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Full interference cancellation for two-path relay cooperative networks

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Full Interference Cancellation for Two-Path Relay Cooperative Networks

Chunbo Luo, Yu Gong and Fuchun Zheng

School of Systems Engineering, The University of Reading, Reading, RG6 6AY,
UK

E-mail: {c.luo, y.gong and f.zheng}@reading.ac.uk

Abstract

This paper proposes the full interference cancellation (FIC) algorithm to cancel the inter-relay interference (IRI) in the two-path cooperative system. Arising from simultaneous data transmission from the source and relay nodes, the IRI may significantly decrease the performance if it is not carefully handled. Compared to the existing partial interference cancellation (PIC) scheme, the FIC approach is more robust yet with less complexity. Numerical results are also given to verify the proposed scheme.

I. INTRODUCTION

The two-path successive relay scheme has attracted recent attention as it greatly improves the spectrum efficiency with an extra relay node to form a virtual full-duplex relay transmission [1], [2]. The two-path relay scheme is illustrated in Fig.1, where there is one source node S , one destination node D , and two relay nodes R_1 and R_2 . In practice, the direct transmission link between S and D may or may not be available. Without losing generality, we assume at odd numbered time slot (Fig.1 (1)), the source S transmits data to the relay R_1 and the destination D (if the direct link exists). At the same time, the other relay node R_2 relays the data received from S at the $(n-1)$ th time slot to D . At the even time slots (Fig.1 (2)), S transmits data to R_2 and D , and R_1 relays data to D . Because now the the source continually transmits data to the two relays alternatively, the loss in bandwidth efficiency is effectively avoided. Specifically, as the destination receives no data at the first time slot, $(N+1)$ time slots are required to transmit N data frames from the source to destination, leading to a bandwidth efficiency of $N/(N+1)$ which is close to full data transmission rate of 1 when N is sufficiently large.

Due to the simultaneous transmission from the source and relay nodes, a relay node receives data not only from the source but also from the other relay. Such data from the other relay forms

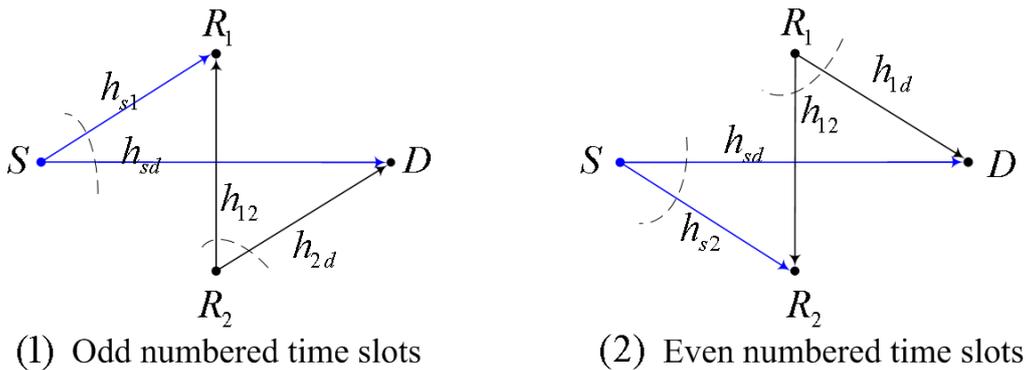


Fig. 1. The two-path successive relay scheme.

the *inter-relay interference* (IRI) which is also passed to the destination. Although for simplicity, the IRI can be treated as noise, this leads to significant performance degradation [3], [4]. IRI suppression approaches therefore become important. The IRI can be cancelled at either the relay nodes or the destination. In [5], an inter-relay self interference cancellation approach was proposed to cancel the IRI at the relay nodes, in which orthogonal training symbols are required to separate out the IRI signals. In this paper, we focus on the IRI cancellation at the destination which is of particularly importance for some mobile relay terminals requiring low complexity.

In [6], a partial interference cancellation (PIC) algorithm was proposed to suppress the IRI at the destination for the two-path relay system without direct link. In the PIC algorithm, the IRI in the received signal at the destination is expressed as a weighted summation of the previous data symbols. Then, if the previous m data symbols are correctly detected and stored, their contribution to the IRI at the destination can be subtracted from the received signal. In order to fully cancel the IRI, m should be larger than $(N - 1)$, where N is the total number of data symbols. When N is large as it often is, it leads to high computational complexity and large buffer storage. It was suggested in [6] that when $\text{SNR} = 20\text{dB}$ and the inter-relay channel gain $v_{12}^2 = 0.5$, m should be set as 6. In general, the choice of m depends on several factors including the channel condition and transmission powers etc. It is thus difficult, if not impossible, to set an appropriate m for all scenarios. Moreover, since the PIC approach depends on the successful detection of the previous data symbols, it is vulnerable to error propagation, i.e. errors from the previous data detection “propagate” into the current detection. These motivate us to explore new IRI cancellation

approaches.

In this paper, we propose a full interference cancellation (FIC) algorithm in which the IRI is expressed as a single iterative term in the received signal itself at the destination and thus can be easily removed. Therefore, the IRI cancellation does not depend on the detection of the previous symbols and only requires to store one previous received signal sample. This makes the FIC not only more robust but also simpler to implement than its PIC counterpart. Furthermore, while the PIC algorithm in [6] was derived only for the system without direct link between the source and destination, it is however difficult, if not impossible, for the PIC algorithm to be applied for the system with direct link. On the contrary, with the data detection approach proposed in this paper, the FIC algorithm can be applied in the system with direct link.

II. SYSTEM MODEL

In this paper, we assume the channels are flat block fading. As is shown in Fig.1, h_{s1} , h_{s2} and h_{sd} are the channel gains from S to R_1 , R_2 and D respectively, h_{1d} and h_{2d} are channel gains from R_1 and R_2 to D respectively, and h_{12} and h_{21} are the inter-relay channel gains from R_1 to R_2 and R_2 to R_1 respectively. For notational simplicity, we assume the same fading variance from S to both relays and from both relays to D , i.e., $E[|h_{s1}|^2] = E[|h_{s2}|^2] = v_s^2$ and $E[|h_{1d}|^2] = E[|h_{2d}|^2] = v_d^2$. We also assume the inter-relay channel is symmetric such that $h_{12} = h_{21}$ with $E[|h_{12}|^2] = v_{12}^2$. We particularly note that these assumptions are for simple notation only and do not affect the effectiveness of the algorithms proposed later. In this paper, we assume the relays apply the amplify-and-forward (AF) protocol because the AF not only has less complexity but also is more flexible in handling the IRI than the other widely used decode-and-forward (DF) protocol.

We assume without losing generality that at the odd numbered time slots n ($n \neq 1$), the source node S transmits data to both the relay node R_1 and the destination node D , and at the same time the relay node R_2 relays data to D . The received signal at the destination is then given by

$$y_d(n) = h_{sd} \cdot x_s(n) + h_{2d} \cdot x_2(n) + w_d(n), \quad (1)$$

where h_{sd} is also assumed to be flat block fading with variance $E\{|h_{sd}|^2\} = v_{sd}^2$. As the relay

nodes apply the AF protocol, we have

$$x_2(n) = \beta_2 \cdot y_2(n-1), \quad (2)$$

where β_2 is the amplifying factor at relay R_2 , $y_2(n-1)$ is the data received by R_2 at the time slot $(n-1)$ which is given by

$$y_2(n-1) = h_{s_2}x_s(n-1) + h_{12} \cdot x_1(n-1) + w_2(n-1), \quad (3)$$

where $w_2(n-1)$ is the noise at the relay R_2 . Substituting (2) and (3) into (1) gives

$$y_d(n) = h_{sd}x_s(n) + h_{2d}\beta_2h_{s_2}x_s(n-1) + h_{2d}\beta_2h_{12} \cdot x_1(n-1) + (h_{2d}\beta_2w_2(n-1) + w_d(n)), \quad (4)$$

where the first and second terms of RHS of (4) contain the information symbols transmitted from the direct and relay links respectively, the third term is the inter-relay interference (IRI), and the last two terms are the noises. Due to the concurrent transmission at the source and relay, the IRI appears as the second term in (3) at a relay node and passes to the received signal at the destination in (4) through the relay operation in (2).

Assuming that the transmission powers at S , R_1 and R_2 are constrained as P_s , P_{r_1} and P_{r_2} respectively. Without losing generality, we can write $P_{r_1} = \alpha_1 P_s$ and $P_{r_2} = \alpha_2 P_s$, where α_1 and α_2 are power factors for R_1 and R_2 respectively. In order to satisfy the power constraint, we should have $\mathbb{E}[|x_2(n)|^2] \leq P_{r_2}$. Then from (2) and (3), we have:

$$\beta_2^2 \leq \frac{P_{r_2}}{\mathbb{E}[|y_2(n-1)|^2]} = \frac{\alpha_2 P_s}{v_s^2 P_s + \alpha_1 v_{12}^2 P_s + \sigma^2}. \quad (5)$$

Similarly, if the time slot index n is even, S transmits to both R_2 and D , and R_1 relays to D so that we have

$$y_d(n) = h_{sd}x_s(n) + h_{1d}\beta_1h_{s_1}x_s(n-1) + h_{1d}\beta_1h_{12} \cdot x_2(n-1) + (h_{1d}\beta_1w_1(n-1) + w_d(n)), \quad (6)$$

with $\beta_1^2 \leq \alpha_1 P_s / (v_s^2 P_s + \alpha_2 v_{12}^2 P_s + \sigma^2)$.

Without losing generality, we assume there are N data symbols in total and N is even. Since

$(N + 1)$ time slots are required to transmit N symbols from S to D , stacking $y_d(n)$ for $(N + 1)$ time slots gives the vector/matrix expression as

$$\mathbf{y}_d = \mathbf{H}\mathbf{x}_s + \mathbf{w}, \quad (7)$$

where $\mathbf{x}_s = [x_s(1), \dots, x_s(N)]^T$, $\mathbf{w} = \mathbf{H}_r\mathbf{x}_r + \mathbf{w}_r$, $\mathbf{H}_r = \text{diag}\{0, 0, \lambda_2 h_{r_1 r_2}, \dots, \lambda_N h_{r_{N-1} r_N}\}$, $\mathbf{x}_r = [0, 0, x_r(1), \dots, x_r(N - 1)]^T$ and

$$\mathbf{H}_s = \begin{bmatrix} h_{sd} & 0 & 0 & \cdots & 0 \\ \beta_1 h_{s1} h_{1d} & h_{sd} & 0 & \cdots & 0 \\ \vdots & \beta_2 h_{s2} h_{2d} & h_{sd} & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & \beta_1 h_{s1} h_{1d} & h_{sd} \\ 0 & 0 & \cdots & \cdots & \beta_2 h_{s2} h_{2d} \end{bmatrix}, \mathbf{w}_r = \begin{bmatrix} w_d(1) \\ w_d(2) + \beta_1 h_{1d} w_1(1) \\ w_d(3) + \beta_2 h_{2d} w_2(2) \\ \vdots \\ w_d(N) + \beta_1 h_{1d} w_1(N - 1) \\ w_d(N + 1) \end{bmatrix},$$

If the IRI is treated as noise, the average data rate over N symbols is obtained as

$$\mathcal{R}_{IRI:direct} = \frac{1}{N + 1} \mathbb{E}\{\log[\det(\mathbf{I} + P_s \mathbf{H}\mathbf{H}^H \mathbf{C}^{-1})]\}, \quad (8)$$

where $\mathbf{C} = \mathbb{E}\{\mathbf{w}\mathbf{w}^H\}$. On the other hand, if the IRI is removed, we have $\mathbf{w} = \mathbf{w}_r$ and the average data rate is obtained similar to (8) but with $\mathbf{C} = \mathbb{E}\{\mathbf{w}_r \mathbf{w}_r^H\}$. It is clear that the IRI can seriously degrade the average data rate if it is not carefully handled.

In some systems where the direct link between the source and destination nodes does not exist or is too weak to detect, the signals received and transmitted at the relay nodes are the same as those in (3) and (2) respectively, but the received signal at the destination becomes:

$$y_d(n) = h_{2d} \cdot x_2(n) + w_d(n). \quad (9)$$

The vector/matrix expression is similar to (7) but with $h_{sd} = 0$ in \mathbf{H}_s .

III. FULL INTERFERENCE CANCELLATION

In this section, we propose the full interference cancellation (FIC) algorithm to remove the IRI at the destination. Similarly to that in [6], we assume that the destination knows the channel state information of every link.

While the n th received signal at the destination is given by (1) or (4), at $(n - 1)$ th time we have $y_d(n - 1) = h_{sd}x_s(n - 1) + h_{1d}x_1(n - 1) + w_d(n - 1)$, or

$$x_1(n - 1) = \frac{1}{h_{1d}} [y_d(n - 1) - h_{sd}x_s(n - 1) - w_d(n - 1)] \quad (10)$$

Substituting (10) into (4) gives

$$y_d(n) = h_{sd}x_s(n) + h_{2d}\beta_2 \left(h_{s2} - \frac{h_{12}h_{sd}}{h_{1d}} \right) x_s(n - 1) + \frac{h_{2d}\beta_2 h_{12}}{h_{1d}} y_d(n - 1) + w'(n), \quad (11)$$

where $w'(n)$ is the noise term which is given by

$$w'(n) = h_{2d}\beta_2 w_2(n - 1) - \frac{h_{2d}\beta_2 h_{12}}{h_{1d}} w_d(n - 1) + w_d(n). \quad (12)$$

It is clear that the IRI appears as a single recursive term, i.e. the third term on the right-hand-side (RHS) of (11), in the received signal at the destination. Therefore, if $y_d(n - 1)$ is stored at the destination at time slot $(n - 1)$, the IRI can be removed by subtracting $\frac{h_{2d}\beta_2 h_{12}}{h_{1d}} y_d(n - 1)$ from (11) as

$$y'_d(n) = h_{sd}x_s(n) + h_{2d}\beta_2 \left(h_{s2} - \frac{h_{12}h_{sd}}{h_{1d}} \right) \cdot x_s(n - 1) + w'(n), \quad (13)$$

It is clear that the first two terms of RHS of (13) contains the information data $x_s(n)$ and $x_s(n - 1)$ which are transmitted through the direct and relay paths respectively.

Similarly, at even numbered time slots n , the signal after the FIC cancellation is given by

$$y'_d(n) = h_{sd}x_s(n) + h_{1d}\beta_1 \left(h_{s1} - \frac{h_{12}h_{sd}}{h_{2d}} \right) \cdot x_s(n - 1) + w'(n), \quad (14)$$

with $w'(n) = h_{1d}\beta_1 w_1(n - 1) - \frac{h_{1d}\beta_1 h_{12}}{h_{2d}} w_d(n - 1) + w_d(n)$.

For better exposition, (13) and (14) can be expressed in an unified form as

$$y'_d(n) = h_{sd} \cdot x_s(n) + B(n) \cdot x_s(n - 1) + w'(n), \quad (15)$$

where

$$B(n) = \begin{cases} B_o, & \text{if } n \text{ is odd} \\ B_e, & \text{if } n \text{ is even} \end{cases}$$

with $B_o = h_{2d}\beta_2(h_{s2} - \frac{h_{12}h_{sd}}{h_{1d}})$ and $B_e = h_{1d}\beta_1(h_{s1} - \frac{h_{12}h_{sd}}{h_{2d}})$. Stacking $y'_d(n)$ for the total $(N + 1)$ time slots gives the vector/matrix expression as

$$\tilde{\mathbf{y}}_d = \tilde{\mathbf{H}}\mathbf{x}_s + \tilde{\mathbf{w}}, \quad (16)$$

where $\tilde{\mathbf{y}}_d = [y'_d(1), \dots, y'_d(N + 1)]^T$ and

$$\tilde{\mathbf{H}} = \begin{bmatrix} h_{sd} & 0 & 0 & \cdots & 0 \\ B_e & h_{sd} & 0 & \cdots & 0 \\ 0 & B_o & h_{sd} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & h_{sd} \\ 0 & 0 & 0 & \cdots & B_o \end{bmatrix}, \tilde{\mathbf{w}} = \begin{bmatrix} w_d(1) \\ w_d(2) + h_{1d}\beta_1[w_1(1) - h_{12}/h_{2d}w_d(1)] \\ \vdots \\ w_d(N + 1) + h_{2d}\beta_2[w_2(N) - h_{12}/h_{1d}w_d(N)] \end{bmatrix}$$

The average data rate after the FIC can be obtained as

$$\mathcal{R}_{FIC:B} = \frac{1}{N + 1} \mathbf{E}\{\log[\det(\mathbf{I} + P_s \tilde{\mathbf{H}}\tilde{\mathbf{H}}^H \tilde{\mathbf{C}}^{-1})]\}, \quad (17)$$

where $\tilde{\mathbf{C}} = \mathbf{E}\{\tilde{\mathbf{w}}\tilde{\mathbf{w}}^H\}$.

Particularly, if there is no direct link between the source and destination, the received signal after the FIC approach can be similarly obtained as

$$y'_d(n) = B(n)x_s(n - 1) + w'(n), \quad (18)$$

with $h_{sd} = 0$ in $B(n)$.

It is clear that the IRI has been completely removed in both (15) and (18). The rest task is to detect $x_s(n)$ from (15) or (18).

IV. DATA DETECTION

If there exists no direct link between the source and destination, the received signal after the FIC is given by (18), and the data detection is simply obtained as $y'_d(n)/B(n)$.

On the other hand, with direct link, the received signal after the FIC is given by (15) which contains both $x_s(n)$ and $x_s(n - 1)$. It is clear in (15) that $x_s(n)$ is the current data transmitted through the direct link and $x_s(n - 1)$ is the previous data through the relay link.

Note that we assume there are N data packets in total and N is even. At the first time slot $n = 1$, the destination node only receives the data from the source since the relay nodes have no data to transmit yet. At the last time slot $n = N + 1$, the source stops transmission as all N data symbols have been transmitted and the destination only receives the last data symbol from a relay node. The received signals after the FIC at the destination can be listed as

$$\begin{aligned}
n = 1 : \quad & y'_d(1) = h_{sd} \cdot x_s(1) + w'(1) \\
n = 2 : \quad & y'_d(2) = h_{sd} \cdot x_s(2) + B_e \cdot x_s(1) + w'(2) \\
& \vdots \\
n = N : \quad & y'_d(N) = h_{sd} \cdot x_s(N) + B_e \cdot x_s(N - 1) + w'(N) \\
n = N + 1 : & y'_d(N + 1) = B_o \cdot x_s(N) + w'(N + 1)
\end{aligned} \tag{19}$$

The forward and backward detection can then be applied to detect the data.

Forward detection

- 1) At $n = 1$, simply let $y^f(1) = y'_d(1)$, and the forward data detection $x_s^f(1)$ is the hard decision of $y^f(1)/h_{sd}$.
- 2) At $n = 2$, the signal sample from the direct link can be separated as $y^f(2) = y'_d(2) - B_e \cdot x_s^f(1)$, and the data detection $x_s^f(2)$ is the hard decision of $y^f(2)/h_{sd}$.
- 3) Repeating step 2) until $n = N$ gives all of the N signal samples from the direct link as $(y^f(1), \dots, y^f(N))$ and the corresponding forward data detection as $(x_s^f(1), \dots, x_s^f(N))$.

Backward detection

- 1) At $n = N + 1$, let $y^b(N) = y'_d(N + 1)$ with the backward data detection $x_s^b(N)$ being as the hard decision of $y^b(N)/B_o$.
- 2) Back to $n = N$, the signal sample transmitted from the relay links can be separated from $y'_d(N)$ as $y^b(N - 1) = y'_d(N) - h_{sd} \cdot x_s^b(N)$, and the data detection $x_s^b(N - 1)$ is the hard decision of $y^b(N - 1)/B_e$.
- 3) Repeating step 2) backward until $n = 2$ gives all of the N signal samples from the relay links as $(y^b(1), \dots, y^b(N))$ and the corresponding backward data detection as $(x_s^b(1), \dots, x_s^b(1)(N))$.

Data combining

Either the forward estimation $x_s^f(n)$ or backward estimation $x_s^b(n)$ may be used as the data detection. Since ideally $y^f(N)$ and $y^b(N)$ are the received signals from the direct and relay links with “channel gains” of h_{sd} and $B(n)$ respectively, a better detection can be achieved by combining $y^f(N)$ and $y^b(N)$ with the “maximum ratio combining” (MRC) as

$$y_s(n) = h_{sd}^* \cdot y^f(n) + B^*(n) \cdot y^b(n), \quad n = 1, \dots, N \quad (20)$$

with the final data estimation being the hard decision of $y_s(n)$.

In practice, there exist hard decision errors in the forward and backward approaches, leading to a performance gap between the proposed forward/backward approach and the ideal case that terms for $x_s(n)$ and $x_s(n-1)$ are perfectly separated. Such performance gap is expected to be significantly narrowed, if not diminished, with turbo detection such that the hard decision is replaced by the soft decision feed back from the decoder (e.g. [7]). The detail is beyond the scope of this paper and would be an interesting topic in future work.

The MRC performance gain from (20) is determined by the dependence between h_{sd} and $B(n)$, or the coefficients for terms $x_s(n)$ and $x_s(n-1)$ in (15) respectively. Due to the non-zero inter-relay channel gain h_{12} , h_{sd} and $B(n)$ are not independent since $B(n)$ is a function of h_{sd} . In other word, subtracting $y_d(n)$ with $y_d(n-1)$ in the FIC approach makes the received signal from the relay links being interfered by those from the direct link. As a result, the full MRC gain can not be achieved unless $h_{12} = 0$. On the other hand, if the channel coefficients for all channels are i.i.d variables with mean zero, we have $E[h_{sd} \cdot B(n)] = 0$ so that h_{sd} and $B(n)$ are uncorrelated to each other. This implies that the MAC approach can still achieve fair performance gain.

We note that the above data detection approach is difficult to apply in the PIC algorithm in which the received signal at the destination would be expressed as a summation of the signal from the direct link and a series of previous data symbols from the relay link.

V. SIMULATION RESULTS

Numerical examples are given in this section to verify the proposed FIC algorithm. In the simulations below, there are 5,000 data frames transmitted in total from the source to the

destination with 64 symbols for each frame, the average channel gains of source-relay link and relay-destination link are assumed to be same such that $v_s^2 = v_d^2 = 1$, the channel gain between the two relay nodes is set at $v_{12}^2 = 1$. For comparison, the results for the PIC algorithm are also shown, where, unless otherwise stated, the number m of the previous detected data used to cancel the IRI is set as 6 as was suggested in [6] and other parameters are the same as those used in the simulations in [6]. As was in the original paper [6] where the PIC algorithm was proposed, we only consider the PIC algorithm for the system without direct link between the source and destination. For better illustration, we use the symbols “A” and “B” in the figures below to refer to the systems without and with direct link respectively. For example, “PIC:A” stands for the PIC algorithm being used in the system without direct link, “FIC:A” and “FIC:B” are for the FIC being used in the system without and with direct link respectively.

Fig. 2 shows the average data rates for different approaches, where “No IRI” refers to the ideal case that the IRI is completely removed at the destination and “IRI” refers to the case that the IRI is treated as noise, and for the PIC both $m = 6$ and $m = 4$ are considered. It is clearly shown that “FIC:A” and “PIC:A (m=6)” have similar average data rates, while both are much larger than that for the case of “IRI:B”. This verifies that the IRI must be suppressed. On the other hand, the performance of the “PIC:A (m=4)” degrades significantly, indicating that the PIC algorithm must carefully choose m . Fig. 2 also shows that “FIC:B” has higher average data rate than the “FIC:A” approach due to the extra performance gain from the direct link.

Fig. 3 compares the BER performance for different approaches, where “FIC:B-Forward” and “FIC:B-Backward” are for the FIC with forward and backward only data detection respectively, “FIC:B-MRC” is for the FIC with MRC data detection, and “perfect separation” is for the ideal case that terms for $x_s(n)$ and $x_s(n - 1)$ in (15) are perfectly separated and combined with MRC. Similar to [3], a practical channel model with the QPSK is considered, where all channel coefficients are Rayleigh fading with effect of path loss and lognormal shadowing as $h_{ab} = r_{ab} \sqrt{d_{ab}^{-\gamma} 10^{\varphi/10}}$, where r_{ab} is a complex Gaussian variable with unit power, d_{ab} is the distance between nodes a and b which are normalized to 1 for the direct link and $1/\sqrt{3}$ for other links, γ is the path loss factor, and φ is the lognormal shadowing term which is set as a normal variable

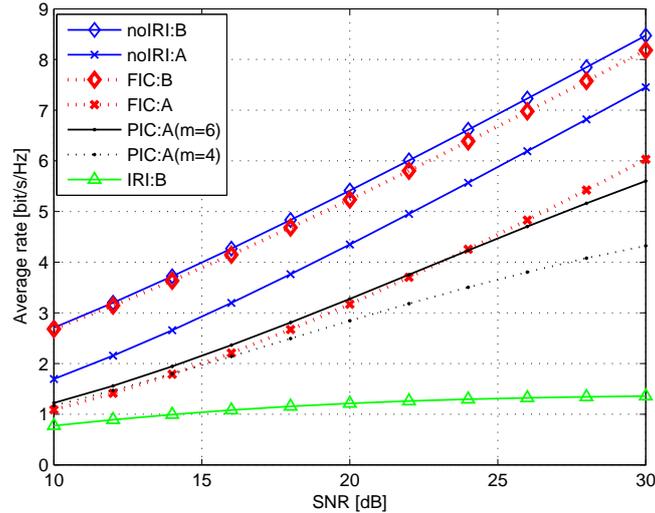


Fig. 2. Average rate for the different schemes.

with mean of 0dB and standard deviation of 8dB.

It is clearly shown in Fig. 3 that all FIC approaches (including the “FIC:A”) have significantly better BER performance than the PIC algorithm. It is also shown that “FIC:B-MRC” is obviously better than the “FIC:B-Forward” and “FIC:B-Backward” due to the MRC performance gain. We note that the “FIC:B-Forward” and “FIC:B-Backward” have similar performance only because we set same average channel gains for all channels. In practice, the performance of the “FIC:B-Forward” and “FIC:B-Backward” approaches depends on how strong the direct and relay links are respectively.

Noting that “FIC:B-Backward” manages to separate the received signal from the relay links, the “FIC:A” approach with no direct link at all can be used as a performance bench mark for the “FIC:B-Backward”. It is interesting to observe that “FIC:A” is slightly better than the “FIC:B-Backward” because: first, subtracting $y_d(n)$ with $y_d(n-1)$ in the “FIC:B” approach makes the received signal from the relay links being interfered by those from the direct link; secondly, there exist detection errors in the backward approach. It is clear that the BER difference for the two approaches is small, indicating that the backward approach is useful to separate the received signal from the relay links.

Finally, we can see a gap between the “FIC:B-MRC” and “perfect separation”. This is due to

the forward/backward detection errors and can be greatly narrowed with approaches such as the turbo detection.

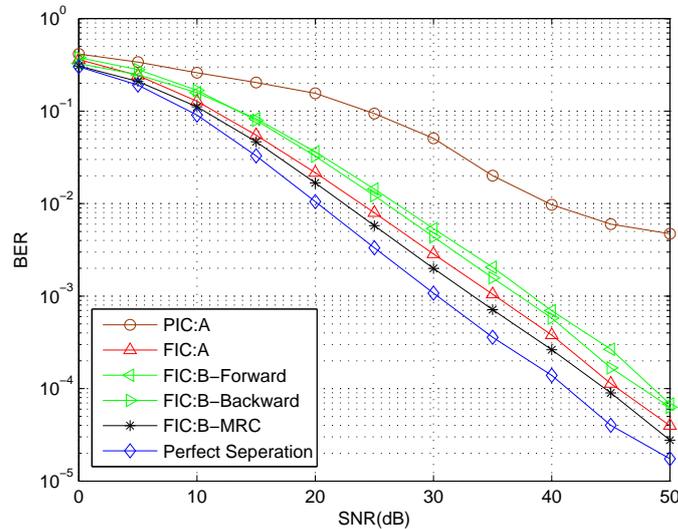


Fig. 3. BER performance for the different schemes

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