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RESEARCH ARTICLE

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# Efficient detection for cooperative communication with two alternating relays

**Abstract** A two-path amplify-and-forward (AF) relaying scheme, which uses two relays to retransmit for the source alternately, was proposed by Rankov [Rankov et al. IEEE Journal on Selected Areas in Communications, 2007, 25 (2): 379–389]. This scheme can avoid half-duplex loss in spectral efficiency, but it cannot work well when the inter-relay channel gain is strong. An efficient detection scheme for two-path AF relaying system is proposed in this paper. In the proposed scheme, interference cancellation is first performed at the destination so that the received signal after interference cancellation is the superposition of two symbols with noise. Then, a low complexity soft maximum a posteriori (MAP) decoder and an iterative soft decoder are employed to extract the diversity of the two relay-destination links. The proposed detection scheme can efficiently improve the system performance compared to the detection scheme presented by Rankov (2007), especially when the inter-relay channel gain is strong.

**Keywords** cooperative diversity, amplify-and-forward (AF), maximum a posteriori (MAP), iterative decoding

## 1 Introduction

Multiple-input multiple-output (MIMO) technique has gained a great deal of attention recently. It is regarded as the next-generation wireless communication technique because it can offer potential spatial diversity and capacity gain compared to single-input single-output (SISO) technique [1,2]. Transmit diversity technique [3] has been proposed to exploit spatial diversity to combat the effect of fading in wireless communication systems. The terminals need to deploy multiple transmit antennas to provide transmit diversity. Since the base station can support multiple antennas, transmit diversity is advantageous for the downlink.

However, for the uplink, users may not be able to support multiple antennas due to limitations of the size, cost or complexity. In this scenario, cooperative diversity has been first proposed in Ref. [4]. The basic idea of cooperative diversity is first studied in Ref. [5]. The spatial diversity can be exploited by cooperating transmission even when each user only has a single antenna. In cooperative communication systems [6,7], each user has partners who serve as relays for it. Reference [6] proposes two classic cooperative diversity schemes called amplify-and-forward (AF) and decode-and-forward (DF). In AF method, each user receives its partners' noise-affected signal and then amplifies and retransmits it. In DF method, each user receives its partners' information, decodes it, and then retransmits it.

Two schemes presented in Ref. [6] can provide significant gain compared to a non-cooperative diversity scheme. However, cooperative communication requires an extra channel used for retransmission, and terminals operate in half-duplex mode; thus, the spectral efficiency is decreased. In order to reduce the loss in spectral efficiency, a lot of research has been done, and some cooperation strategies are presented in Refs. [8–13]. In Ref. [8], distributed space-time codes are used for retransmission. In Ref. [9], multiple-user cooperative diversity is considered, and data are jointly encoded. In Ref. [10], spectral efficiency of cooperation scheme is improved by exploiting signal space diversity. In Ref. [11], coded cooperation that does not reduce the spectral efficiency is proposed. In Ref. [12], superposition modulation is used for DF cooperating transmission. In this scheme, each user superposes its own data with its partner's data and then transmits them. Therefore, there is no loss in spectral efficiency, too. Reference [13] considers the generalization of the scheme proposed in Ref. [12] to a multiple-user scenario.

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On the other hand, two-path relaying scheme is proposed in Refs. [14–17]. In this scheme, each user has two half-duplex relays that alternately listen and relay information. Thus, the half-duplex loss in spectral efficiency can be avoided. In Ref. [14], orthogonal direct sequence spreading codes are used, and the scheme is based on DF cooperation. The scheme presented in Ref. [15] is also based on DF cooperation, and a V-BLAST detection algorithm is performed at the receiver. In Ref. [16], the two-path relaying method is first proposed. Interference cancellation is performed at one relay to reduce the inter-relay interference that leads to an equivalent space-time delay coded system. The received signal at the destination is the superposition of three or four symbols with noise, and the maximum-likelihood sequence estimator (MLSE) is employed. The main disadvantage of this scheme is that implementation complexity is increased greatly because one of the relays must estimate the inter-relay channel coefficient, and store the analog signal received in the previous slot, and then performs interference cancellation. Reference [17] considers a similar two-path relaying scheme, but neither of the relays performs interference cancellation. Moreover, the scenario where there is no direct connection between the source and the destination is considered, and successive decoding with partial or full cancellation of the inter-relay interference at the destination is performed in Ref. [17]. Therefore, the complexity of this scheme is low.

However, the scheme presented in Ref. [17] can only work well when the inter-relay channel gain is not strong. When the inter-relay channel gain is strong, the accumulated noise interference will damage the system performance. In order to improve the system performance, we propose an efficient detection scheme for the system presented in Ref. [17] in this paper. To keep the low implementation complexity of AF cooperation, relays do not perform interference cancellation; they only amplify and retransmit signals. The destination performs interference cancellation to dispose the previously received signal. Simultaneously, the previous noises from relays are also canceled. Moreover, the received signal after interference cancellation at the destination is the superposition of two symbols with noise, which is similar to the received signal in the cooperation scheme based on superposition modulation [12]. Then, a low complexity soft maximum a posteriori (MAP) demodulator similar to that presented in Ref. [12] is employed to extract the diversity of the two relay-destination links. The proposed scheme outperforms the scheme presented in Ref. [17], especially when the inter-relay channel gain is strong. Furthermore, when source-relay channels are additive white Gaussian noise (AWGN), the iterative soft decoding is studied. In this scenario, diversity order of two can be achieved, while the scheme presented in Ref. [17] still cannot provide diversity.

The rest of this paper is organized as follows. In Sect. 2, system model is described, and interference cancellation performed at the destination is introduced. The decoding scheme is presented in Sect. 3, and simulation results are provided in Sect. 4. Finally, Sect. 5 contains the main conclusions.

## 2 System model

In this paper, we adopt the system model described in Ref. [17]. Each terminal has a single antenna, and all channels between terminals are assumed to be quasi-static Rayleigh flat-fading channels, which remain constant over at least one frame. The source terminal $T_1$ attempts to transmit information to the destination terminal $T_2$, and the terminals $T_3$ and $T_4$ serve as relays for $T_1$. Assume that $T_3$ and $T_4$ cannot receive and transmit simultaneously due to the half-duplex constraint, and the source is far away from the destination so that there is no direct connection between $T_1$ and $T_2$. The transmission schedule is shown in Fig. 1. In each slot, $T_1$ transmits a new message, and relays alternately receive and transmit. Without loss of generality, we assume that $T_3$ receives in odd slots and transmits in even slots, whereas $T_4$ receives in even slots and transmits in odd slots. Therefore, there is no half-duplex loss in spectral efficiency.

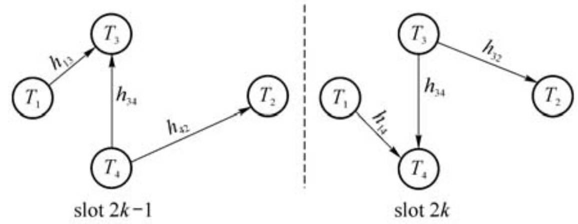

**Fig. 1** Transmission schedule for two-path relaying with alternating relays

Channel reciprocity for inter-relay channels is assumed, and the channel fading coefficient between terminals $T_i$ and $T_j$ $(i,j \in \{1,2,3,4\})$ is denoted as $h_{ij}$. The variances of $h_{13}$ and $h_{14}$ are assumed to be equal and set as

$$\varepsilon\{|h_{13}|^2\} = \varepsilon\{|h_{14}|^2\} = v_1,$$

and the variances of $h_{32}$ and $h_{42}$ are set as

$$\varepsilon\{|h_{32}|^2\} = \varepsilon\{|h_{42}|^2\} = v_2.$$

Note that $\varepsilon$ denotes the expectation operator. For the simplicity of notation, we consider the symbolwise retransmission at relays, but the generalization to blockwise retransmission is straightforward.

Assume a frame of $2N$ symbols $\{x[n]\}_{n=1}^{2N}$ is transmitted from $T_1$ in $2N$ slots. Then the received signal at $T_3$ in slot $2k-1$ $(k = 1,2,\ldots,N+1)$ can be expressed as

$$\begin{aligned} y_3[2k-1] &= h_{13}x[2k-1] + n_3[2k-1] \\ &\quad + \sum_{i=1}^{k-1}\{h_{13}x[2k-1-2i] + n_3[2k-1-2i]\}f^{2i} \\ &\quad + \sum_{i=1}^{k-1}\{h_{14}x[2k-2i] + n_4[2k-2i]\}f^{2i-1}, \end{aligned} \tag{1}$$

and the received signal at $T_4$ in slot $2k$ $(k = 1,2,...,N)$ can be expressed as

$$\begin{aligned} y_4[2k] &= h_{14}x[2k] + n_4[2k] \\ &\quad + \sum_{i=1}^{k-1}\{h_{14}x[2k-2i] + n_4[2k-2i]\}f^{2i} \\ &\quad + \sum_{i=1}^{k}\{h_{13}x[2k+1-2i] + n_3[2k+1-2i]\}f^{2i-1}, \end{aligned} \tag{2}$$

where

$$f = \beta h_{34}, \tag{3}$$

and $n_3[2k-1]$ and $n_4[2k]$ are additive noises at $T_3$ and $T_4$, respectively. They are modeled as independent complex zero-mean Gaussian random variables, and

$$\varepsilon\{|n_3[2k-1]|^2\} = \varepsilon\{|n_4[2k]|^2\} = N_0 \ (k = 1,2,...,N+1).$$

$\beta$ is the amplification factor, and

$$\beta = \begin{cases} \sqrt{\dfrac{P_{\mathrm{R}}}{P_1 v_1 + N_0}}, & \text{the first retransmission of each frame}, \\ \sqrt{\dfrac{P_{\mathrm{R}}}{P_{\mathrm{R}}|h_{34}|^2 + N_0}}, & \text{the last retransmission of each frame}, \\ \sqrt{\dfrac{P_{\mathrm{R}}}{P_1 v_1 + P_{\mathrm{R}}|h_{34}|^2 + N_0}}, & \text{else}, \end{cases} \tag{4}$$

where $P_1$ is the average transmit power of $T_1$, and $P_{\mathrm{R}}$ is the average transmit power of $T_3$ and $T_4$. In this paper, we set $P_1 = P_{\mathrm{R}}$. Signals $y_3[2k-1]$ and $y_4[2k]$ are amplified with $\beta$ and then retransmitted by $T_3$ and $T_4$; the received signals at $T_2$ in slot $2k$ and slot $2k+1$ can be written as

$$\begin{cases} y_2[2k] = h_{32}\beta y_3[2k-1] + n_2[2k] & (k = 1,2,...,N+1), \\ y_2[2k+1] = h_{42}\beta y_4[2k] + n_2[2k+1] & (k = 1,2,...,N), \end{cases} \tag{5}$$

where $\{n_2[k]\}_{k=2}^{2N+2}$ are additive noises at $T_2$. They are also modeled as independent complex zero-mean Gaussian random variables with variance $N_0/2$ per real dimension. Note that $T_2$ does not receive in the first slot.

Assume that perfect channel state information between $T_3$ and $T_4$ is available at the destination. Then $T_2$ performs interference cancellation. By subtracting the previous received signal, we obtain

$$y[k] = y_2[k+1] - f^2 y_2[k-1] \ (k = 1,2,...,2N+1). \tag{6}$$

Equation (6) can be written as

$$\begin{cases} y[2k-1] = h_{32}\beta\{h_{13}x[2k-1] + fh_{14}x[2k-2]\} \\ \qquad + n[2k-1] \quad (k = 1,2,...,N+1), \\ y[2k] = h_{42}\beta\{h_{14}x[2k] + fh_{13}x[2k-1]\} + n[2k] \\ \qquad (k = 1,2,...,N), \end{cases} \tag{7}$$

where

$$\begin{aligned} n[2k-1] &= h_{32}\beta n_3[2k-1] + h_{32}\beta f n_4[2k-2] \\ &\quad + n_2[2k] - f^2 n_2[2k-2], \end{aligned} \tag{8}$$

and

$$\begin{aligned} n[2k] &= h_{42}\beta n_4[2k] + h_{42}\beta f n_3[2k-1] \\ &\quad + n_2[2k+1] - f^2 n_2[2k-1]. \end{aligned} \tag{9}$$

Equation (7) shows that the received signal after interference cancellation is the superposition of two symbols with noise. Hence, this scheme can be regarded as an extension of cooperation scheme based on superposition modulation proposed in Ref. [12].

## 3 Decoding

The destination $T_2$ is assumed to have the knowledge of channel coefficients $h_{13}$, $h_{14}$, $h_{32}$, $h_{42}$, and $h_{34}$. In AF cooperation, the destination must know the inter-relay channel coefficient $h_{34}$, which can be achieved by implementing some mechanism of exchanging or estimating the information of $h_{34}$ [7]. In Ref. [17], the symbol $x[k]$ is decoded from $y_2[k+1]$ given in Eq. (5). Symbols $\{x[n]\}_{n=1}^{k-1}$ are regarded as accumulated inter-relay interference, and they are subtracted using the previous estimations, which will lead to error propagation. In this paper, we propose a new decoding algorithm to improve the bit error rate (BER) performance.

In Ref. [12], soft MAP demodulator is employed to demodulate the superposition modulation. This demodulator can also be used to demodulate the superposition signal expressed in Eq. (7). However, noises $\{n[k]\}_{k=1}^{2N+1}$

expressed in Eqs. (8) and (9) are not white. They must be whitened for optimal detection, but it is complex. Here, we discuss low-complexity detectors that ignore the noise correlation.

For the simplicity of discussion, we consider binary pulse amplitude modulation (BPAM), but extension to multi-level two-dimensional modulations is immediate. Denote the variance of noise $n[k]$ as $\sigma_k^2$. Then the demodulator computes the a posteriori log-likelihood ratio $L(x[2k-1]|y[2k-1],y[2k])$ and $L(x[2k]|y[2k],y[2k+1])$ for symbols $x[2k-1]$ and $x[2k]$, respectively, which are expressed as follows:

$$L(x[2k-1]|y[2k-1],y[2k]) = \ln\frac{\sum\exp\left(-\frac{|y[2k]-\beta h_{42}h_{14}x[2k]-f\beta h_{42}h_{13}|^2}{\sigma_{2k}^2}\right)p(x[2k])}{\sum\exp\left(-\frac{|y[2k]-\beta h_{42}h_{14}x[2k]+f\beta h_{42}h_{13}|^2}{\sigma_{2k}^2}\right)p(x[2k])}$$

$$+\ln\frac{\sum\exp\left(-\frac{|y[2k-1]-f\beta h_{32}h_{14}x[2k-2]-\beta h_{32}h_{13}|^2}{\sigma_{2k-1}^2}\right)p(x[2k-2])}{\sum\exp\left(-\frac{|y[2k-1]-f\beta h_{32}h_{14}x[2k-2]+\beta h_{32}h_{13}|^2}{\sigma_{2k-1}^2}\right)p(x[2k-2])}, \tag{10}$$

$$L(x[2k]|y[2k],y[2k+1]) = \ln\frac{\sum\exp\left(-\frac{|y[2k+1]-\beta h_{32}h_{13}x[2k+1]-f\beta h_{32}h_{14}|^2}{\sigma_{2k+1}^2}\right)p(x[2k+1])}{\sum\exp\left(-\frac{|y[2k+1]-\beta h_{32}h_{13}x[2k+1]+f\beta h_{32}h_{14}|^2}{\sigma_{2k+1}^2}\right)p(x[2k+1])}$$

$$+\ln\frac{\sum\exp\left(-\frac{|y[2k]-f\beta h_{42}h_{13}x[2k-1]-\beta h_{42}h_{14}|^2}{\sigma_{2k}^2}\right)p(x[2k-1])}{\sum\exp\left(-\frac{|y[2k]-f\beta h_{42}h_{13}x[2k-1]+\beta h_{42}h_{14}|^2}{\sigma_{2k}^2}\right)p(x[2k-1])}, \tag{11}$$

where $p(x[k])$ is the a priori probability of symbol $x[k]$. Then the decision is made in terms of Eqs. (10) and (11). We observe from Eq. (7) that the potential diversity between links $T_3-T_2$ and $T_4-T_2$ is exploited, and the BER is mainly dominated by the link $T_1-T_3$ or $T_1-T_4$. While in Ref. [17], BER is not only dominated by the link $T_1-T_3$ or $T_1-T_4$, but also by the link $T_3-T_2$ or $T_4-T_2$. Hence, our scheme can improve the BER performance.

When source-relay channels are AWGN, i.e., $h_{13}=h_{14}=1$, it is observed from Eq. (7) that our scheme can provide diversity order of two. On the other hand, the scheme presented in Ref. [17] still cannot provide diversity. Furthermore, iterative soft decoding can be employed to further improve the BER performance. The a priori probability of $x[k]$ is set as 1/2 when computing the a posteriori log-likelihood ratio without iteration. Now, we use the probability information of $x[k-1]$ and $x[k+1]$ to compute the a posteriori probability of symbol $x[k]$ for iterative decoding. The a posteriori probability of symbol $x[k]$ can be computed as follows:

$$p(x[2k-1]=1) = \left\{1+\frac{\sum\exp\left(-\frac{|y[2k]-\beta h_{42}h_{14}x[2k]+f\beta h_{42}h_{13}|^2}{\sigma_{2k}^2}\right)p(x[2k])}{\sum\exp\left(-\frac{|y[2k]-\beta h_{42}h_{14}x[2k]-f\beta h_{42}h_{13}|^2}{\sigma_{2k}^2}\right)p(x[2k])}\right.$$

$$\left.\times\frac{\sum\exp\left(-\frac{|y[2k-1]-f\beta h_{32}h_{14}x[2k-2]+\beta h_{32}h_{13}|^2}{\sigma_{2k-1}^2}\right)p(x[2k-2])}{\sum\exp\left(-\frac{|y[2k-1]-f\beta h_{32}h_{14}x[2k-2]-\beta h_{32}h_{13}|^2}{\sigma_{2k-1}^2}\right)p(x[2k-2])}\right\}^{-1}, \tag{12}$$

$$p(x[2k]=1)=\left\{1+\frac{\sum \exp\left(-\frac{|y[2k+1]-\beta h_{32}h_{13}x[2k+1]+f\beta h_{32}h_{14}|^2}{\sigma^2_{2k+1}}\right)p(x[2k+1])}{\sum \exp\left(-\frac{|y[2k+1]-\beta h_{32}h_{13}x[2k+1]-f\beta h_{32}h_{14}|^2}{\sigma^2_{2k+1}}\right)p(x[2k+1])}\right.$$
$$\left.\times\frac{\sum \exp\left(-\frac{|y[2k]-f\beta h_{42}h_{13}x[2k-1]+\beta h_{42}h_{14}|^2}{\sigma^2_{2k}}\right)p(x[2k-1])}{\sum \exp\left(-\frac{|y[2k]-f\beta h_{42}h_{13}x[2k-1]-\beta h_{42}h_{14}|^2}{\sigma^2_{2k}}\right)p(x[2k-1])}\right\}^{-1}, \tag{13}$$

$$p(x[k]=-1)=1-p(x[k]=1). \tag{14}$$

When the probability information of $x[k-1]$ and $x[k]$ is obtained, the iteration processes are illustrated as follows:

1) First, the probability of $x[k+1]$ is computed using the probability information of $x[k]$.

2) Then the probability of $x[k]$ is computed using the probability information of $x[k-1]$ and $x[k+1]$; at the same time, the symbol $x[k]$ is decoded.

3) These processes are repeated to decode the other symbols.

When source-relay channels are AWGN, iterative soft decoding can further provide performance gain. However, if source-relay channels are also Rayleigh fading channels, then iterative soft decoding almost cannot provide performance gain. That is because the BER is mainly dominated by the fading link $T_1-T_3$ or $T_1-T_4$, and iteration almost cannot provide extra information for decoding. These results are demonstrated in the simulation.

## 4 Simulation results

In the simulation, the channel model described in Sect. 2 is used, and BPAM is employed. The power of the transmitter is constrained to 1 for all terminals, i.e., $P_1=P_R=1$. The variance of $h_{34}$ is denoted as

$$\varepsilon\{|h_{34}|^2\}=v_{34},$$

and the variances of $h_{32}$ and $h_{42}$ are set as $v_2=1$. The signal-to-noise ratio (SNR) is defined as

$$\mathrm{SNR}=1/N_0.$$

The scheme presented in Ref. [17] is denoted as "Rankov" in the simulation, and all interference from previous symbols is subtracted using the previous estimations.

Figures 2 and 3 show the simulation results of BER performance for various $v_{34}$ when source-relay channels are Rayleigh fading channels and $v_1=1$. The proposed detection scheme can efficiently improve the BER performance compared to Rankov's scheme, and the relative improvement increases with increasing inter-relay channel gain $v_{34}$. Moreover, Fig. 3 demonstrates that iteration almost cannot provide gain when source-relay channels are Rayleigh fading channels.

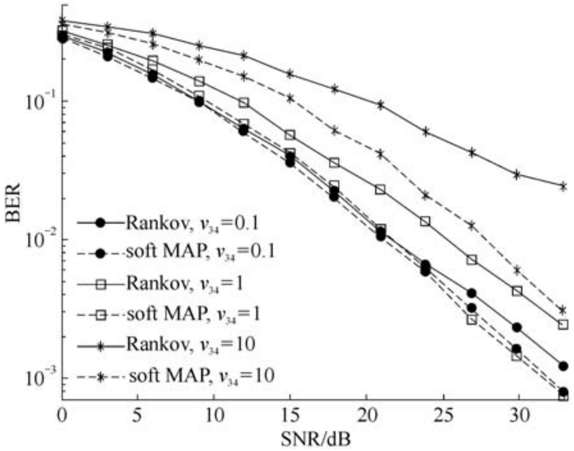

**Fig. 2** BER performance of Rankov's scheme and proposed soft MAP decoding scheme (source-relay channels are Rayleigh fading channels, $v_1=1$)

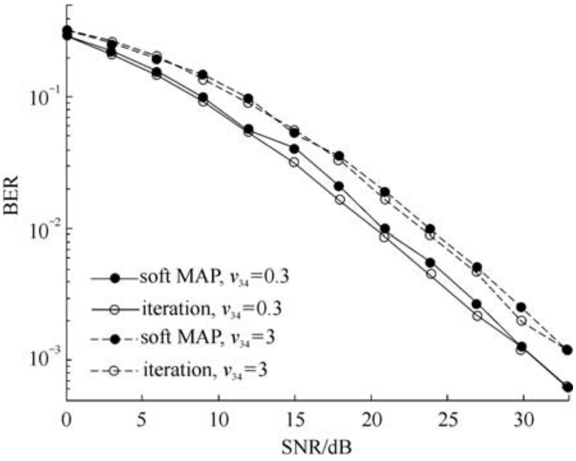

**Fig. 3** BER performance of soft MAP decoding and iterative soft decoding (source-relay channels are Rayleigh fading channels, $v_1=1$)

Figures 4 and 5 show the simulation results of the BER performance for various $v_{34}$ when source-relay channels are AWGN. The proposed detection scheme can provide diversity order of two, and it greatly outperforms Rankov's scheme that cannot provide diversity. It is shown in Fig. 5 that iterative soft decoding outperforms soft MAP decoding. When $v_{34} = 0.3$, the performance improvement between soft MAP decoding and iterative soft decoding is small. While when $v_{34} = 3$, the performance improvement is significant. Hence, iterative soft decoding can provide significant performance gain when the inter-relay channel gain is strong.

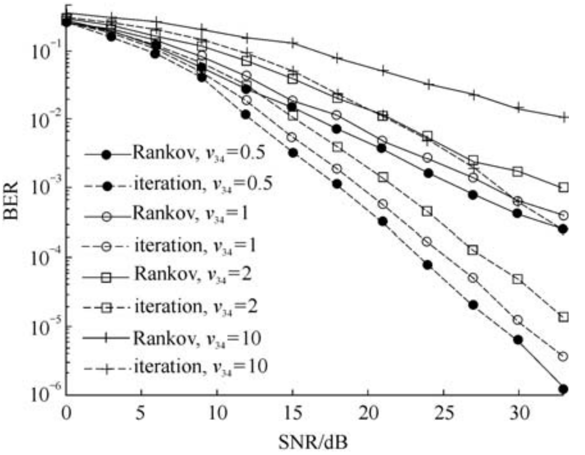

**Fig. 4** BER performance of Rankov's scheme and proposed iterative soft decoding scheme (source-relay channels are AWGN)

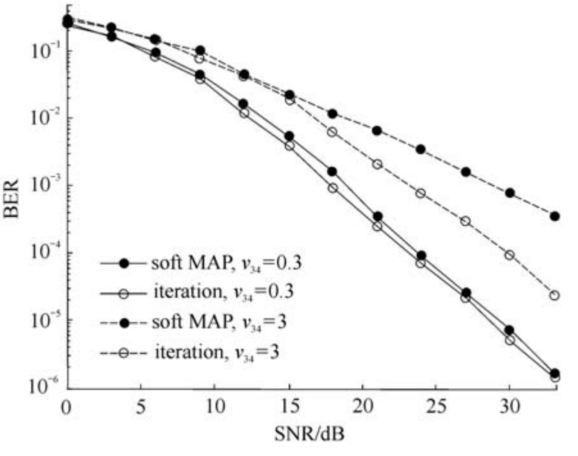

**Fig. 5** BER performance of soft MAP decoding and iterative soft decoding (source-relay channels are AWGN)

## 5 Conclusions

We propose an efficient detection algorithm for the two-path AF relaying scheme, which is presented in Ref. [17]. This detection algorithm can efficiently improve the system performance, especially when the inter-relay channel gain is strong. Furthermore, both interference cancellation and soft decoding are performed at the destination. Relays only need to amplify and retransmit their received signals. Therefore, the implementation complexity at relays keeps low, which is the main advantage of AF cooperation.

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## References

1. Foschini G J, Gans M J. On limits of wireless communications in a fading environment when using multiple antennas. Wireless Personal Communications, 1998, 6(3): 311–335
2. Telatar I E. Capacity of multi-antenna Gaussian channels. European Transactions on Telecommunications, 1999, 10(6): 585–595
3. Alamouti S M. A simple transmit diversity technique for wireless communications. IEEE Journal on Selected Areas in Communications, 1998, 16(8): 1451–1458
4. Sendonaris A, Erkip E, Aazhang B. User cooperation diversity – Part I: System description. IEEE Transactions on Communications, 2003, 51(11): 1927–1938
5. Cover T M, ElGamal A A. Capacity theorems for the relay channel. IEEE Transactions on Information Theory, 1979, 25(5): 572–584
6. Laneman J N, Tse D N C, Wornell G W. Cooperative diversity in wireless networks: efficient protocols and outage behavior. IEEE Transactions on Information Theory, 2004, 50(12): 3062–3080
7. Nosratinia A, Hunter T E, Hedayat A. Cooperative communication in wireless networks. IEEE Communications Magazine, 2004, 42 (10): 74–80
8. Laneman J N, Wornell G W. Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks. IEEE Transactions on Information Theory, 2003, 49(10): 2415–2425
9. Shalvi O. Multiple source cooperation diversity. IEEE Communications Letters, 2004, 8(12): 712–714
10. Cao M W, Bi G G. Bandwidth efficient cooperative diversity scheme based on constellation rotation. IEEE Signal Processing Letters, 2008, 15: 869–872
11. Hunter T E, Nosratinia A. Diversity through coded cooperation. IEEE Transactions on Wireless Communications, 2006, 5(2): 283–289
12. Larsson E G, Vojcic B R. Cooperative transmit diversity based on superposition modulation. IEEE Communications Letters, 2005, 9 (9): 778–780
13. Ding Z, Ratnarajah T, Cowan C C F. On the diversity-multiplexing tradeoff for wireless cooperative multiple access systems. IEEE Transactions on Signal Processing, 2007, 55(9): 4627–4638
14. Ribeiro A, Cai X, Giannakis G B. Opportunistic multipath for bandwidth-efficient cooperative networking. In: Proceedings of

IEEE International Conference on Acoustics, Speech, and Signal Processing. 2004, 4: 549–552

15. Fan Y, Wang C, Thompson J, Poor H V. Recovering multiplexing loss through successive relaying using repetition coding. IEEE Transactions on Wireless Communications, 2007, 6(12): 4484–4493
16. Oechtering T, Sezgin A. A new cooperative transmission scheme using the space-time delay code. In: Proceedings of Information Technology Society Workshop on Smart Antennas. 2004, 41–48
17. Rankov B, Wittneben A N. Spectral efficient protocols for half-duplex fading relay channels. IEEE Journal on Selected Areas in Communications, 2007, 25(2): 379–389