Dual-threshold symbol selective relaying in cooperative networks

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Abstract: In order to efficiently mitigate error propagation and reduce computational complexity, this paper proposes a scheme for traditional cooperative networks, named as dual-threshold symbol selective demodulate-and-forward. In the scheme, two log likelihood ratio (LLR)-based thresholds are devised to measure the reliability of received signals for the relay and the destination, respectively. One of the threshold guarantees that the relay only forwards reliable symbols, thus less error will be propagated to the destination. The other threshold is used at the destination for determining the reliability of symbols received from the source. The destination will directly demodulate reliable symbols received from the source. Otherwise, when the symbols received from the source are not reliable, the maximum ratio combiner (MRC) is used to combine symbols received from the source and the relay. Closed-form expression of the bit error probability (BEP) of the proposed scheme is derived and analyzed under binary phase shift keying (BPSK) modulation. Then, the relationship and closed-form solutions of two LLR-based thresholds are derived. Simulation results prove that the theoretical BEP of the proposed scheme closely matches the simulated ones. The proposed scheme can achieve high performance with low computational complexity compared to existing schemes.

Keywords: demodulate-and-forward, relaying strategies, error propagation, cooperative networks.

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1. Introduction

Cooperative relaying strategies can be classified into two categories [1]: (i) amplify-and-forward (AF), where the signals are amplified by the relay and then forwarded to the destination, and (ii) decode-and-forward (DF), where the signals being decoded and remodulated before forwards to the destination. For AF, the destination needs full knowledge of the channel-state-information (CSI) of each link. The scheme becomes complicated when the CSI is unknown. For DF, there is no error propagation compared with AF because DF relaying only forwards symbols upon

successful decoding. However, there will be few frames being forwarded to the destination when the signal-to-noise ratio (SNR) between the source and the relay is too low. In that case, the relay cannot successfully decode most received signals [2].

In order to reduce the computation complexity in DF at the relay, demodulate-and-forward (DmF) was proposed in [3]. The relay demodulates the received signals and then forwards remodulated symbols to the destination without decoding. However, signals that are forwarded by the relay have equal weights and do not carry any information about the degree of uncertainty [4,5]. Thus, DmF can be viewed as a suboptimal scheme and cannot effectively mitigate error propagation.

To mitigate error propagation in DmF, threshold-based DmF relaying schemes were introduced, including SNR-based selective relaying schemes and LLR-based selective relaying schemes [6–21]. For SNR-based schemes [6–16], the received signals at the relay will be detected and forwarded to the destination only when their SNR is above a predefined threshold. However, SNR-based schemes rely on that the relay knows the instantaneous SNR of the source-destination (S-D) link. Once the instantaneous SNR cannot be obtained accurately, the applying of the average SNR will degrade the system performance [6]. For log likelihood ratio (LLR)-based schemes [17–21], the authors derive the theoretical BEP and a near-optimal threshold is calculated by minimizing the system bit error probability (BEP).

The above studies only focus on the error propagation mitigation on the relay side. To further improve the BEP performance, Ikki et al. [22] demonstrated that the error performance highly depends on the threshold employed at the destination. Zeng et al. [23,24] proposed joint threshold-based relaying and maximum-likelihood (ML) detection at the destination, and the optimal threshold of the relay is obtained by minimizing the BEP using the exhaustive grid search method. However, performance analysis of ML detection is quite complicated especially for

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3. Performance analysis

3.1 Computation complexity analysis

In the proposed scheme, MRC is used at the destination when the relay forwards symbols to the destination and the symbols received from the source are not reliable. Since an LLR-based threshold is applied at the destination, fewer symbols from the source and the relay need to be combined at the destination. This is more efficient than the scheme [23] that requires an ML detector for all symbols from the source and the relay.

The ML detector [23] for BPSK when $|L_{sr}| > T_r$ can be expressed as

$$\hat{x}_d^{ML} \approx \arg \max_{\alpha \in \{\pm 1\}} \left(\max_{\beta \in \{\pm 1\}} F_{\alpha, \beta} \right) \quad (10)$$

where

$$F_{\alpha, \beta} = \text{Re} \left\{ \frac{1}{\sigma_{sd}^2} h_{sd}^* r_{sd} \alpha + \frac{1}{\sigma_{rd}^2} h_{rd}^* r_{rd} \beta \right\} + \ln P(x_r = \beta | x_s = \alpha). \quad (11)$$

Clearly, comparing (9) with (10), the ML detector is more complex, especially for higher-order constellations. Table 1 presents the computational cost of the proposed method and the scheme [23] at the destination when the relay forwards received reliable symbols.

Table 1 Computation complexity analysis of the proposed method and the scheme [23] at the destination when the relay forwards symbols

Method	Computational cost	
	Multiplication	Addition
Proposed scheme when $ L_{sd} \leq T_d, L_{sr} > T_r$	2N	N
Proposed scheme when $ L_{sd} > T_d, L_{sr} > T_r$	2N	0
Scheme [23]	2N	8N

3.2 BER analysis

The closed-form expression of E2E BEP can be expressed as

$$\begin{aligned} P_e(\varepsilon) &= P_e(\varepsilon_{sd}, |L_{sd}| > T_d) + \\ &P_e(\varepsilon_{sd}, |L_{sd}| \leq T_d, |L_{sr}| \leq T_r) + \\ &P_e(\varepsilon_{MRC}, |L_{sd}| \leq T_d, |L_{sr}| > T_r) \end{aligned} \quad (12)$$

where $P_e(\varepsilon_{sd}, |L_{sd}| > T_d)$ is the BEP at the destination when the signal received from the source y_{sd} is viewed as reliable symbol. $P_e(\varepsilon_{sd}, |L_{sd}| \leq T_d, |L_{sr}| \leq T_r)$ is the BEP at the destination when the received signal y_{sd} is not reliable when the relay keep silent. $P_e(\varepsilon_{MRC}, |L_{sd}| \leq T_d, |L_{sr}| > T_r)$ is the BEP at the destination after combination of the S-D link signals y_{sd} and the R-D link signals y_{rd} .

The PDF of received signals for i - j link can be ex-

pressed as (as shown in Appendix A of [19])

$$f_{y_{ij}}(y_{ij}) = \alpha_{ij} \exp(\beta_{ij} x_i y_{ij}) \exp(-\chi_{ij} |y_{ij}|) \quad (13)$$

where

$$\begin{aligned} \alpha_{ij} &= 1/\sqrt{d_{ij}^{-\alpha} 2\sigma_{ij}^2 (1 + \bar{\gamma}_{ij})} \\ \beta_{ij} &= 1/\sigma_{ij}^2 \\ \chi_{ij} &= \sqrt{(1 + \bar{\gamma}_{ij})/\bar{\gamma}_{ij}}/\sigma_{ij}^2. \end{aligned} \quad (14)$$

We set

$$\begin{aligned} \varphi_{ij} &= \frac{\beta_{ij} - \chi_{ij}}{L_c^{ij}} = \frac{-P_B(\bar{\gamma}_{ij})}{1 - 2P_B(\bar{\gamma}_{ij})} \\ \varphi_{ij}^C &= \frac{\beta_{ij} + \chi_{ij}}{L_c^{ij}} = \frac{1 - P_B(\bar{\gamma}_{ij})}{1 - 2P_B(\bar{\gamma}_{ij})}. \end{aligned} \quad (15)$$

To calculate (12), we use the expression of BEP with BPSK modulation [29], that is

$$P_B(\bar{\gamma}) = \frac{1}{2} \left(1 - \sqrt{\frac{\bar{\gamma}}{1 + \bar{\gamma}}} \right) \quad (16)$$

where $\bar{\gamma}$ is the average SNR.

If the LLR of y_{sd} is greater than the threshold T_d , the destination will directly demodulate signals received from the S-D link. To simplify the analysis of the proposed scheme, we assume that all symbols transmitted from the source is $+1$ ($u_s = +1$). The error probability can be derived as

$$\begin{aligned} P_e(\varepsilon_{sd}, |L_{sd}| > T_d) &= \int_{-\infty}^{-T_d/L_c^{sd}} f_{y_{sd}}(y_{sd}) dy_{sd} = \\ &P_B(\bar{\gamma}_{sd}) \exp(-\varphi_{sd}^C T_d). \end{aligned} \quad (17)$$

Thus, if symbols transmitted from the source is $u_s = +1$, an error occurs when L_{sd} is negative.

If the LLR of y_{sd} and y_{sr} are less than the threshold T_d and T_r respectively, the relay will keep silent and only S-D link signals y_{sd} will be considered when the destination performs detection. The error probability can be derived as

$$\begin{aligned} P_e(\varepsilon_{sd}, |L_{sd}| \leq T_d, |L_{sr}| \leq T_r) &= \\ &\int_{-T_r/L_c^{sr}}^{T_r/L_c^{sr}} \int_{-T_d/L_c^{sd}}^0 f_{y_{sd}}(y_{sd}) f_{y_{sr}}(y_{sr}) dy_{sd} dy_{sr} = \\ &(1 - P_B(\bar{\gamma}_{sr}) e^{-\varphi_{sr}^C T_r} - (1 - P_B(\bar{\gamma})) e^{\varphi_{sr} T_r}). \\ &P_B(\bar{\gamma}_{sd}) (1 - e^{-\varphi_{sd}^C T_d}). \end{aligned} \quad (18)$$

If the LLR of y_{sd} is less than the threshold T_d , and the LLR of y_{sr} is greater than the threshold T_r , the relay will forward the remodulated reliable symbols received from the source to the destination. Then, the destination will combine both the S-D link signals y_{sd} and the R-D link signals y_{rd} by MRC. Thus, the BEP at the destination after MRC can be derived as

$$P_e(\varepsilon_{MRC}, |L_{sd}| \leq T_d, |L_{sr}| > T_r) =$$

$$P_e(\varepsilon_{prop})P_e(\varepsilon_r, |L_{sr}| > T_r) + P_e(\varepsilon_{coop})P(\varepsilon_r^C, |L_{sr}| > T_r) \quad (19)$$

where $P_e(\varepsilon_r, |L_{sr}| > T_r)$ is the BEP at the relay when the erroneous detected symbol is selected for retransmission. $P(\varepsilon_r^C, |L_{sr}| > T_r)$ is the probability at the relay when the symbol is detected as correct. $P_e(\varepsilon_{prop})$ is the BEP at the destination when the relay forwards erroneous detected symbol and an MRC combiner is used at the destination. $P_e(\varepsilon_{coop})$ is the BEP at the destination when the relay forwards correctly detected symbol and an MRC combiner is used at the destination.

In the proposed relaying scheme, only reliable symbols are forwarded to the destination in order to reduce the influence of error propagation. However, if the relay makes an incorrect detection and the corresponding symbols are selected for retransmission, the error probability at the destination can be derived as

$$P_e(\varepsilon_{prop}) = P_e(\varepsilon_{MRC}, |L_{sd}| \leq T_d | \varepsilon_r, |L_{sr}| > T_r) = \int_{-T_d/L_c^{sd}}^{T_d/L_c^{sd}} \int_{-\infty}^{-L_c^{sd} y_{sd}/L_c^{rd}} f_{y_{sd}}(y_{sd}) f_{y_{rd}}(y_{rd}) dy_{rd} dy_{sd} = \frac{\alpha_{sd}}{L_c^{sd}} \frac{1 - P_B(\bar{\gamma}_{rd})}{\varphi_{sd} + \varphi_{rd}} (e^{(\varphi_{sd} + \varphi_{rd})T_d} - 1) + \frac{\alpha_{sd} - P_B(\bar{\gamma}_{rd})}{L_c^{sd} \varphi_{sd}^C + \varphi_{rd}^C} (1 - e^{-(\varphi_{sd}^C + \varphi_{rd}^C)T_d}) + P_B(\bar{\gamma}_{sd})(1 - e^{-\varphi_{sd}^C T_d}). \quad (20)$$

When the relay detects symbols correctly, the error event will occur at the destination after the combination of the S-D link signals y_{sd} and the R-D link signals y_{rd} . The error probability at the destination can be derived as

$$P_e(\varepsilon_{coop}) = P_e(\varepsilon_{MRC}, |L_{sd}| \leq T_d | \varepsilon_r^C, |L_{sr}| > T_r) = \int_{-T_d/L_c^{sd}}^{T_d/L_c^{sd}} \int_{-\infty}^{-L_c^{sd} y_{sd}/L_c^{rd}} f_{y_{sd}}(y_{sd}) f_{y_{rd}}(y_{rd}) dy_{rd} dy_{sd} = \frac{\alpha_{sd}}{L_c^{sd}} \frac{2P_B(\bar{\gamma}_{rd}) - 1}{\varphi_{sd} - \varphi_{rd}^C} (e^{(\varphi_{sd} - \varphi_{rd}^C)T_d} - 1) + P_B(\bar{\gamma}_{sd})(1 - e^{-\varphi_{sd}^C T_d}). \quad (21)$$

Substituting the result of (20) and (21) into (19), the BER after MRC is derived. Then the BER of the proposed system is derived by inserting (17), (18) and (19) into (12), the BER expression of the proposed system can be obtained by

$$P_e(\varepsilon_d) = P_B(\bar{\gamma}_{sd}) + \frac{\alpha_{sd}}{L_c^{sd}} \frac{2P_B(\bar{\gamma}_{rd}) - 1}{\varphi_{sd} - \varphi_{rd}^C} (e^{(\varphi_{sd} - \varphi_{rd}^C)T_d} - 1) (1 - P_B(\bar{\gamma}_{sr})) e^{\varphi_{sr} T_r} +$$

$$\frac{\alpha_{sd}}{L_c^{sd}} \frac{1 - P_B(\bar{\gamma}_{rd})}{\varphi_{sd} + \varphi_{rd}} (e^{(\varphi_{sd} + \varphi_{rd})T_d} - 1) P_B(\bar{\gamma}_{sr}) e^{-\varphi_{sr}^C T_r} + \frac{\alpha_{sd} - P_B(\bar{\gamma}_{rd})}{L_c^{sd} \varphi_{sd}^C + \varphi_{rd}^C} (1 - e^{-(\varphi_{sd}^C + \varphi_{rd}^C)T_d}) P_B(\bar{\gamma}_{sr}) e^{-\varphi_{sr}^C T_r}. \quad (22)$$

3.3 Calculation of two thresholds

Equation (22) can be expressed as

$$P_e(\varepsilon_d) = \frac{\alpha_{sd}}{L_c^{sd}} (1 - 2P_B(\bar{\gamma}_{rd})) (1 - 2P_B(\bar{\gamma}_{sr})) f(T_r, T_d) + P_B(\bar{\gamma}_{sd}) \quad (23)$$

where

$$f(T_r, T_d) = -\frac{\varphi_{sr}^C}{\varphi_{sd} - \varphi_{rd}^C} (e^{(\varphi_{sd} - \varphi_{rd}^C)T_d} - 1) e^{\varphi_{sr} T_r} - \frac{\varphi_{rd}^C \varphi_{sr}}{\varphi_{sd} + \varphi_{rd}} (e^{(\varphi_{sd} + \varphi_{rd})T_d} - 1) e^{-\varphi_{sr}^C T_r} - \frac{\varphi_{rd} \varphi_{sr}}{\varphi_{sd} + \varphi_{rd}^C} (1 - e^{-(\varphi_{sd}^C + \varphi_{rd}^C)T_d}) e^{-\varphi_{sr}^C T_r}. \quad (24)$$

The thresholds T_r and T_d can be obtained by minimizing $P_e(\varepsilon_d)$, which also means minimizing $f(T_r, T_d)$. By calculating the partial derivative of function $f(T_r, T_d)$ with respect to T_d equal to 0, we can get the relationship between T_r and T_d as

$$T_d \approx T_r + \ln \left(\frac{1 - P_B(\bar{\gamma}_{sr})}{\varphi_{rd}^C P_B(\bar{\gamma}_{sr})} \right). \quad (25)$$

As shown in (25), there exists a one-to-one relationship between T_r and T_d . Therefore, we can calculate the threshold T_r when T_d is given and vice versa.

By calculating the partial derivative of function $f(T_r, T_d)$ with respect to T_r equal to 0, we can get the relationship between T_r and T_d as

$$\frac{\partial f(T_r, T_d)}{\partial T_r} \approx \frac{\varphi_{sr} \varphi_{sr}^C}{\varphi_{sd} - \varphi_{rd}^C} e^{\varphi_{sr} T_r} + \frac{\varphi_{rd}^C \varphi_{sr} \varphi_{sr}^C}{\varphi_{sd} + \varphi_{rd}} (e^{(\varphi_{sd} + \varphi_{rd})T_d} - 1) e^{-\varphi_{sr}^C T_r} \quad (26)$$

where $e^{(\varphi_{sd} - \varphi_{rd}^C)T_d} \approx 0$, $e^{-(\varphi_{sd} + \varphi_{rd}^C)T_d} \approx 0$ and $\frac{\varphi_{rd} \varphi_{sr} \varphi_{sr}^C}{\varphi_{sd} + \varphi_{rd}^C} e^{-\varphi_{sr}^C T_r} \approx 0$ in high SNR.

The threshold T_r can be obtained by substituting (25) into (26), and we apply Taylor series to obtain a closed-form solution for T_r by

$$\frac{\varphi_{sd} + \varphi_{rd}}{\varphi_{rd}^C (\varphi_{sd} - \varphi_{rd}^C)} = e^{-T_r} (1 - C_2 e^{(\varphi_{sd} + \varphi_{rd})T_r}) \quad (27)$$

$$\ln \frac{\varphi_{sd} + \varphi_{rd}}{\varphi_{rd}^C (\varphi_{sd} - \varphi_{rd}^C)} = -T_r + \ln(1 - C_1) +$$

$$\ln \left(1 + \frac{-C_1}{1 - C_1} (\varphi_{sd} + \varphi_{rd}) T_r \right) \quad (28)$$

$$\text{where } C_1 = \left(\frac{1 - P_B(\bar{\gamma}_{sr})}{\varphi_{rd}^C P_B(\bar{\gamma}_{sr})} \right)^{(\varphi_{sd} + \varphi_{rd})}.$$

Consequently, we obtain a closed-form solution for T_r as

$$T_r \approx \frac{(C_2 - 1)}{C_2^2} + \frac{1}{C_2^2} \left[(C_2 - 1)^2 + 2C_2^2 \ln \left(\frac{\varphi_{rd}^C (\varphi_{sd} - \varphi_{rd}^C)}{\varphi_{sd} + \varphi_{rd}} (1 - C_1) \right) \right]^{\frac{1}{2}} \quad (29)$$

where $C_2 = -\frac{C_1}{1 - C_1} (\varphi_{sd} + \varphi_{rd})$, and the threshold T_d can be derived by (29) and (25).

Unlike the scheme proposed in [23], where the threshold of the relay is obtained by minimizing the BEP using the exhaustive grid search [30], closed form solutions for the thresholds are derived in our scheme. This can reduce the computational cost.

4. Simulation results

In this section, we verify the proposed scheme by simulations.

Fig. 2 shows the relationship between T_r and T_d . As shown in Fig. 2, the thresholds derived from (29) and (25) match well with the thresholds obtained from simulations. Further, with given T_r , the analysis threshold T_d by (25) accords with the simulation ones too, which proves the linearity of two thresholds in (25).

Fig. 2 Theoretical and simulation results of two thresholds T_r and T_d with different SNR when $d_{sd} = 1$, $d_{sr} = d_{rd} = 1/2$, $\bar{\gamma}_{sd} = \bar{\gamma}_{sr} = \bar{\gamma}_{rd}$

Based on the relationship between T_r and T_d in (25), we can plot BEP as a function of T_r in Fig. 3. It shows that the simulation result matches well with the theoretical ones. The BEP firstly decreases and then increases when T_r increases. This can be explained by the fact that in the

low-threshold range, more symbols with incorrect detection will be forwarded to the destination and degrade the performance of the system. In the high-threshold range, fewer symbols will be forwarded to the destination, and the performance is influenced with the increase of the threshold. Next, we compare the BEP performance of the proposed scheme with other schemes: i) LLR-based threshold selective relaying scheme [19]; ii) LLR-based threshold selective relaying with ML detector [23]; iii) ideal relay selective scheme. In the simulations, the path loss factor is set as $\gamma = 3$. Fig. 4 gives the simulation results of the four schemes.

Fig. 3 Comparison of the theoretical BEP and the simulation BEP with respect to T_r when $d_{sr} = 1$, $d_{sr} = d_{rd} = 1/2$, $\bar{\gamma}_{sd} = \bar{\gamma}_{sr} = \bar{\gamma}_{rd} = 15$ dB

Fig. 4 E2E BEP performance comparisons when $d_{sd} = 1$, $d_{sr} = d_{rd} = 1/2$, $\bar{\gamma}_{sd} = \bar{\gamma}_{sr} = \bar{\gamma}_{rd}$

In Fig. 4, the “no thresholding and MRC” represents the relay directly forwards symbols to the destination node.

The “ideal relaying and MRC” indicates that the relay only forwards symbols that are correctly detected to the destination while discards symbols that are incorrect. Simulation results prove that the theoretical BEP of the proposed scheme closely matches the simulated ones. We observe that the performance of the proposed schemes is close to that of scheme [23], and both of them achieve a better performance than LLR-based threshold and MRC [19].

Further, we compare the computational complexity of the proposed method with the method in [23]. Table 2 shows the number of real multiplications and additions of the two methods with a frame length of 10^7 bits. It can be observed from Table 2 that the numerical computation cost required by the proposed scheme is much less than the scheme [23], especially in high SNR. This accords with the analytical results in Table 1.

Table 2 Computation cost at the destination of the proposed scheme and scheme [23] when $L = 10^7$, $d_{sd} = 1$, $d_{sr} = d_{rd} = 1/2$, $\tilde{\gamma}_{sd} = \tilde{\gamma}_{sr} = \tilde{\gamma}_{rd}$

SNR/dB	Scheme	Computational cost	
		Multiplication	Addition
0	Proposed scheme	19 405 410	6 440 826
	Scheme [23]	19 418 974	75 351 792
10	Proposed scheme	19 912 128	1 897 254
	Scheme [23]	19 912 059	79 296 472
20	Proposed scheme	19 990 088	279 889
	Scheme [23]	19 990 067	79 920 536

5. Conclusions

In this paper, we propose an LLR-based dual-threshold symbol selective DmF scheme for three-node cooperative networks. The thresholds are used at the relay and the destination to measure the reliability of received signals, respectively. The relay only forwards reliable symbols to the destination to mitigate error propagation. At the destination, the computing burden is reduced by only combining unreliable symbols from the source with the symbols from the relay. To achieve the LLR-based thresholds, we derive E2E BEP under BPSK. Other than the scheme in [23], closed-form solutions of the thresholds are derived. Simulation results show that the analytical thresholds are close to the simulation ones. And it also proves that the computation costs of the proposed method is less than the method in [23] with almost the same BEP performance.

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