. In DF and SDF schemes R may uses a different FEC code for re-encoding of the decoded data. D after signal reception in both phases needs to properly combine and decode the received signals $\boldsymbol{y}_1$, and $\boldsymbol{y}_2$. When S and R uses identical FECs, the calculated bit reliabilities obtained from de-modulation of $\boldsymbol{y}_1$, and $\boldsymbol{y}_2$. will be combined and fed to a soft-input decoder. A common measure for bit reliability is log-likelihood ratio (LLR). Using this measure bit reliability combining will be realized through the addition of bit LLRs. In the general case when FECs in S and R are not identical an iterative decoding based on exchange of soft information between their corresponding soft-input soft-output decoders should be exercised [10].

III. Soft Decode and Forward

In the SDF scheme as described in [8] and [9], R performs soft processing of the signal received from S. This is done through soft-input soft-output (SISO) decoding algorithms developed for most of the powerful and commonly used FEC codes such as convolutional codes, turbo codes (parallel or serial concatenation), low density parity check codes (LDPC), and product codes. As elaborated in [8] and [11] extension of soft processing capability to FEC encoders' counterparts is straight forward and in fact with a minor modification a SISO decoding algorithm can be used to also perform SISO encoding. In order to use SDF scheme in conjunction with a higher order modulation, a soft mapping function will be required to map m_2 bits to a point in complex plane $\mathbb{C}$. The original hard mapping $\mu_2:\{0,1\}^{m_2} \to \mathcal{X}_2$ will map the hard value bits to a point in the set $\mathcal{X}_2$. While the functionality and objective of the hard mapping is quite clear, the soft mapping requires a certain criterion and a clear relation with its hard version. To get more insight on this we first review the soft de-map function and define soft map as its pseudo inverse.

A. Soft Bit De-mapping

Here for the sake of notational simplicity we drop the used subscripts. Let's assume that a signal x belonging to constellation $\mathcal{X} \subset \mathbb{C}$, with size $|\mathcal{X}| = 2^m$ has been transmitted over a frequency flat fading channel with average SNR γ, and complex channel gain h. The received signal y will be:

$$y = h\sqrt{\gamma}x + n, \tag{1}$$

where n is additive white Gaussian noise, circularly symmetric, zero-mean, and with unit power. Let's denote $\boldsymbol{c} = (c_1, c_2 \ldots, c_m)$ as the m bits input to the modulator, i.e. $x=\mu(\boldsymbol{c})$. Upon the observation of $\boldsymbol{y}$ and also ideal knowledge on h, soft de-map function needs to calculate a posteriori probabilities $p\left(c_i \middle| y,h\right)$ for i=1,…,m. Assuming uniform a priori probabilities for the bits we can calculate bit likelihoods instead. Extension to nonuniform a priori probability is straight forward [12]. For high SNR regime the bit LLRs defined as the logarithm of likelihoods' ratio are accurately approximated as [12]:

$$\begin{aligned}\lambda_i(\bar{y}) &\overset{\Delta}{=} \log\left(\frac{p\left(y \middle| c_i = 1, h\right)}{p\left(y \middle| c_i = 0, h\right)}\right), \\ &\approx \tilde{\gamma}\left(\max_{x\in\mathcal{X}_1^i}\left(-\left|\bar{y}-x\right|^2\right) - \max_{x\in\mathcal{X}_0^i}\left(-\left|\bar{y}-x\right|^2\right)\right)\end{aligned} \tag{2}$$

In above equation $\mathcal{X}_b^i$ denotes a subset of the constellation $\mathcal{X}$ formed by all points with their ith label bit equal to $b\in\{0,1\}$. $\bar{y} = ye^{-j\angle h}/\sqrt{\tilde{\gamma}}$ is equalized and normalized received signal with $\angle h$ denoting the angle of the complex value h, and $\tilde{\gamma} = |h|^2\gamma$ is instantaneous SNR.

Obviously $\lambda_i(\bar{y})$ is a function of $\bar{y}$, bit position i, SNR $\tilde{\gamma}$, and also constellation $\mathcal{X}$ and its corresponding labelling map μ. As it is observed the approximated bit LLRs are linearly proportional to SNR $\tilde{\gamma}$. Figure 2 illustrates functionality of normalized bit LLR $\bar{\lambda}_i(\bar{y}) = \lambda_i(\bar{y})/\tilde{\gamma}$ versus complex variable $\bar{y}$, for 16QAM constellation with Gray and set partitioning based labellings. As it is observed it demonstrates piece-wise linearity with respect to $\bar{y}$. In the next section we explain how soft mapping can be defined as a pseudo inverse of soft bit de-map function $\bar{\boldsymbol{\lambda}}(\bar{y}) = \left(\bar{\lambda}_1(\bar{y}), \ldots, \bar{\lambda}_m(\bar{y})\right)$, and how the observed piece-wise linear property of $\bar{\boldsymbol{\lambda}}(\bar{y})$ could be properly exploited to propose a low complexity soft mapping function.

B. *Soft Mapping*

Let $p(c_i)$ and l_i for i=1,…,m denote bit probabilities and bit LLRs to be used to do a soft mapping and generate a complex value to be transmitted over R-D link. Let's also denote soft-map function with $x = \tilde{\mu}(\boldsymbol{l})$, where $\boldsymbol{l}=(l_1,\ldots, l_m)$. Two simple kinds of soft mapping for BPSK modulation have been used for SDF scheme. Reference [8] uses the LLR value itself as the soft mapped point. This can also be extended to QPSK with Gray labelling where the first and second LLR values construct the real and imaginary components of the output point. Reference [11] takes another approach and uses the expectation of BPSK points as the output, i.e. $x=-p(c=0)+p(c=1)$. Obviously extension of the first approach for m greater than 2 is not possible. The second approach is possible to be extended to higher order modulations and in fact it has already been successfully exploited in low complexity minimum mean square error (MMSE) version of turbo multi user detection [13]. There the output of soft mapper is used to partially cancel interference at each iteration stage. Even though their soft map function is quite efficient for their applied problem, this function turns out to be deficient as the resulted point could be close to a constellation point that its label bits are considerably different from hard values of the input bits. Here we deduce the soft map function as a mapping $\tilde{\mu}: \mathbb{R}^{m_2} \rightarrow \mathbb{C}$ that if its resulted output point is used to recalculate the bit LLRs it introduces the least distortion:

$$\tilde{\mu}(\boldsymbol{l}) = \arg\min_{\bar{y}} D\left(\alpha \boldsymbol{l}, \bar{\boldsymbol{\lambda}}(\bar{y})\right), \tag{3}$$

This approach will try to protect the soft information contents of the bits as much as possible. α is a factor to scale LLRs $\boldsymbol{l}$ such that they can be corresponded to SNR-normalized quantities $\bar{\boldsymbol{\lambda}}(\bar{y})$. D is a distortion measure between two LLR vectors. As a typical example the mean squared error could be used as a distortion measure. The brute force approach for calculation of (3) requires full search of the complex plane $\mathbb{C}$ which is a formidable task. The piece wise linear structure of $\bar{\boldsymbol{\lambda}}(\bar{y})$ can be exploited to obtain a feasible and simple method to calculate (3).

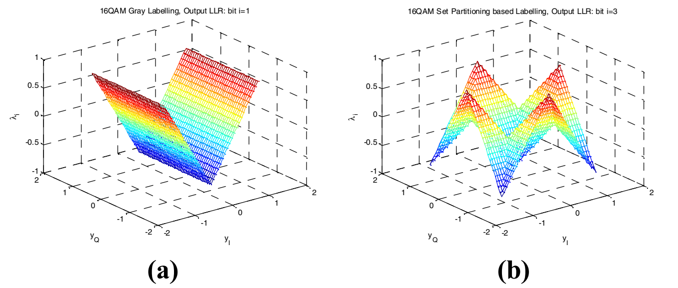

Figure 2 bit LLR $\lambda_i(\bar{y})$ plotted for different points $\bar{y}$: (a) i=1, 16QAM with Gray labelling, and (b) i=3, 16QAM with set partitioning based labelling.

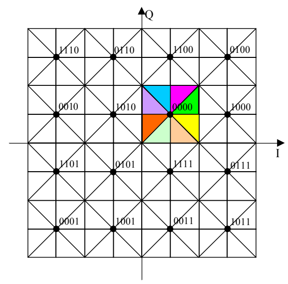

Figure 3 triangular piecewise linear regions for soft bit de-map function for 16QAM modulation

$\bar{\boldsymbol{\lambda}}(\bar{y})$ can be expressed through a linear relation for different regions of the complex plane. Examining different QAM constellations with different labellings it revealed that the boundaries of the piecewise linear regions coincides with all the possible pair-wise decision boundaries. This as depicted in Figure 3 leads to triangular regions where in each region the normalized soft value vector $\bar{\boldsymbol{\lambda}}(\bar{y})$ can be linearly expressed in terms of $\bar{y}$:

$$\bar{\boldsymbol{\lambda}}(\bar{y}) = \mathbf{A}_r \cdot \begin{bmatrix} \bar{y}_I \\ \bar{y}_Q \end{bmatrix} + \bar{\boldsymbol{\lambda}}_{r,0}, \tag{4}$$

where subscript r denotes the considered triangular region, $\mathbf{A}_r$ is a m×2 real matrix and $\bar{\boldsymbol{\lambda}}_{r,0}$ is a m×1 real vector. The subscripts I and Q are used to represent the real and imaginary parts of $\bar{y}$. It should be noted that $\mathbf{A}_r$ and $\bar{\boldsymbol{\lambda}}_{r,0}$ are fixed for a given region and do not depend on channel condition and SNR.

1) *The Least Squared Error Soft Map*

Using the least squared error criterion and the linear relation (4) for each triangular region the soft map will be expressed as follows:

$$\tilde{\mu}_{r,LS}(\boldsymbol{l}) = \mathbf{B}_{r,LS}\left(\alpha \boldsymbol{l} - \bar{\boldsymbol{\lambda}}_{r,0}\right), \tag{5}$$

where $\mathbf{B}_{r,LS}$, a 2×m real matrix, is pseudo inverse of $\mathbf{A}_r$:

$$\mathbf{B}_{r,LS} = \left(\mathbf{A}_r^t \mathbf{A}_r\right)^{-1} \mathbf{A}_r^t, \tag{6}$$

where superscripts t and -1 denote matrix transposition, and inversion, respectively. The resulted point from (5) might not necessarily belong to region r, and therefore an orthogonal projection will be required to bring the resulted point back to the region. $\mathbf{B}_{r,LS}$ can be pre-calculated for each region as it only depends on $\mathbf{A}_r$ who is fixed and is not depending on channel condition and input LLR values $\boldsymbol{l}$. To be able to find the global point we need to check all the regions and choose the point that has the least distortion. However we can restrict this to only regions around the hard map point. Adjustment of scaling parameter α requires associating an SNR value to input LLR bits. This associated SNR value should be signaled to destination in order to properly calculate bit LLRs at destination receiver. In this regard due to limitation on signaling overhead only one SNR value should be associated to the whole block of the forwarded signal sequence. One possible approach is to adjust α such that the variance of the scaled input bit LLRs becomes equal to the variance of the normalized $\bar{\lambda}(\bar{y})$ over the whole of the covered triangular regions:

$$\alpha = \sqrt{\sigma_{ref}^2 / \sigma_l^2}\ ,\ \sigma_l^2 = \frac{1}{mN}\sum_{k=1}^{mN} l_k^2\ ,\ \gamma_{\tilde{\mu}} = 1/\alpha^2 \tag{7}$$

where it is assumed that there are N m-tuples of input bit LLRs, and input LLRs are zero mean, which is a valid assumption for most of the practical conditions. σ_{ref}^2 is the variance of $\bar{\lambda}_i(\bar{y})$ calculated over all values of i=1,…,m, and all values of $\bar{y}$ on the whole complex plane area covered by triangular regions. It should be noted that σ_{ref}^2 only needs to be calculated once. $\gamma_{\tilde{\mu}}$ is SNR associated to soft mapping function and should be signaled to destination.

The overall soft mapping procedure is summarized as follows: *i*) scale input LLR values with α given in (7); *ii*) compute the hard map point; iii) for each triangular region around the hard map point perform soft mapping using (5) and (6), and calculate its corresponding distortion; *iv*) choose the region with least distortion, and use its soft map point as the output. Similar to AF scheme the block of soft mapped complex values should be further scaled to obtain desired transmission power level for relay.

The complexity of the proposed soft-mapping approach is proportional to the number of surrounding linear regions around each constellation point which is at most 8. For commonly used Gray labeling the number of linear regions are much less and the procedure could be further simplified.

C. Soft Bit De-Mapping at Destination

Received bit LLRs calculation in the second phase at destination node needs to properly take into account the associated SNR $\gamma_{\tilde{\mu}}$ and also the R-D link SNR. An appropriate model for bit LLR calculation could be a concatenation of an AWGN channel with SNR $\gamma_{\tilde{\mu}}$ with the fading channel of R-D link:

$$y_{2,k} = h_{2,k}\beta\sqrt{\gamma_2}\left(\bar{x}_{2,k} + \eta_k\right) + n_{2,k}\,, \tag{8}$$

Here subscript 2 is used to indicate that corresponding variables are related to channel 2. $\bar{x}_{2,k}$ is the hard map point, η_k is additive zero mean white Gaussian noise with power $1/\gamma_{\tilde{\mu}}$, and β is power normalization factor. Using this model calculation of likelihood and bit LLR values will be straight forward. This model will result in following equivalent SNR:

$$\gamma_{eq} = \frac{\tilde{\gamma}_2\gamma_{\tilde{\mu}}}{\tilde{\gamma}_2 + \gamma_{\tilde{\mu}}}\,, \tag{9}$$

where $\tilde{\gamma}_2 = \beta^2|h_2|^2\gamma_2$ for static fading, and $\tilde{\gamma}_2 = \beta^2\gamma_2$ for fast fading condition of R-D channel.

IV. Simulation Results

Here we provide some simulation results to demonstrate the efficiency of the proposed SDF scheme. As explained before, the main pitfall of the original DF scheme is related to conditions when relay forwards an erroneously decoded packet. This condition is more frequent in static fading conditions when S-D link is in outage. In this regard this section only presents results for static fading channel. Similar trend is observed for fast fading channel but with different performance gains. Three schemes of AF, DF, and SDF are considered with different modulation setting for the last two schemes. An identical Convolutional code with rate 1/2, and octal code generator of (7,5) is used for both S and R. Information bits block size is 598, that with two zero bits used for termination of the code results a block of 1200 coded bits. No puncturing is performed in S and R, and coded bits are bit interleaved with a pseudo random interleaving pattern prior to their mapping into modulation symbols. QPSK modulation is used for source transmission in the first phase, and relay used QPSK, 16QAM, and 64QAM with Gray labeling for its transmission in DF and SDF schemes. Full soft processing is used for SDF scheme and the least square based soft mapping introduced in previous section is used for 16QAM and 64QAM constellations. For QPSK odd and even LLR values after being scaled are transmitted over the in phase and quardature axes. The S-R and R-D links' SNRs are adjusted relative to the direct link S-D SNR: $\gamma_0=\Delta_{sr}.\gamma_1$, $\gamma_2=\Delta_{rd}.\gamma_1$, where Δ_{sr} and Δ_{rd} represent SNR offsets of these two links with respect to SNR of the direct S-D link.

Figure 4 shows the BER performance for the links SNR configuration of (Δ_{sr},Δ_{rd})=(0,5) dB. Results are presented for all the three schemes and also all possible modulation configurations. DF scheme in this configuration is inefficient as the destination receiver is mislead by high SNR of the R-D link and will give more priority to the signal received through the relay while the quality of the S-D link is much better than the overall quality of the relayed S-R-D route. As it is observed the DF scheme performs poor compared to the rest. Interestingly increasing the modulation order of the second phase improves the DF performance. This is understandable as this lessens the domination of the relayed route on the overall performance. The best performance is achieved by both AF and SDF QPSK-QPSK schemes. AF has the least complexity, however it is not spectrum efficient as system is not able to shorten the second phases' duration. In this regard SDF with 16QAM and 64QAM phase II modulations are efficient candidates as they are able to attain the same level of diversity as AF and also provide better spectrum efficiency.

Figure 5 shows BER performance results for different link SNR offset configurations: (Δ_{sr},Δ_{rd})=(0,0), (0,5), and (5,0) dB. 16QAM modulation is used for phase II. The (5,0) configuration is the best condition for DF scheme. As it is observed SDF is quite insensitive to different link conditions and exhibits satisfactory performance in all cases.

V. Conclusion

In this paper soft decode and forward (SDF) approach is extended to higher order MQAM modulations. A new soft mapping function is defined based on minimization of a distortion measure between input bit LLRs and the LLRs resulted from soft de-mapping of soft map output. A low complexity least squared based soft mapping method is proposed. The SDF scheme using this soft map function overcomes the weakness of the original DF and is able to attain same diversity level of amplify and forward (AF) scheme while achieving better spectrum efficiency through the use of higher order MQAM modulations.

Future work can include mixed strategies such as DF-DAF scheme in reference [9] to further improve system performance by exploiting soft processing capability of the proposed scheme combined with merits of selective relaying strategies. Another possible area for the future work is the application and tuning of this scheme to be used in conjunction with distributed turbo coding techniques.

VI. Acknowledgment

This work was performed in the framework of the IST FIREWORKS project, which is funded by the European Commission.

References

[1] E. C. van der Meulen, ''Transmission of information in a T-terminal discrete memoryless channel,'' Ph.D. dissertation, Univ. California, Berkeley, CA,Jun. 1968.

[2] H. Sato, ''Information transmission through a channel with relay,'' The Aloha System, University of Hawaii, Honolulu, Tech. Rep. B76-7, Mar. 1976.

[3] T. M. Cover and A. A. El Gamal, ''Capacity theorems for the relay channel,'' *IEEE Trans. Inf. Theory*, vol. IT-25, no. 5, pp. 572–584, Sep. 1979.

[4] A. Sendonaris, E. Erkip, and B. Aazhang, 'User Cooperation Diversity Part I - System Description," *IEEE Trans. Cornniun.,* Nov 2003, pp. 1927-1938.

[5] A. Sendonaris, E. Erkip, and B. Aazhang, 'User Cooperation Diversity Part II - Implementation aspects and performance analysis,"*IEEE Trans. Comun.,* Nov. 2003, pp. 1939-1948.

[6] J. N. Laneman, D. N. C. Tse, *and* G. W. Wornell, *"*Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," IEEE Trans. Inform. Theory, Vol. 50, No. 12, pp. 3062-3080, Dec. 2004.

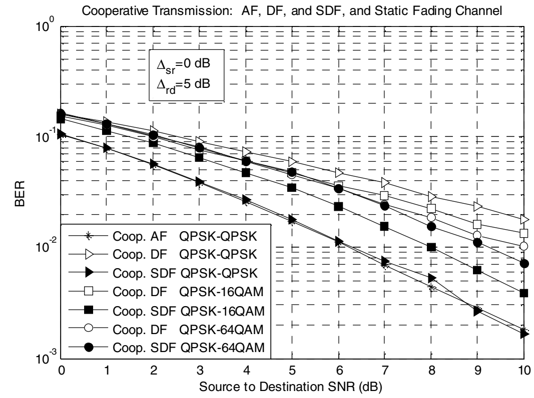

Figure 4 BER performance for cooperative AF, DF, and SDF schemes with QPSK modulation in first phase and QPSK, 16QAM, and 64 QAM modulations in the second phase.

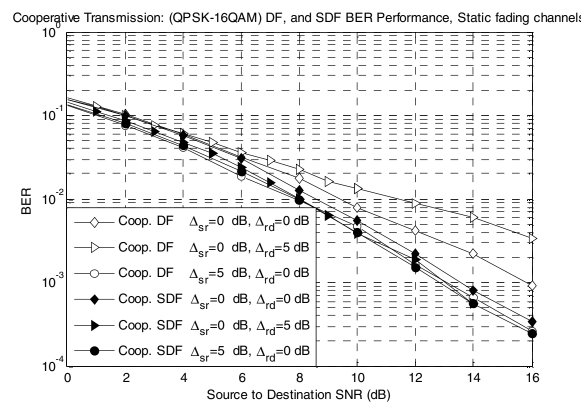

Figure 5 BER performance for cooperative DF, and SDF schemes for different link SNR offsets with QPSK and 16QAM modulations in the first and second phases, respectively.

[7] M. Janani, A, Heday& T. Hunter, A. Nosratinia, 'Coded cooperation in wireless communications: space-time transmission and iterative decoding," *IEEE* Trans. *Signal Processing,* pp. 362-371, Feb 2004.

[8] H. H. Sneesens, and L. Vandendorpe, "Soft decode and forward improves cooperative communications", 1st IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing, pp. 157 – 160, Dec. 2005.

[9] X. Bao, and J. Li, "Decode-amplify-forward (DAF): a new class of forwarding strategy for wireless relay channels" IEEE 6th Workshop on Signal Processing Advances in Wireless Communications, pp. 816 – 820, June 2005.

[10] **.** B. Zhao and M. C. Valenti, "Distributed turbo coded diversity for relay channel," *Electron. Lett.*, vol. 39, no. 10, pp. 786–787, May 2003.

[11] Y. Li, B. Vucetic, T. F. Wong, M. Dohler, "Distributed Turbo Coding With Soft Information Relaying in Multihop Relay Networks," *IEEE* Journal on Select. Areas in Commun. (JSAC) Vol. 24, No. 11, pp. 2040-2050, Nov 2006.

[12] L. Xiaodong, and J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding**,"** *IEEE Commun. Lett.,* Vol. 1, No. 6, pp. 169-171, Nov. 1997.

[13] Xiaodong Wang, and H.V. Poor, "Iterative (turbo) soft interference cancellation and decoding for coded CDMA," *IEEE Trans. Commun.,*Vol. 47, No. 7, pp. 1046-1061, July 1999.