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Research Article

Performance of Amplify and Forward Relays with Predicted CSI

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Abstract: In cooperative relay networks, Channel State Information (CSI) is estimated at receiver. The estimated CSI is sent back to the relays through feedback link. This estimated CSI is often outdated due to feedback delay and the estimated outdated CSI is used for relay selection and detection which affects the performance of the system. The outage and error rate performance of the relay selection schemes is highly dependent on the correlation between the actual channel and their corresponding outdated channel estimates. In this study, the first part of the work investigates the effect of feedback delay on the outage and error rate performance of Amplify and-Forward (AF) cooperative relay network. In the second part of the work, actual CSI is predicted using Minimum Mean Square Error (MMSE) prediction and this predicted CSI is used for relay selection and detection. The best relay selection and partial relay selection are considered in this study. From the simulation results it is observed that the effect of correlation coefficient between the actual channel and the corresponding channel estimate is more significant in the best relay selection than partial relay selection and also the improvement in outage and BER performance are evident if the actual CSI is predicted.

Keywords: Amplify and Forward (AF) relay, best relay selection, channel prediction, feedback delay, outdated CSI, partial relay selection, relay selection

INTRODUCTION

Various cooperative relay schemes have been employed recently in wireless networks and they result in the performance benefits such as throughput improvements and cellular signal coverage enhancements (Hasna and Alouini, 2003; Hasna and Alouini, 2004; Pabst *et al*., 2004). Hence, mobile broadband communication networks such as 3GPP LTE-Advanced standards prefer to support relay based communication. Relays in wireless networks can be classified as:

- Decode-and-Forward (DF) relays, which decode and re-encode the information before forwarding it
- Amplify and-Forward (AF) relays, which amplify and forward the signal without hard decoding of relay selection

The cooperative relays give diversity gain but at the expense of spectral efficiency since the source and all the relays must transmit in orthogonal channels (Laneman *et al*., 2004). The inefficient utilization of the channel resources can be minimized by relay selection. One such scheme is the best relay selection protocol. In this scheme, a single best relay is selected for data transmission to the destination. Therefore only two orthogonal channels are required in this case. In (Bletsas *et al*., 2006), a diversity gain has been achieved in the order of the number of relays by selecting the relay with the best end-to-end path between the source and the destination in the case of best relay selection. However, resource-constrained ad hoc and sensor networks, monitoring the connectivity of all links can limit the network lifetime. Such problems have been mitigated by the development of partial relay selection schemes, which require channel state information of either the source-relay links, or the relay-destination links (Krikidis *et al*., 2008).

Several concept of relay selection schemes have been carried out in (Hasna and Alouini, 2003, 2004; Pabst *et al*., 2004; Laneman *et al*., 2004; Bletsas *et al*., 2006; Ikki and Ahmed, 2007; Krikidis *et al*., 2008). Most of these works deal with the case where perfect CSI is available for relay selection. Recently in (Vicario *et al*., 2009; Torabi and Haccoun, 2010; Suraweera *et al*., 2010; Seyfi *et al*., 2011; Michalopoulos *et al*., 2012; Kejalakshmi and Arivazhagan, 2015), the issue of imperfect CSI was considered. In (Vicario *et al*., 2009), the outage probability analysis and the asymptotic behaviour of DF best relay selection with outdated channel estimates has been studied and in (Torabi and Haccoun, 2010), the capacity of AF relay with the imperfect CSI of the source-relay and relay-destination channels has been investigated. Further, in (Suraweera *et al*., 2010), the effect of feedback delay on the performance of AF relays with the k^{th} worst partial relay selection scheme has been studied. Then, in (Seyfi

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et al., 2011) impact of outdated channel state information due to feedback delay and channel estimation error on the performance of decode-and forward relays with the partial relay selection scheme has been reviewed. In (Michalopoulos *et al*., 2012), the impact of outdated CSI on the outage performance of AF relay selection schemes has been reviewed. Also in (Bin Zhong *et al*., 2013), the performance of partial relay selection has been reviewed with outdated CSI for Cognitive radio networks. In (Zhang *et al*., 2014), the optimization of AF relays has been done with beam forming by considering the imperfect CSI.

The aim of this study is to predict the actual CSI by using MMSE prediction to overcome the adverse effect of outdated CSI due to feedback delay. The predicted CSI is used for relay selection and detection. The effect of prediction is reviewed on the outage probability and error rate for best selection schemes and partial selection schemes.

METHODOLOGY

System model: The cooperative relay setup system shown in Fig. 1, consists of a single source terminal, S, number of relays N denoted as R_i, where, i = 1, …, N and a single destination terminal, D. All relays operate in the half-duplex AF mode and they use CSI-assisted variable gain G for amplification. This relaying gain depends on the instantaneous channel amplitude of the corresponding S-R_i link. The fading in all S-R_i and R_i-D paths are assumed to be independent and identically distributed (i.i.d) with h~CN $(0,\sigma_h^2)$ There is no direct S-D link. Hence, S can communicate with D only via the relay terminals. Let h_{AB}be the circularlysymmetric complex Gaussian channel gain between nodes A and B. Let γ_{AB} be the instantaneous SNR of link A-B, so that $\gamma_{AB}=\frac{|h_{AB}|^2}{N_0}$ where N_0represents the Additive White Gaussian noise (AWGN) power and it is assumed that all nodes transmit with unit power.

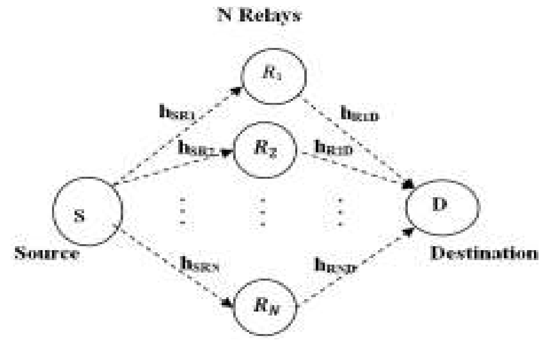

Fig. 1: System model

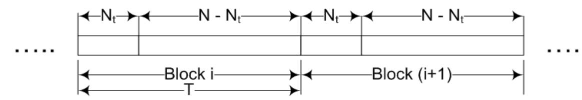

Fig. 2: Training model

Relay selection with outdated CSI:

Channel estimation: There are two phases of transmission. One is training phase and the other is data transmission. The training phase takes up a fraction of the whole block duration. It is assumed that the source and relay have same transmit power. During the training phase, the source transmits the known training sequences to relay. The relay estimates the source relay link channel using training method.

In this study, block fading scheme is considered. At the beginning of every block, the first N_t symbols are assigned for training. Therefore, channel is estimated once in every T seconds, where T is the frame duration. The channel realizations are assumed to be constant over a block and correlated across blocks. The correlation coefficient between the k^{th} and $(k+i)^{th}$ block is $\rho = J_0(2\pi f_d Ti)$ where f_d is the Doppler frequencyand T is the block duration. At the beginning of each block, the relay nodes estimate the channel with training symbols. It is assumed that the number of training symbols in each frame is sufficiently lesser than the data symbols so that increasing the training symbols' power results in negligible increase in average power (Fig. 2).

For Relay selection process, the participating relays send flag packets to the destination, announcing that they are ready to cooperate. The destination terminal estimates the downlink CSI in each relay for the entire path. The Central Unit (CU) receives estimated CSI and relay selection is made. It feeds back the result of the relay selection. The relay selections have to be completed within the channel coherence time. Otherwise outdated CSI would result in erroneous selection of relay, causing poor performance in the system.

Let the estimated channel be $\hat{h}$ and the old estimated CSI be $\hat{h}_0$. $\hat{h}_0$ and $\hat{h}$ are related by (Torabi and Haccoun, 2010):

$$\hat{h} = \sigma_h^2 \left(\frac{\rho}{\sigma_{\hat{h}_0}} \hat{h}_0 + \sqrt{1-\rho^2}\,\omega\right) \quad (1)$$

where,

$\hat{h}_0$ = The channel which is used for relay selection $h_R = h_{d,old} = \hat{h}_0$

$\hat{h}$ = The channel used for detection i.e., $h_d = \hat{h}$

The correlation between actual true channel and the estimated channel is given by $\rho = J_0(2\pi f_d T\Delta)$.

where,

f_d = The Doppler frequency

T = The block duration

Δ = Feedback delay, ω~CN(0, 1)

Best relay selection: Best relay selection is a scheme in which relay for data transmission is selected by considering both the S-R_i and R_i-D links. In particular, it is assumed that the relay with the strongest "bottleneck" link is selected. Hence, the end-to-end SNR used by CU for relay selection based on outdated estimates is given as:

$$\hat{\gamma}_i = min(\hat{\gamma}_{SR_i}, \hat{\gamma}_{R_iD}) \quad (2)$$

where, $\hat{\gamma}_{AB=|\hat{h}_{AB}|^2/N_0}$ denotes the estimate of γ_{AB}. The CU activates the relay which satisfies the condition:

$$k = \arg max_i(\hat{\gamma}_i) \quad (3)$$

Partial relay selection: The selection procedure is modified accordingly so that only one of the two links of either the S-Rior the Ri-D path is considered for partial relay selection. The selected relay is thus determined by considering S-RiCSI and is given as:

$$k = \arg max_i(\hat{\gamma}_{SR_i}) \quad (4)$$

The selection can also be done with the channel conditions of the R_i-D links:

$$k = \arg max_i(\hat{\gamma}_{R_iD}) \quad (5)$$

Relay selection with predicted CSI: To overcome the effect of feedback delay, the actual CSI is predicted by an L−tap linear MMSE prediction filter using the past channel estimates $[\hat{h}(k-\Delta), \hat{h}(k-\Delta-1)\ldots.\hat{h}(k-\Delta-L)]$ as in (Vicario *et al*., 2009).

The past channel estimates are represented in vector form $h_\Delta(k) = [\hat{h}(k-\Delta),\hat{h}(k-\Delta-1)\ldots.\hat{h}(k-\Delta-L)]$ where, Δ is the feedback delay. Let the predicted CSI be:

$$\tilde{h}(k) = w^H h_\Delta(k) \quad (6)$$

where, w is the prediction filter coefficients and is given as:

$$w = R^{-1}p \quad (7)$$

$R = E\{h_\Delta(k)h_\Delta(k)^H\}$is the correlation matrix and $p = E\{h(k)h_\Delta(k)\}$ is the cross correlation vector:

The correlation coefficient $\rho_{pred} = \sqrt{\frac{p_s}{p_{s+\sigma_n^2}} p^H R^{-1} p}$ where, p_s is the power of source and σ_n^2 is noise variance.

After prediction at receiver, the relay selection has been done by CU with predicted CSI. Hence $h_R = h_{d,old} = \tilde{h}$ and $h_d = \tilde{h}$. The best relay selection is determined by:

$$\tilde{\gamma}_i = min(\tilde{\gamma}_{SR_i}, \tilde{\gamma}_{R_iD}) \quad (8)$$

where, $\tilde{\gamma}_{AB=|\tilde{h}_{AB}|^2/N_0}$denotes the predicted γ_{AB}. The CU activates the relay which satisfies the condition:

$$k = \arg max_i(\tilde{\gamma}_i) \quad (9)$$

The partial relay selection is done by considering:

$$k = \arg max_i(\tilde{\gamma}_{SR_i}) \quad (10)$$

The selection can also be done with the channel conditions of the R_i-D links:

$$k = \arg max_i(\tilde{\gamma}_{R_iD}) \quad (11)$$

After relay selection process, the data communication takes place in two time slots; during the first time slot the source S transmits the signal to the k^{th}relayR_k:

$$y_{R_k} = \sqrt{p_s} h_{SR_k} x + n_{R_k} \quad (12)$$

where, h_{SR_k} denotes the S-R_k link, $k \in [1, N]$channel coefficient and $n_{R_k}, k \in [1, N]$ denotes the additive white Gaussian noise component withvariance N_r. During the second time slot, the selected relay R_k multiplies the received signal by gain G and retransmits itto D. The received signal at D is given as:

$$\begin{aligned} y_{R_{kD}} &= \sqrt{p_r} h_{R_{kD}} G y_{R_k} + n_D \\ &= \sqrt{p_r} h_{R_{kD}} G(\sqrt{p_s} h_{SR_k} x + n_{R_k}) + n_D \end{aligned} \quad (13)$$

where,

$h_{R_{kD}}$ = The channel coefficient of the selected relay link $R_k - D$

n_D = The AWGN component at D with variance N_U

Due to the CSI-assisted AF mode of operation, the end-to-end SNR for thek^{th} selected relay, γ_k, = 1,..., N, can be expressed as in (Pabst *et al*., 2004):

$$\gamma_k = \frac{\gamma_{SR_k}\gamma_{R_{kD}}}{\gamma_{SR_k} + \gamma_{R_{kD}} + 1} \quad (14)$$

PERFORMANCE ANALYSIS

Hence, in this section, the outage probability for the best relay selection and partial relay selection with prediction is derived. The outage probability is defined as the probability that drops below a predefined SNR threshold. Therefore, to derive the outage probability for the best relay selection scheme with channel prediction, the CDF $F_{\gamma_k}(\gamma)$ is given as:

$$\begin{aligned} F_{\gamma_k}(\gamma_T) &= Pr\left(\frac{\gamma_{SR_k}\gamma_{R_kD}}{\gamma_{SR_k}+\gamma_{R_kD}+1} < \gamma_T\right) \\ &= \int_0^\infty Pr\left(\frac{\gamma_{SR_k}y}{\gamma_{SR_k}+y+1} < \gamma_T\right) f_{\gamma_{R_kD}}(y)dy \end{aligned} \quad (15)$$

And γ_{SR_k} and $\hat{\gamma}_{SR_k}$ are correlated exponential distributions given by (Pabst *et al*., 2004):

$$f_{\gamma_{SR_k},\hat{\gamma}_{SR_k}}(x,y) = \frac{e^{-\frac{x+y}{\left(1-\rho_{1,pred}^2\right)\bar{\gamma}_{SR}}}}{\left(1-\rho_{1,pred}^2\right)\bar{\gamma}_{SR}^2} I_0\left(\frac{2\sqrt{\rho_{1,pred}^2 xy}}{\left(1-\rho_{1,pred}^2\right)\bar{\gamma}_{SR}}\right) \quad (16)$$

The conditional PDF is given as:

$$f_{\gamma_{SR_k}|\hat{\gamma}_{SR_k}}(x|y) = \frac{f_{\gamma_{SR},\hat{\gamma}_{SR}}(x,y)}{f_{\hat{\gamma}_{SR}}(y)} \quad (17)$$

And substitute:

$$f_{\hat{\gamma}_{SR}}(y) = \frac{1}{\bar{\gamma}_{SR}} e^{-\frac{y}{\bar{\gamma}_{SR}}} \quad (18)$$

Hence,

$$f_{\gamma_{SR_k}|\hat{\gamma}_{SR_k}}(x|y) = \frac{e^{-\frac{x+\rho_{1,pred}^2 y}{\left(1-\rho_{1,pred}^2\right)\bar{\gamma}_{SR}}}}{\left(1-\rho_{1,pred}^2\right)\bar{\gamma}_{SR}} I_0\left(\frac{2\sqrt{\rho_{1,pred}^2 xy}}{\left(1-\rho_{1,pred}^2\right)\bar{\gamma}_{SR}}\right) \quad (19)$$

Using the above equation, the outage probability for the best relay selection scheme with channel prediction is obtained as in (Pabst *et al*., 2004) and it is shown in Eq. (20). In equation (20), $\rho_{pred}=\sqrt{\frac{p_s}{p_{s+\sigma_n^2}}} p^H R^{-1} p$ is the prediction coefficient.

Similarly, the outage probability for partial relay selection scheme with channel prediction is obtained as in (Pabst *et al*., 2004) and it is shown in Eq. (21) and in Eq. (21), $\rho_{1,pred}=\sqrt{\frac{p_s}{p_{s+\sigma_n^2}}} p^H R^{-1} p$ is the prediction coefficient of S-R_k link:

$$F_{\gamma_k}(\gamma_T) = \sum_{n=0}^{N-1} \frac{N\left(n+1+ne^{-\frac{(2n+1)\gamma_T \rho_{pred}^2}{\bar{\gamma}\, S(1,1,n,\rho_{pred})}} - (2n+1)e^{\frac{\gamma_T}{\bar{\gamma}}}\right)}{e^{\frac{\gamma_T}{\bar{\gamma}}}\left[(-1)^{n+1}\binom{N-1}{n}\right]^{-1}(n+1)(2n+1)} + \sum_{n=0}^{N-1}\sum_{m=0}^{N-1} \frac{N^2(-1)^{n+m+1}(n+1)^{-1}\binom{N-1}{n}\binom{N-1}{m}}{\bar{\gamma}(2m+1)(2n+1)S(1,1,m,\rho_{pred})}\ X$$

$$\left[\frac{2n+1}{n+1}\left(\bar{\gamma}e^{-\frac{\gamma_T}{\bar{\gamma}}} + \frac{m\bar{\gamma}e^{-\frac{2(m+1)\gamma_T}{\bar{\gamma}S(1,1,m,\rho_{pred})}}}{m+1}\right) - 2e^{-\frac{2\gamma_T}{\bar{\gamma}}}\sqrt{\gamma_T+\gamma_T^2}K_1\left(\frac{2\sqrt{\gamma_T+\gamma_T^2}}{\bar{\gamma}}\right) - \right.$$

$$2\left[m\frac{e^{-\frac{\gamma_T[S(1,1,m,\rho_{pred})+2m+2]}{\bar{\gamma}S(1,1,m,\rho_{pred})}} K_1\left(2\sqrt{\frac{2(m+1)(\gamma_T+\gamma_T^2)}{\bar{\gamma}^2 S(1,1,m,\rho_{pred})}}\right)}{\sqrt{(m+1)S(1,1,m,-\rho_{pred})}\left[2(\gamma_T+\gamma_T^2)\right]^{-\frac{1}{2}}} + n\frac{e^{-\frac{\gamma_T[S(1,1,n,\rho_{pred})+2n+2]}{\bar{\gamma}S(1,1,n,\rho_{pred})}} K_1\left(2\sqrt{\frac{2(n+1)(\gamma_T+\gamma_T^2)}{\bar{\gamma}^2 S(1,1,n,\rho_{pred})}}\right)}{\sqrt{(n+1)S(1,1,n,\rho_{pred})}\left[2(\gamma_T+\gamma_T^2)\right]^{-\frac{1}{2}}}\right] +$$

$$\left. 4mn\sqrt{\frac{e^{-\frac{4\gamma_T\left[(n+2)-(3n+2)\left(1-\rho_{pred}^2\right)+m(4n+3)\left(1-\rho_{pred}^2\right)+1\right]}{\bar{\gamma}S(1,1,m,\rho_{pred})S(1,1,n,\rho_{pred})}}(n+1)S(1,1,m,\rho_{pred})K_1^2\left(4\sqrt{\frac{(m+1)(n+1)(\gamma_T+\gamma_T^2)}{\bar{\gamma}^2 S(1,1,m,\rho_{pred})S(1,1,n,\rho_{pred})}}\right)}{(m+1)S(1,1,n,\rho_{pred})(\gamma_T+\gamma_T^2)^{-1}}}\right] \quad (20)$$

$$F_{\gamma k}(\gamma_T) = 1 - 2N\sum_{m=0}^{N-1}\left[(-1)^m\binom{N-1}{m} \times \sqrt{\frac{\gamma_T(\gamma_T+1)}{\bar{\gamma}_{RD}\bar{\gamma}_{SR}(m+1)\left[1+m\left(1-\rho_{1,pred}^2\right)\right]}}\right.$$
$$\left. X\ exp\left(-\frac{\left[\bar{\gamma}_{RD}+\bar{\gamma}_{SR}+m\left(\bar{\gamma}_{RD}+\bar{\gamma}_{SR}-\bar{\gamma}_{SR}\rho_{1,pred}^2\right)\right]\gamma_T}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}\left[1+m\left(1-\rho_{1,pred}^2\right)\right]}\right) \times K_1\left(2\sqrt{\frac{(m+1)\gamma_T(\gamma_T+1)}{\bar{\gamma}_{SR}\bar{\gamma}_{RD}\left[1+m\left(1-\rho_{1,pred}^2\right)\right]}}\right)\right] \quad (21)$$

SIMULATION RESULTS AND DISCUSSION

The computer simulations are done with using MATLAB 7.7. The number of relays used in this study is considered to be 3 and all participating links are assumed to be symmetrical so that $\bar{\gamma}_{SR_k} = \bar{\gamma}_{R_kD}$ i = 1, 2, 3.

Figure 3 describes the outage probability performance of the best relay selection scheme of AF relays against the normalized average SNR of S-R_k and R-D_k links for various values of correlation coefficients with prediction and without prediction. The outage performance for perfect CSI is also shown in the figure for comparison.

It is observed that there is a gap between the outage curves for $\rho = 1$ and $\rho = 0.95$ resulting with a small deviation in the feedback delay ($\rho = 0.95$) from perfect CSI ($\rho = 1$), there is a large degradation in the outage performance. Even there is a small feedback delay, the performance degradation is significant. This outage degradation can be compensated by predicting the channel using MMSE predictor. The prediction length is assumed to be L = 6. The curve which corresponds to the channel prediction with $\rho = 0.95$ shows better performance than the curve which corresponds to $\rho = 0.95$ without prediction. Channel prediction on the other hand, improves the correlation between the actual channel values and the CSI available for relay selection i.e., $\rho_{pred} > \rho$. Therefore, the degradations due to channel variations are reduced. Thus, with the channel prediction at the receiver, when the correlation coefficient is $\rho = 0.95$ the SNR gain of 1dB is obtained. The outage curves correspond to correlation coefficient $\rho = 0.5$ and $\rho = 0.707$ with prediction and without prediction show nearby performance. Hence, it is observed that when feedback delay is high; channel prediction does not improve the outage performance. It is also noted that the set of outage curves which corresponds to $\rho = 0.95$ shows better outage performance than the curves corresponds to $\rho = 0.5$ and $\rho = 0.707$.

Figure 4 shows the outage performance of partial relay selection for various values of correlation coefficient with and without channel prediction. In this scheme, outage performance degradation is less affected by feedback delay. This is due to the partial channel knowledge either S-R_i or R-D_i link used for selection. The set of outage curves which corresponds to $\rho = 0.5$ and $\rho = 0.707$ have nearby performance. The curve which corresponds to the channel prediction with $\rho = 0.95$ gives SNR gain of 0.5dB than the curve which corresponds to $\rho = 0.95$ without prediction.

Figure 5 describes the BER performance of best relay selection against average normalized SNR for various values of frame delay with and without channel prediction. The BPSK modulated symbols are used for this simulation. The set of error rate curves which

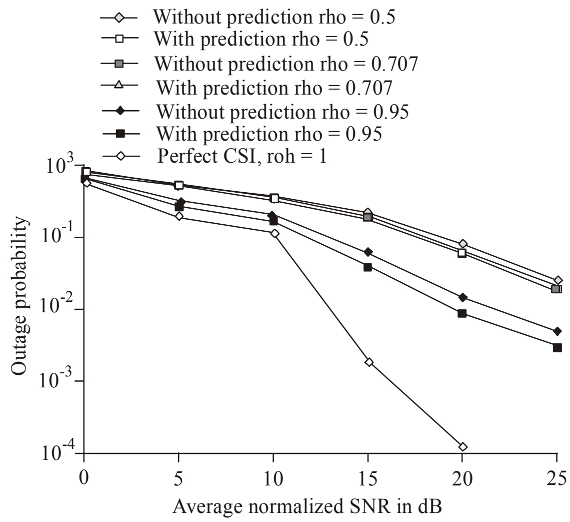

Fig. 3: Outage performance of best relay selection

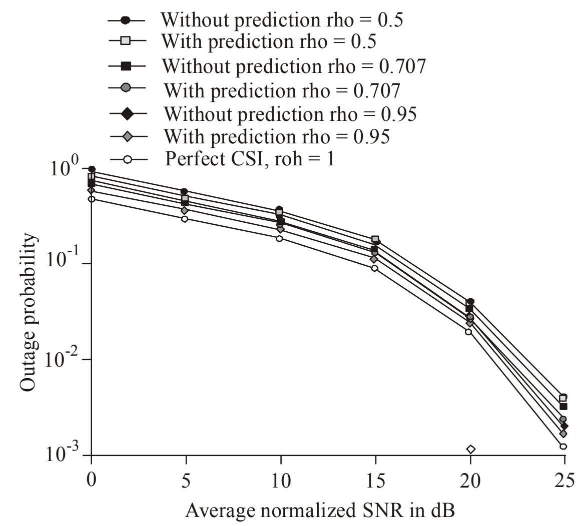

Fig. 4: Outage performance of partial relay selection

corresponds to $\rho = 0.5$ and $\rho = 0.707$ shows nearby performance. The set of curve which corresponds to $\rho = 0.95$ has better BER performance than the curves which corresponds to $\rho = 0.5$ and $\rho = 0.707$. When no frame delay is supposed to be $\rho = 1$ and the small deviation at $\rho = 0.95$ results with degradation in the error rate performance. The curve which corresponds to channel prediction (prediction length L = 6) with $\rho = 0.95$ results in SNR gain of 1 dB than the curve with $\rho = 0.95$ without channel prediction.

Figure 6 describes the BER performance of partial relay selection against average normalized SNR. The error rate performance is less affected by the CSI imperfections in partial relay scheme. The outage curves which correspond to $\rho = 0.5, \rho = 0.707$ and $\rho = 0.95$ show nearby performance. The curve which corresponds to the channel prediction with $\rho = 0.95$

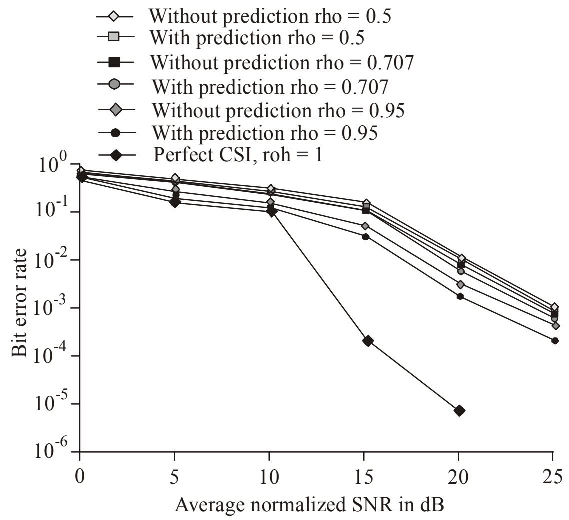

Fig. 5: BER performance of best relay selection

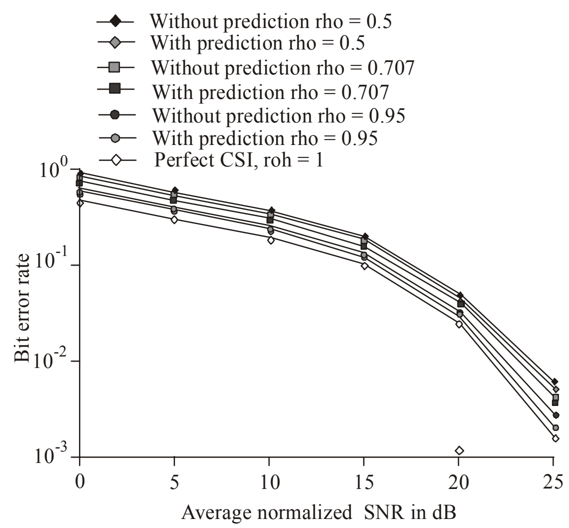

Fig. 6: BER performance of partial relay selection

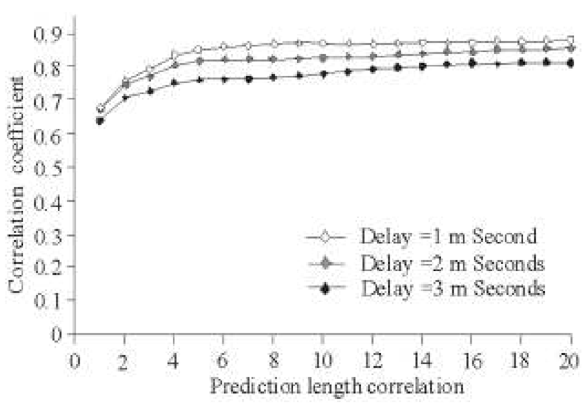

Fig. 7: Correlation coefficient Vs. prediction length

gives SNR gain of 0.5dB than the curve which corresponds to $\rho = 0.95$ without prediction.

The dependence of correlation coefficient on delay and prediction length is shown in Fig. 7. The correlation increases with filter length. For delay of 1msec the maximum value of $\rho = 0.97$ whereas for a delay of 3 m sec, the maximum $\rho = 0.85$. When delay increases, the inputs to the channel predictor are less correlated with the actual channel. Hence, there is degradation in the prediction performance.

CONCLUSION

The effects of outdated channel estimates of amplify and forward best relay selection and partial relay selection schemes on outage and error rate performance has been analysed. Simulation results out of these analysis show that performance degradation is significant even if it deviates slightly from the perfect value ($\rho = 1$), $\rho = 0.95$ and this degradation effect has been minimized by MMSE prediction adopted in this study. This channel prediction results with SNR gain of 1dB in case of best relay selection scheme and 0.5dB in case of partial relay selection scheme proposed in this study.

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