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Average Mutual Information Analysis of Multiple Input and Multiple Output System with Multihop Relaying in Wireless Communication System

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Abstract: Problem statement: Multiple Input and Multiple Output (MIMO) system with Multihop relaying techhnique is significant and active areas of wireless communication. In a rich scattering environment MIMO antenna system provides better channel capacity and data rates than single antenna systems. To provide high throughput, reliable transmission and broad coverage, wireless relaying techniques are essential in a variety of applications. In a cellular environment a relay can be used to overcome shadowing effect due to obstacles and multihop relaying can improve the throughput for mobiles suffering from poor signal to interference, noise ratio at the edge of a cell and reduce cell size to increase spectral efficiency. **Approach:** This study analyzes average mutual information of the Ricean channel for single hop Multiple Input Multiple Output (MIMO) system for different antenna configuation and dependence of capacity on the Rice factor for cellular system. The asymptotic capacity of multiuser two-hop MIMO system with Regularization Block Diagonalization (RBD) precoding techniques for Indepenent Identically Distributed (IID) channal and realistic Mobile to Mobile fading channel model was examined. In this realistic model, Non-Line-Sight (NLOS) propagation conditions are assumed from source mobile station to mobile relay and also from mobile relay to destination station. A non regenerative Amplify and Forward (AF) relay is used to optimize the capacity between the source and destination and also the evaluation was made for multiuser multi-hop relay system with correlated fading channel model using RBD precoding matrix. **Results:** The simulation results for average mutual information of single hop MIMO relay system for different antenna configuration with ricean channel model, ergodic sum mutual information for two hop relay system with RBD precoding technique and mutual information results for multiuser multihop relay system with correlated channel model was presented. **Conclusion/Recommendations:** Cellular systems generally operated at a fairly low SINR which can be increased on each hop by adding relays. Multiuser two hop relay system with RBD precoding for realistic mobile to mobile fading channel model is simulated and compared with IID channel model. Multiuser Multi-hop relay with optimal precoding and RBD precoding technique results were analyzed for correlated fading channel and found that capacity offered by RBD precoding scheme is better than other relaying systems.

Key words: Amplify-and-forward, mobile to mobile fading channel, multihop relay, correlated channel, regularization block diagonalization, MIMO system, relay network

INTRODUCTION

In MIMO system both transmitter and receiver are provided with more than one antenna. MIMO performs well in scattering rich environment. For rich scattering environment channel it is possible to increase the data rate by transmitting separate information streams on each antenna. MIMO system is a key technique in modern cellular system which provides high spectral efficiency and good coverage. Wireless system must have reasonable throughput with acceptable error rate, but due to fading, multipath propagation, high signal losses and interference, a strongly attenuated and corrupted signal appears at the receiver. In order to overcome this problem, wireless systems must use sophisticated transmission and receiver processing techniques. In Cellular systems, Signal to Interference and Noise Ratio (SINR) at the mobile user is low when the user is at cell edges. So Multihop relaying and MIMO techniques are used to improve spectral efficiency of cellular system (Jacobson and Krzymien, 2011). MIMO transmission can improve the capacity within a given bandwidth by considering advantage of rich scattering in a typical wireless channel (Foschini and Gans, 1998). MIMO system provides, higher capacity gains at high SINR, but cellular system

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operates at low SINR level leads to poor at cell edges. In multihop relaying (Schultz *et al*., 2003; Irnich *et al*., 2003; Bolukbasi *et al*., 2004) inculsion of transitional wireless relays between transmitter and receiver, to reduce the path loss. SINR can be increased by placing short hop link which reduces the path loss and also avoid the obstacles. This provieds to obtain higher link capacities and reliablity due to low random signal fluctuation and scattering. This higher SINR level increased the MIMO performance.

In both uplink and downlink transmission multiple antenna elements are used at the base station and terminals to increase the capacity and data rate. Next-generation cellular systems will have large number of users with very high data transmission rates and MIMO is the best tool for increasing spectral efficiency of wireless transmission (Sayadi *et al*., 2009). The MIMO technologies are mainly used in cellular system due to the existance of spatial diversity and beam forming.The knowledge of Channel State Information (CSI) at base station is essentialiy needed to improve the throughput of cellular system. Multi-antenna techniques involving multi user scenario delivered the spatial data to different users by utilysing all the degrees of freedom in MIMO system. In Single-User MIMO, in addition to beamforming, transmit diversity and spatial multiplexing techniques are also adopted for transmission. This will help to increase the peak user data rate in higher-order MIMO system.

MATEIALS AND METHODS

MIMO with relay system: The MIMO relay scheme is supported both in uplink and downlink of the wireless system. The channel state information is assumed to be known by the receiver.In multiuser system multiple number of users are present at the source side. In the downlink, if a User Equipment (UE) is configured in MU-MIMO transmission mode, it receives the information only about its own precoding matrix. The transmit power level for each user is configurated in long term manner to support the higher order modulation like 16QAM and 64 QAM. Zero-Forcing is the most common precoding technique in which the weight vectors are selected as the pseudo-inverse of the channel matrix of the users to avoid interference (Poongodi and Shanmugam, 2011; Caire and Shamai, 2001; Viswanathan *et al*., 2003). Dirty Paper Coding (Costa, 1993) is another multi-user precoding strategy based on interference pre-subtraction, however the high computational problem occurs when large number of users in the system at the same time. For designing the beamforming vectors, precoding by maximization of signal to leakage ratio (Tarighat *et al*., 2003; Wang *et al*., 2005) is another approach, but it does not have any limitations on the number of transmit antennas and potential for the use of Block Diagonalization (BD).

Relaying is another technique used to improve the performance of wireless system, in terms of coverage and throughput. According to 3GPP (Akyildiz *et al*., 2010), the use of relay will provide the improvements in data rate, throughput enhancement and coverage extension. The distance between the base station and the UE is separated into distance from the base station to relay and from relay to UE. For minimising the base station, relay and UE transmit power, the relay must be located in the suitable location. The reduction in power consumption is acieved through the lowering the path loss, enhanced relaying schemes and interference control. This reduction in power consumption also lowered the operational costs.

Single hop relay system: Considering single hop relay system with M transmit antennas, N receive antennas and the standard MIMO model described by M × N matrix H. Elements of matrix H is a random variable, which captures the stochastic nature of wireless channel, consists of both Line of Sight (LOS) and Non-Line of Sight (NLOS) conditions as given below:

$$H=\sqrt{\frac{K_r}{1+K_r}}H_{LOS}+\sqrt{\frac{1}{1+K_r}}H_{NLOS} \quad (1)$$

In Eq. 1, H_{NLOS} is the rayleigh distributed scattered component with unity variance. H_{LOS} is the Line of sight component and its elements are deterministic. H_{LOS} has maximum rank r_{LOS} = min (M, N) but in practical system H_{LOS} is rank deficient and has rank $r_{LOS} = 1$ (Paulraj *et al*., 2003; Salo *et al*., 2006). Kr represents rice factor, defined as the ratio of power in the specular component to the power in the scattered component. The capacity of a MIMO link is given in Eq. 2:

$$C = E\left[\log_2\left(\det\left(I_N + \rho HH^{+} / N\right)\right)\right] \quad (2)$$

where, ρ is the Signal to Interference and Noise Ratio (SINR) at the receiver determined by transmit power, path loss and antenna gain and I_N is the identity matrix. The capacity is maximum for full rank channel matrix but H_{LOS} is usually low rank in practical systems. The low rank H_{LOS} and high Rice factor, disintegrate the considerable amount of energy in fewer eigenmodes of H and hence reduced the capacity. Monte Carlo simulation with large number of samples used to find the average capacity of MIMO system. However, (Salo *et al*., 2006) provides average mutual information for Ricean MIMO channel E[IH] with rank 1 line of sight component and it is given by Eq. 3:

$$E(I_H) \le \log_2\left[1+\sum_{p=1}^{K}\sum_{j=0}^{1}\left(\frac{\rho b^2}{M}\right)^p (K_r KP)^j \times (P-p+1)_{p-j}\binom{K-j}{p-j}\right] \quad (3)$$

where, K = min(M, N), $b=\sqrt{\frac{1}{K_r+1}}$, p = max(M, N) and $(n)_p$ is the Pochhammer symbol given by $(n)_p$ = n(n+1)…..(n+p-1) and n_0 = 1 (Jacobson and Krzymien, 2011).

In Multihop system, base station transmits data to Mobile Station at the cell edge through Relay Stations. The cell radius (r) is divided into n_{hops} ie., equally spaced relays and rn_{hops}, k = r/n_{hops}, k = 1, 2, ..., n_{hops}. In a MH MIMO system, there are n_{hops} channel matrices, each k hop has M, k transmit antennas and N, k receive antennas. In Eq. 4, the channel matrix for each hop k, is given as:

$$H_k^{n_{hops}} = \gamma_k^{n_{hops}}\left[\sqrt{\frac{K_{r,k}^{n_{hops}}}{1+K_{r,k}^{n_{hops}}}}H_{LOS,k}^{n_{hops}} + \sqrt{\frac{1}{1+K_{r,k}^{n_{hops}}}}H_{NLOS,k}^{n_{hops}}\right] \quad (4)$$

Where:

$\gamma_k^{n_{hops}}$ = Averaged path gain

$K_{r,k}^{n_{hops}}$ = Rice factor for k^{th} hop. In this channel matrix, Rice factor Kr(x), is represented as:

$$K_r(x)=\begin{cases}0 & b<x<5{,}000\text{m}\\ 10^{1.3-0.003x} & 20\text{m}<x<b\end{cases} \quad (5)$$

From Eq. 5, elements of channel matrix are modeled as Rayleigh random variables when b < x <5,000 m and Ricean (with Kr >0) when 20 m < x < b.

Multiuser two hop relay MIMO system: In multiuser MIMO system, assumed that number of users (Nu) are present at the source side and i^{th} user has Mi antennas (i = 1, 2 …Nu). The total number of transmit antennas $M=\sum_{i=1}^{Nu}M_i$ and the channel of i^{th} user is denoted by $H_i \in C^{M_i\times L}$. The combined channel matrix for all users is given by Eq. 6:

$$H=\left[H_1^T \quad H_2^T \quad .... \quad H_{N_u}^T\right]^T \in C^{M\times L} \quad (6)$$

The system model for two hop wireless relay is shown in Fig. 1. The source, relay and destination nodes are equipped with M, N and L antennas respectively. By considering the system having with no line of sight between source and destination due to path loss. The modulated signal vector at the i^{th} user is linearly precoded by precoding matrix. The slot source transmits precoded signal to relay and is given by Eq. 7:

$$y = H_1Fs + n \quad (7)$$

where, y is received data and n is zero mean additive white Gaussian noise at the input of receive antennas. The joint precoding and decoding matrices are denoted by F and G respectively. This MU-MIMO system uses RBD, Regularized Successive Optimization THP (RSO-THP) precoding and Iterative Regularized BD (IRBD) precoding techniques (Young, 2009).

Here an Amplify and Forward (AF) relay is used which simply amplify and forward the received signal to designation and is given by Eq. 8:

$$Y = H_2x_2 + V_2 \quad (8)$$

where, $x_2 = F_2y$, H_2 is the L×N channel matrix between relay and destination, F_2 is relay amplifying matrix and V_2 is complex white Gaussian noise vector with zero mean (Khandaker and Rong, 2010). In this study analysis was made for ergodic capacity of two hop relay system with RBD (Tang and Hua, 2007) precoding techniques for independent identical distributed and Mobile to Mobile fading channel models (Batool and Patzold, 2011).

Multiuser multi-hop relay system: The multi-access system with Nu users simultaneously transmitting information to a common destination node through L-1 relay node is shown in Fig. 2 (Yue and Xiang, 2011). The $M_i\times 1$ modulated signal vector s_i at the i^{th} user is linearly precoded by the $M_i\times M_i$ user precoding matrix B_i and the precoded signal vector $x_i = B_is_i$ is transmitted to first relay node (Toding *et al*., 2010). The signal received at the first relay node is given in Eq. 9:

$$y_j = \sum_{i=1}^{Nu} G_ix_i + v_1 = H_1x_1 + v_1 \quad (9)$$

where, G_i is $N_1\times M_1$ MIMO channel matrix between the first relay node and the i^{th} user, v_1 is independent identically distributed additive white Gaussian noise vector at the first relay node, the equivalent first hop MIMO channel (H1) = $\lfloor G_1\ G_2 \ldots G_{Nu}\rfloor$ and $x_1 = F_1S$ where F_1 is equivalent precoding matrix = bd(B_1, B_2 … B_{Nu}).

The input output relationship at the l^{th} relay nodes is given by Eq. 10:

$$x_{j+1} = F_{j+1} y_j,\ j = 1,....L-1 \qquad (10)$$

where, F_{j+1} is the amplifying matrix at l^{th} relay node and y_j is signal received at l^{th} relay node written as Eq. 11:

$$y_j = H_j x_j + v_j,\ j = 1,2,....L-1 \qquad (11)$$

where, H_j is the MIMO channel matrix of l^{th} hop. The received signal vector at destination node is given by $y_j = As + \bar{v}$ where A is the equivalent MIMO channel matrix from all users to the destination and it is given by $A = \otimes_{i=L}^{1}(H_i F_i)$ and assumed that instantaneous Channel State Information (CSI) is available only at the destination node, but CSI is unknown at all users and all relay nodes. In realistic channel MIMO channel is correlated at both transmitter and receiver side. So the instantaneous channel matrices can be represented as Eq. 12:

$$\begin{aligned} G_i &= \phi_r^{1/2} G_i^w \phi_{t,i}^{1/2},\ i = 1,2,....N_u \\ H_i &= \phi_{r,j}^{1/2} H_i^w \theta_{t,1}^{1/2},\ j =,2,....L \end{aligned} \qquad (12)$$

Where:

G_i^w and H_j^w = Gaussian random matrices with IID zero mean and unit variance

$\theta_{t,j}$ and $\theta_{r,j}$ = Correlation matrix at the transmit and receive side of H_i respectively

$\phi_{t,i}$ and ϕ_r = Correlation matrices at the transmit and receive side of G_i

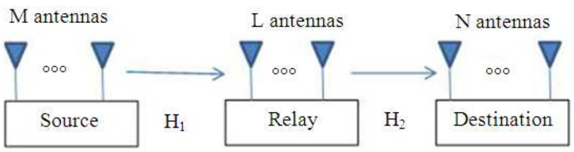

Fig. 1: MIMO AF relay networks with M source, L relay and N destination antennas

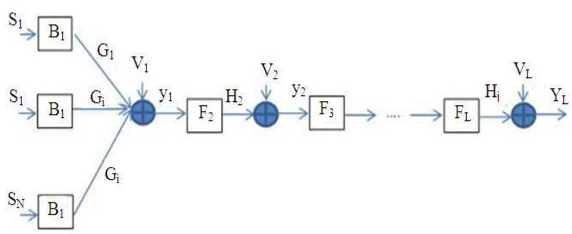

Fig. 2: Block diagram of an Nu users L-hop relay system

The sum mutual information of the users-destination channel is given in Eq. 13:

$$MI = \log \left| IN_0 + \underset{i=1}{\overset{L}{\otimes}}(F_i^H H_i^H) \left(\sum_{j=2}^{L} \left(\begin{matrix} \underset{i=L}{\overset{j}{\otimes}}(H_i F_i \underset{i=j}{\overset{L}{\otimes}}) \\ (F_i^H H_i^H) \end{matrix} \right) + I_{N_L} \right)^{-1} \underset{i=L}{\overset{1}{\otimes}}(H_i F_i) \right| \qquad (13)$$

where, $|\ |$ and $(\ )^{-1}$ denote matrix determinant and inversion respectively (Veljko and Martin, 2008). The optimal structures of user precoding matrix (B_i) and relay matrices in the form of singular value decomposition is given by $B_i = U_{\phi,i}\ \Delta_{b,i}$, $i = 1,\ldots N_u$ and $F_j = U_{\theta,j}\ \Delta_{f,j}\ V_{\theta,j-1}^H$, $j = 2,\ldots.L$. This result is more general, since it holds for multiuser scenarios by considering MIMO relays.

RESULTS

The addition of multiple relays in single hop MIMO system for Ricean channel model, shorten the hop distance, reduces path loss and scattering. This effect is very much helpful in a single hop link before analysing the entire network. The frequency of operation is 5.8 GHz. The SNR is varied from 0 to 30dB.

The average mutual information for 4×4 and 6×6 MIMO and link with full rank HNLOS and rank 1 HLOS channel is shown in Fig. 3 and 4 respectively. The capacity dependence on Rice factor and antenna configuration is shown in Fig. 5.

Rice factor in cellular systems ranged from 3-20dB, however it is in the steep reduction of capacity level. Figure 6 shows mutual information calculation for multiuser two-hop relay system with RBD precoding matrix for IID and M2M fading channel model.

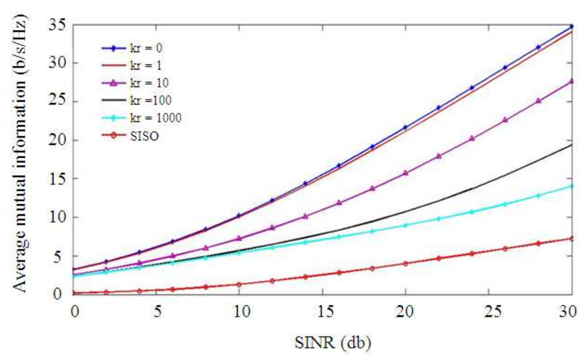

Fig. 3: Average mutual information for (4×4) Ricean MIMO hop

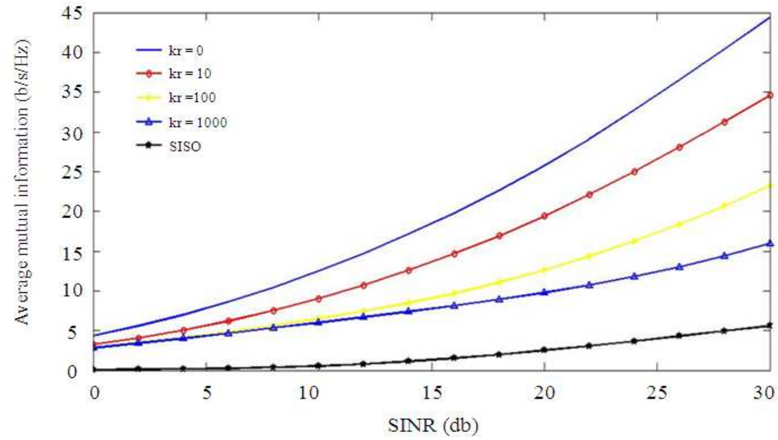

Fig. 4: Average mutual information for (6×6) Ricean MIMO hop

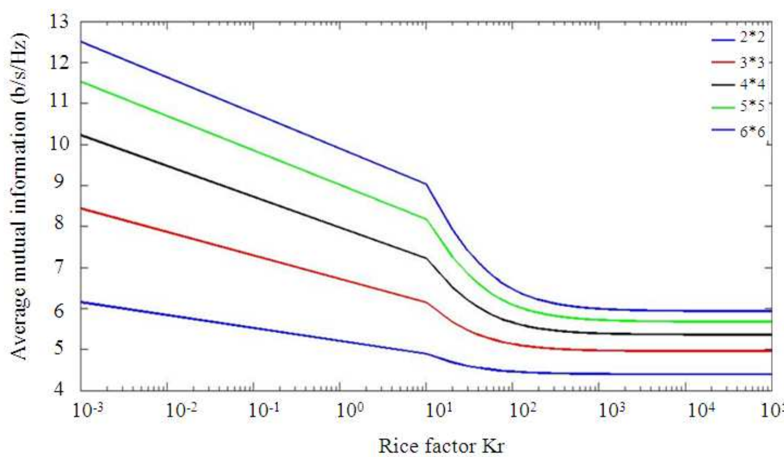

Fig. 5: Average mutual information for a Ricean MIMO hop for SINR = 10dB

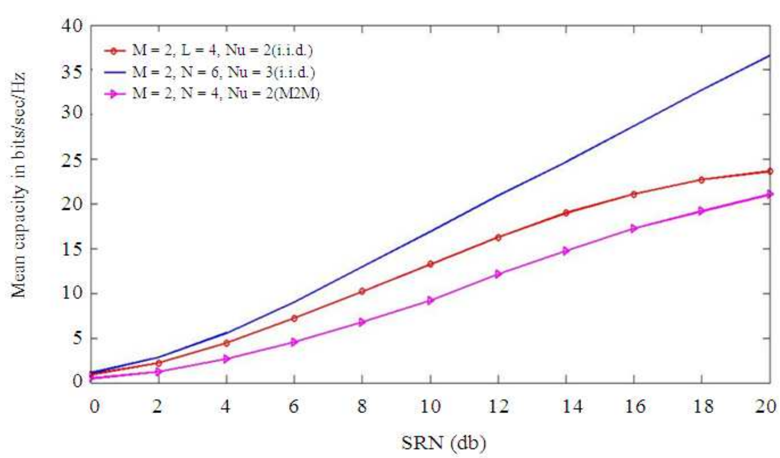

Fig. 6: Mean capacity of two hop relay system for IID and realistic channel model

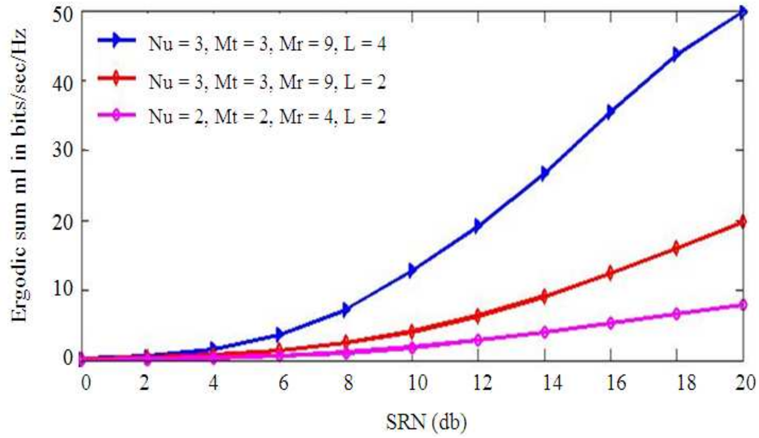

Fig. 7: Ergodic sum mutual information of Multiusermulti-hop relay system with correlated fading model

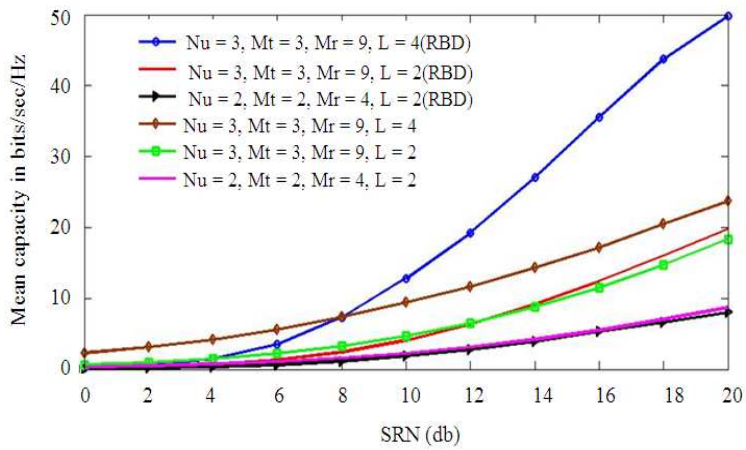

Fig. 8: Mean capacity of multiuser Multihop relay system with optimal and RBD precoding technique

Ergodic sum mutual information of multiuser multi-hop relay system with correlated channel environment is shown in Fig. 7, where relay at each level perform linear precoding on their received signal prior to retransmitting to the next level. Figure 8 shows mutual information for multi-hop relay system with optimal and RBD precoding technique.

DISCUSSION

Cellular systems usually operate at a moderately low SINR as seen in Fig. 3 and 4, however the rate advantage due to MIMO is very less at low SINR level. The SINR increased on every hop by adding relays, but simultaneously the increase in Kr reduces the MIMO capacity gain. From the Eq. 5 indicated that Kr is still around 10 in a distance of 100 m and thus lower the MIMO gain without lost the gain completely. The dependence of capacity on rice factor and antenna configuration revealed that more antennas offer higher capacities, although the capacity loss occurs with increasing Kr. In two hop and Multihop relay system all Nu users have same number of antennas, all relay nodes and destination nodes are outfitted with same number of antennas (i.e., Nj = N, j = 1,2,…L). By assuming that all users having identical transmit power qi = P/Nu, all relay nodes with same transmission power $p_j = P$ (j = 1,2,…L), the mutual information of system increases with number of relay elements.

CONCLUSION

Multiuser two hop relay system with RBD precoding for realistic mobile to mobile fading channel model is simulated and compared with IID channel model by using non-regenerative Amplify and Forward relay (AF) scheme. Multiuser Multi-hop relay with optimal and RBD precoding technique results are compared with correlated fading channel and found that the capacity obtainable by RBD precoding scheme is better than other relaying systems.

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