QoS Guaranteed Joint Precoder Design For MIMO Relay Network

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***Abstract*—Precoding designs are used for transmitting the in relay networks where multiple antennas are used at the transmitter and receiver. Applying a minimum-mean-square-error (MMSE) strategy, the objective is to design quality-of-service (QoS) aware joint precoder at source and relay to fulfill minimum signal-to-noise ratio (SNR) requirement at users in amplify-and-forward MIMO relay network. In this approach non-convex optimization problem is solved by dividing into two problems: primary and secondary using primal decomposition which are convex in nature and solvable. Numerical result shows that joint source/relay precoding scheme has better bit error rate (BER) performance as compared with relay precoding scheme while considering minimum SNR constraint and BER performance of both scheme improves with increase in signal-to-noise ratio (SNR).**

I. Introduction

Relay based technology has attention due to its significant benefits to enhance throughput, increase network coverage and reduce transmission power in cellular network [1]. Moreover, use of multiple antennas in wireless communication has significant advantages to increase the system throughput. Implementation of multiple-input multiple-output (MIMO) technique in recent wireless communication standard such as long-term evolution (LTE) and IEEE 802.16m improves spectral efficiency and transmission reliability [2]. To increase the overall performance single antenna in wireless communication system has been replaced by multiple antennas.

Furthermore, authors in [3] compared amplify-and-forward (AF) relaying technique with decode-and-forward (DF). Amplify-and-forward (AF) relays are more practical compared to decode-and-forward (DF) since they are low complex and transparent to source and destination [3], [4]. Precoding is mainly used to mitigate the effect of multiuser interference in MIMO system. Extensive work on AF MIMO precoding mainly pays attention on maximizing capacity [5],[6]. However, these papers considered precoding at relay nodes only. Recently, authors have made efforts to propose joint source and relay precoding. Work in [7], proposed joint relay precoder and decoder for cooperative network where single antenna is used at source, relay and destination while [8] employed multiple antennas at both source and relay. Moreover, authors in this work used dirty paper coding to achieve sum rate capacity within transmit power constraints at source and relay and capacity is maximized without any provision of QoS. In [9], authors satisfied minimum signal-to-interference-noise ratio (SINR) at users but did not consider any power budget constraints at source and relay. Later, in [10], idea was proposed to design joint precoder at relay and destination to minimize MSE in MIMO relay system having source, relay and destination. In addition to more, Joint relay and destination optimization is done assuming perfect CSI and used Weiner filter in the destination and relay precoder is designed with in transmission power constraints . However, author did not consider any constraint to fulfil minimum SNR.

Authors in [8]-[10] proposed precoding techniques which mainly focused to minimize MSE within minimum transmission power constraints but did not guarantee any QoS in term of predefind SNR. In the proposed work, however, joint precoder design at source and relay is adopted to minimize MSE while satisfying the minimum predefined SNR requirement at users. MMSE is non-convex and complicated function of precoding matrices used at source and relay. Under perfect channel state information (CSI) the problem of a non-convex optimization is solved by deviding into two problems: primary and secondary which are convex and can be solved using standard convex optimization technique.

Remaining paper is organized as follows: System model and problem formulation is presented in Section II. Section III introduces Proposed joint precoder design. Section IV describes the simulation results of proposed scheme under the SNR constraints. Finally conclusion of paper is given in section V.

II. System Model and Problem Formulation

A. System Model

This section describes the downlink AF MIMO model consisting of the source S, relay R, and destination D having number of antennas M_s, M_r, ans M_d, respectively. Let $\mathbf{W}_s$ be the precoding matrix at source S of dimension $M_s \times M_s$. Transmitted signal vector at source S is given by $\mathbf{x} = \mathbf{W}_s\mathbf{s}$ where $\mathbf{s}$ is a $M_s \times 1$ vector where each entry represent the modulated symbol with unit power, e.g., $|s_k|^2 = 1$. Transmitted power at source is given as $p_t = E[||\mathbf{x}||^2] = tr(\mathbf{W}_s{\mathbf{W}_s}^H)$.

The signal received at relay R is given as

$$\mathbf{y}_r = \mathbf{H}_1\mathbf{x} + \mathbf{n}_r \quad (1)$$

where $\mathbf{H}_1$ is $M_s \times M_r$ MIMO Rayleigh channel between source S and relay R and $\mathbf{n}_r$ is the AWGN vector of dimension

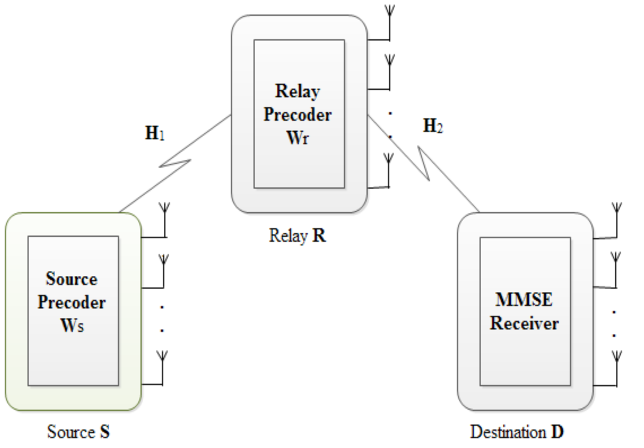

Fig. 1. System model for MIMO network consisting of Source, Relay and Destination.

$M_s \times 1$ with variance $E[\mathbf{n}_r \mathbf{n}_r{}^H] = \sigma_n{}^2 \mathbf{I}$.

After AF operation the signal transmitted from relay is given by

$$\mathbf{x}_0 = \mathbf{W}_r \mathbf{y}_r = \mathbf{W}_r \mathbf{H}_1 \mathbf{x} + \mathbf{W}_r \mathbf{n}_r \qquad (2)$$

where $\mathbf{W}_r$ is the precoding matrix at relay R of dimension $M_r \times M_r$. The transmitted power at relay R is given as $p_r = E[||\mathbf{x}_0||^2] = tr((\mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s)^H \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s + \sigma_n{}^2 \mathbf{W}_r{}^H \mathbf{W}_r)$. Therefore, the received signal at destination D is given by

$$\mathbf{y}_d = \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s \mathbf{s} + \mathbf{H}_2 \mathbf{W}_r \mathbf{n}_r + \mathbf{n}_d \qquad (3)$$

where $\mathbf{H}_2$ is $M_d \times M_r$ MIMO Rayleigh channel between relay R and destination D and $\mathbf{n}_d$ is the AWGN vector of dimension $M_d \times 1$ with variance $E[\mathbf{n}_d \mathbf{n}_d{}^H] = \sigma_n{}^2 \mathbf{I}$. Let $\mathbf{W}$ be the decoding matrix at destination D to recover transmitted signal :

$$\hat{\mathbf{s}} = \mathbf{W}^H \mathbf{y}_d \qquad (4)$$

At destination apply minimum mean square error (MMSE) criterion for precoding, expression of MSE is given as $\mathbf{M} = \mathbf{E}[(\mathbf{s} - \hat{\mathbf{s}})(\mathbf{s} - \hat{\mathbf{s}})^{\mathbf{H}}]$. Substituting (3) and (4), MSE expression can be further written as

$$\mathbf{M} = \mathbf{W}^H \mathbf{C}_{nn} \mathbf{W} + [\mathbf{W}^H \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s - \mathbf{I}] \\ [\mathbf{W}^H \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s - \mathbf{I}]^H \qquad (5)$$

where

$$\mathbf{C}_{nn} = \sigma_n^2 [\mathbf{H}_2 \mathbf{W}_r (\mathbf{H}_2 \mathbf{W}_r)^H + \mathbf{I}] \qquad (6)$$

MSE of k^{th} user is given by

$$\mathbf{M}_k = \mathbf{w}_k^H \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s (\mathbf{H}_2 \mathbf{W}_r H_1 \mathbf{W}_s)^H \mathbf{w}_k + \mathbf{w}_k^H \mathbf{C}_{nn} \mathbf{w}_k \\ + 1 - 2\Re\{\sigma_n^2 \mathbf{w}_k^H \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{w}_{k,s}\} \qquad (7)$$

where $\mathbf{w}_k$ and $\mathbf{w}_{k,s}$ are the k^{th} column of decoding matrix $\mathbf{W}$ and precoding matrix $\mathbf{W}_s$ respectively and $\Re\{.\}$ is real part of variable inside the bracket. From (3) and (4), SNR at k^{th} user is defined as

$$\gamma_k = \frac{|\mathbf{w}_k^H \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{w}_{k,s}|^2}{\mathbf{w}_k^H \mathbf{C}_k \mathbf{w}_k}, \qquad \forall k = 1, \ldots, M_s \quad (8)$$

where $\mathbf{C}_k$ is interference noise covariance matrix can be written as

$$\mathbf{C}_k = \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s \mathbf{W}_s^H (\mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1)^H + \mathbf{C}_{nn} \\ - \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{w}_{k,s} \mathbf{w}_{k,s}^H (\mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1)^H \qquad (9)$$

B. *Problem Formulation*

Let $\mathbf{\Gamma}$ be the SNR matrix. The objective is to minimize MSE while guaranteeing minimum SNR for users at destination within average transmission power budget, therefore, problem can be formulated as

$$\min_{\{\mathbf{W}_s, \mathbf{W}_r\}} tr\{\mathbf{M}\} \qquad (10)$$

$$\mathbf{\Gamma} \geq \Gamma_{min} \qquad (11)$$

$$tr\{\mathbf{W}_s \mathbf{W}_s^H\} \leq p_t \qquad (12)$$

$$tr\{\mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s (\mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s)^H + \sigma_n{}^2 \mathbf{W}_r \mathbf{W}_r{}^H\} \leq p_r \qquad (13)$$

where Γ_{min} is predefined diagonal SNR matrix to guarantee QoS for users at destination.

III. Proposed Joint Precoding Design

Lets knowledge of channel matrices $\mathbf{H}_1$ and $\mathbf{H}_2$ is available at source S and relay R so precoding matrices $\mathbf{W}_s$, $\mathbf{W}_r$ and decoding matrix $\mathbf{W}$ can be designed jointly to minimize trace of MSE $\mathbf{M}$. To find the optimal decoding matrix $\mathbf{W}$ which minimize the MSE expression in (5) apply $\frac{\partial}{\partial W} tr\{M(W, F, G)\} = 0$ and is written as

$$\mathbf{W}_{opt} = [\mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s (\mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s)^H + \mathbf{C}_{nn}]^{-1} \\ \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s \qquad (14)$$

Equation (14) is the equation of Wiener Filter , substitute (14) into (5), and apply matrix inversion lemma, the MSE expression can be written as

$$\mathbf{M}_{\mathbf{W}=\mathbf{W}_{opt}} = [\mathbf{I} - (\mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s)^H \mathbf{C}_{nn}^{-1} \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{W}_s]^{-1} \qquad (15)$$

From (7) and (15), the MSE expression of k^{th} user at destination is given by

$$\mathbf{M}_k = [\mathbf{w}_{k,s}^H (\mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1)^H \mathbf{C}_k^{-1} \mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1 \mathbf{w}_{k,s} + 1]^{-1} \qquad (16)$$

Upper bound of SNR of k^{th} user in (8) can be given by applying Cauchy Schwarz inequality

$$\gamma_k \leq \mathbf{w}_{k,s}^H (\mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1)^H \mathbf{C}_k^{-1} (\mathbf{H}_2 \mathbf{W}_r \mathbf{H}_1) \mathbf{w}_{k,s} \qquad (17)$$

from (16) and (17) now SNR of k^{th} user at destination is written as

$$\gamma_k = 1/\mathbf{M}_k - 1 \qquad (18)$$

It can be seen from (15) MSE is a complicated function of precoding matrices $\mathbf{W}_s$ and $\mathbf{W}_r$ at source S and relay R and trace of MSE expression is non-convex in $\mathbf{W}_s$ and $\mathbf{W}_r$. To find optimal precoder $\mathbf{W}_s$ and $\mathbf{W}_r$ which diagonalize the MSE expression in (15), apply singular value decomposition for channel matrices at source S and relay R such that $\mathbf{H_1} = \mathbf{U_1 \Sigma_1 V_1}$ and $\mathbf{H_2} = \mathbf{U_2 \Sigma_2 V_2}$ where $\mathbf{\Sigma_1}$

and $\mathbf{\Sigma_2}$ are non-diagonal matrices of dimensions $M_r \times M_s$ and $M_d \times M_r$, respectively. $\mathbf{U}_1$, $\mathbf{U}_2$, $\mathbf{V}_1$, and $\mathbf{V}_2$ are unitary matrices calculated from SVD of $\mathbf{H}_1$ and $\mathbf{H}_2$. To diagonalize the trace of MSE optimal choices for $\mathbf{W}_s$ and $\mathbf{W}_r$ is given as

$$\hat{\mathbf{W}}_s = \mathbf{W}_s\mathbf{W}_s^H = \mathbf{V}_1\mathbf{\Theta}_s\mathbf{V}_1^H \tag{19}$$

$$\mathbf{W}_r = \mathbf{V}_2\mathbf{\Theta}_r\mathbf{U}_1^H \tag{20}$$

Substituting (19) and (20) into (15), trace of MSE is given as

$$tr\{\mathbf{M}\} = tr\{[\mathbf{I} + \sigma_n^{-2}\mathbf{\Theta}_s\mathbf{\Sigma}_1^H(\mathbf{I} + \mathbf{\Lambda}_2\mathbf{\Theta}_r^2)^{-1}\mathbf{\Lambda}_2\mathbf{\Theta}_r^2\mathbf{\Sigma}_1]^{-1}\} \tag{21}$$

where $\mathbf{\Lambda}_2 = \mathbf{\Sigma}_2^H\mathbf{\Sigma}_2$. From (18) SNR can be expressed as

$$\mathbf{\Gamma} = \sigma_n^- 2\mathbf{\Theta}_s\Sigma_1^H(\mathbf{I} + \mathbf{\Lambda}_2\mathbf{\Theta}_r^2)^{-1}\mathbf{\Lambda}_2\mathbf{\Theta}_r^2\Sigma_1 \tag{22}$$

Substitute (19) and (20) into (12) and (13), power budget at source S and relay R is given by

$$tr\{\mathbf{\Theta}_s\} \le p_t \tag{23}$$

$$tr\{\mathbf{\Theta}_r^2(\sigma_n^{-2}\mathbf{I} + \mathbf{\Sigma}_1\mathbf{\Theta}_s\mathbf{\Sigma}_1^H)\} \le p_r \tag{24}$$

From (22) Problem can be formulated as

$$\min_{\{\mathbf{\Theta}_s,\mathbf{\Gamma}\}} tr\{(\mathbf{I} + \mathbf{\Gamma})^{-1}\} \tag{25}$$

$$\mathbf{\Gamma} \ge \Gamma_{min} \tag{26}$$

$$tr\{\mathbf{\Theta}_s\} \le p_t \tag{27}$$

$$tr\{\mathbf{\Lambda}_2^{-1}(\sigma_n^{-2}\mathbf{\Sigma}_1\mathbf{\Gamma}^{-1}\mathbf{\Theta}_s\mathbf{\Sigma}_1^H - \mathbf{I})^{-1}(\sigma_n^{-2}\mathbf{I} + \mathbf{\Sigma}_1\mathbf{\Theta}_s\mathbf{\Sigma}_1^H)\} \le p_r \tag{28}$$

Constraints (25), (26), and (27) can be verified to be convex in $\mathbf{\Gamma}$ and $\mathbf{\Theta}_s$, however (28) is not convex in $\mathbf{\Gamma}$ and $\mathbf{\Theta}_s$ jointly. Optimal solution of such problem can not be found directly, therefore it would be better to use decomposition methods to solve this problem.

Decomposition is an approach to solve a problem by breaking it into smaller problems and solve each problem separately [11]. When there are multiple variables and constraints in any optimization problem, it can be solved by decomposing into two smaller problems: primary and secondary. Primary problem then accords the secondary problem using joint variables.

In primal decomposition problem optimization is done over variables, e.g., $\min_{u,v} f(u, v) = \min_v \min_u f(u, v)$. This method decomposes (25) to (28) into primary problem with $\mathbf{\Gamma}$ as a design parameter and secondary problem with $\mathbf{\Theta}_s$ as a design parameter. In secondary problem solution of $\mathbf{\Theta}_s$ is found as a function of $\mathbf{\Gamma}$, e.g. $\mathbf{\Theta}_s = f_{\mathbf{\Theta}_s}(\mathbf{\Gamma})$. Now, in primary problem for a given $\mathbf{\Theta}_s$ obtained from secondary problem, optimal $\mathbf{\Gamma}_{opt}$ is calculated.

Let λ_{1i}, λ_{2i}, γ_i and θ_i are the diagonal $(i, i)^{th}$ entry of matrices $\mathbf{\Lambda}_1$, $\mathbf{\Lambda}_2$, $\mathbf{\Gamma}$ and $\mathbf{\Theta}_s$ respectively.

A. Secondary Problem

As seen in (25) to (28), design parameter $\mathbf{\Theta}_s$ appears only in (27) and (28), so secondary problem can be written as:

$$\min_{\theta_i} \sum \lambda_{2i}^{-1}[\sigma_n^{-2}\lambda_{1i}\gamma_i^{-1}\theta_i - 1]^{-1}(\sigma_n^2 + \lambda_{1i}\theta_i) \tag{29}$$

$$\sum_i \theta_i \le p_t \tag{30}$$

This is convex optimization problem and whose proof and solution are given below

Solution: Second derivative of (29) is given by

$$\frac{\delta^2}{\delta\theta_i^2} = 2(\sigma_n^2\lambda_{1i}\theta_i - \gamma_i)^{-3}\sigma_n^{-2}\lambda_{1i}^2\lambda_{2i}^{-1}\gamma_i(1 + \gamma_i) \tag{31}$$

(29) would be convex in θ_i only when (31) is positive and (31) would be positive only when $\sigma_n^{-2}\lambda_{1i}\theta_i > \gamma_i$. Therefore, Another constraint for secondary problem can be defined as

$$\theta_i > \sigma_n^2\lambda_{1i}^{-1}\gamma_i \tag{32}$$

The Lagrangian of secondary problem is written as

$$L(\theta_i) = \sum_i \lambda_{2i}^{-1}[\sigma_n^{-2}\lambda_{1i}\theta_i - 1]^{-1}\gamma_i(\sigma_n^2 + \lambda_{1i}\theta_i)$$
$$+\mu[\sum_i \theta_i - p_t] - \sum_i \beta_i(\theta_i - \sigma_n^2\lambda_{1i}^{-1}\gamma_i) \tag{33}$$

After applying KKT condition, solution of problem is given by

$$\theta_i = \sigma_n^2\lambda_{1i}^{-1}[\gamma_i + \sqrt{\lambda_{1i}\lambda_{2i}^{-1}\gamma_i(1 + \gamma_i)\mu^{-1}}] \tag{34}$$

where

$$\mu_i = [\sum_i \sigma_n^2\sqrt{\lambda_{1i}^{-1}\lambda_{2i}^{-1}\gamma_i(1 + \gamma_i)}]^2[p_t - \sum_i \sigma_n^2\lambda_{1i}^{-1}\gamma_i]^{-2}.$$

B. Primary Problem

Optimal solution of θ_i obtained in secondary problem is substituted in constraints (28) and optimization problem then is given as:

$$\min_{\gamma_i} \sum_i (1 + \gamma_i)^{-1} \tag{35}$$

$$\gamma_i \ge \gamma_{i,min} \tag{36}$$

$$[\sum_i \sigma_n^2\sqrt{\lambda_{1i}^{-1}\lambda_{2i}^{-1}\gamma_i(1 + \gamma_i)}]^2[p_t - \sum_i \sigma_n^2\lambda_{1i}^{-1}\gamma_i]^{-1}$$
$$+\sum_i \sigma_n^2\lambda_{2i}^{-1}\gamma_i \le p_r \tag{37}$$

similar to secondary problem, it can be easily varied that (35) is also convex in nature [12] and can be solved efficiently using available software packages [13].

IV. Result and Discussion

The performance of joint precoding scheme is analyzed in this section with the help of simulation results.To solve the primary problem which is convex in nature, interior point method is used. Relay and Destination can estimate the channel using pilot signals transmitted by Source and relay and fed it to Source by using feedback channel directly or through relay node.

A. Simulation Setup

The channel matrices $\mathbf{H}_1$ and $\mathbf{H}_2$ are considered as Rayleigh fading channels, i.e., elements of each channel matrix is independent identically distributed and having zero mean. Transmission power at source and relay is given by $p_t = M_s \times (SNR)s$ and $p_r = M_r \times (SNR)r$. Noise power at source and relay is taken 1, i.e., unit variance. Average SNR at source and relay are same, i.e., $(SNR)_s = (SNR)_r$ and $M_s = M_r = M_d = M$. Minimum SNR requirement of 0 dB is assumed at destination for QoS aware transmission.

B. Simulation Result

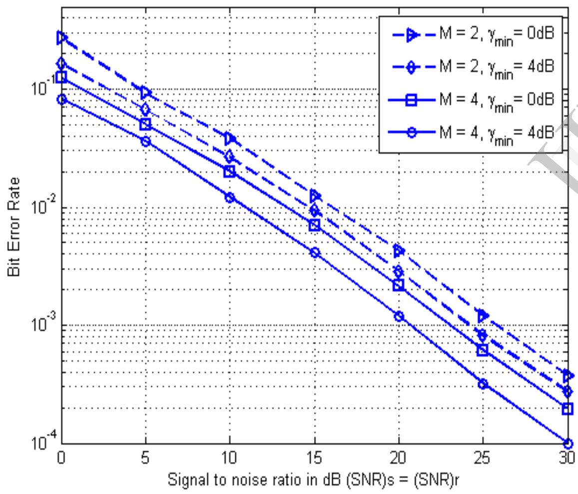

Fig. 2. BER performance of joint precoding scheme.

Fig. 2 shows the BER performance of proposed joint precoding design. Here results of BER versus average $(SNR)_s$ have been plotted for $M = 2$ and $M = 3$ with various SNR requirement (in dB) $\gamma_{min} = 0$ and $\gamma_{min} = 4$. Results show that in both case $M = 2$ and $M = 3$ for a given γ_{min}, BER decrease with increase in $(SNR)_s$. Furthermore, for a given $(SNR)_s$, if γ_{min} increases BER performance also improves but upper bound for $\gamma_{min}$is given by (17). Reason for this is explained as if optimal value of γ calculated from proposed scheme does not satisfy the minimum SNR requirement γ_{min}, transmission will be seized and outage may occur. Therefore, higher γ_{min} means higher γ or higher SNR is given to user, therefore, BER performance is also improved.

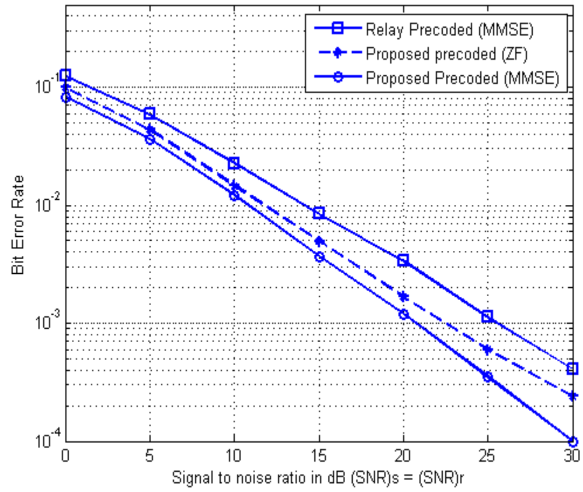

Fig. 3. BER Comparison of proposed precoding scheme with relay precoding scheme.

Fig. 3 compares the proposed joint precoding design with relay only precoding in which source precoder given in (19) is fixed by $\mathbf{\Theta}_s = \frac{p_t}{M}\mathbf{I}$. Moreover, to understand the behavior of proposed design, it has been simulated for both ZF (Zero Forcing) and MMSE receiver. It is clear from figure proposed precoded design outperforms the relay only precoding design because the proposed design finds the optimal precoders at both source and relay. However, in relay only precoding scheme, optimal value of precoder is calculated at relay node only and source node precoding is dene by assuming that all antennas are having equal power. It can be seen in Fig. 3, for $BER = 10^{-3}$, performance of proposed precoding (MMSE) scheme has SNR gain of 5 dB from relay only precoding scheme.

V. Conclusion

This paper presents a QoS guaranteed joint precoding design scheme for MIMO relay network. Proposed precoding method has been designed to minimize the MSE while satisfying the minimum SNR constraint for users at destination. Since MSE is a complicated function of precoding matrices, and non-convex in nature. To solve this non-convex problem, it is divided into primary and secondary problem which are now convex optimization problem and can be solved easily. Comparison is also done for proposed joint precoding method with relay precoding method where all antennas are having equal power at source and it can be concluded that proposed scheme has better BER performance than relay only precoded scheme. In the proposed work optimal precoders are obtained with in transmission power budget while satisfying QoS for each user.

REFERENCES

[1] J. Park, H. Son, and S. Lee, "Throughput and qos improvement via fixed relay station cooperated beam-forming," *Wireless Communications, IEEE Transactions on*, vol. 8, no. 5, pp. 2400–2409, 2009.

[2] Q. Li, G. Li, W. Lee, M.-i. Lee, D. Mazzarese, B. Clerckx, and Z. Li, "Mimo techniques in wimax and lte: a feature overview," *Communications Magazine, IEEE*, vol. 48, no. 5, pp. 86–92, 2010.

[3] Y. Fan and J. Thompson, "Mimo configurations for relay channels: Theory and practice," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 5, pp. 1774–1786, 2007.

[4] S. Berger, M. Kuhn, A. Wittneben, T. Unger, and A. Klein, "Recent advances in amplify-and-forward two-hop relaying," *Communications Magazine, IEEE*, vol. 47, no. 7, pp. 50–56, 2009.

[5] X. Tang and Y. Hua, "Optimal design of non-regenerative mimo wireless relays," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 4, pp. 1398–1407, 2007.

[6] H.-M. K. H.-K. S. I.-M. Kim, "Relay precoding for non-regenerative mimo relay systems with partial csi in the presence of interferers," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 4, pp. 1521–1531, 2012.

[7] Z. Yi and I.-M. Kim, "Joint optimization of relay-precoders and decoders with partial channel side information in cooperative networks," *Selected Areas in Communications, IEEE Journal on*, vol. 25, no. 2, pp. 447–458, 2007.

[8] C.-B. Chae, T. Tang, R. W. Heath, and S. Cho, "Mimo relaying with linear processing for multiuser transmission in fixed relay networks," *Signal Processing, IEEE Transactions on*, vol. 56, no. 2, pp. 727–738, 2008.

[9] R. Zhang, C. C. Chai, and Y.-C. Liang, "Joint beamforming and power control for multiantenna relay broadcast channel with qos constraints," *Signal Processing, IEEE Transactions on*, vol. 57, no. 2, pp. 726–737, 2009.

[10] Y. Fu, W.-P. Zhu, and C. Liu, "Joint design of linear relay and destination processing for two-hop mimo multi-relay networks," in *Vehicular Technology Conference (VTC Fall)*. IEEE, 2012, pp. 1–4.

[11] A. Tanikawa and H. Mukai, "A new technique for nonconvex primal-dual decomposition of a large-scale separable optimization problem," *Automatic Control, IEEE Transactions on*, vol. 30, no. 2, pp. 133–143, 1985.

[12] S. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge university press, 2004.

[13] M. Grant and S. Boyd, "Cvx: Matlab software for disciplined convex programming, version," 2011.