Abstract: This study deals with the error probability optimisation problem in three-phase bidirectional amplify and forward relaying systems. Different from the common two-phase strategy, in the three-phase counterpart, the relay power is split into two different terminals in terms of data error probability. With such a three-phase division, the authors present a unified optimisation algorithm based on the exact symbol error probability (SEP) and its upper bound expression. In addition, by virtue of the dual decomposition algorithm, the authors derive the optimal power allocation and demonstrate its uniqueness at both terminals and the relay node. Moreover, the unified optimisation algorithm can be reduced to some special cases, such as the maximum minisation problem and unbalanced link problem. The proposed results reveal that the proposed algorithm has a significant impact on SEP reduction.

1 Introduction

Bidirectional relaying has been proposed as a more efficient transmission scheme than the one-way counterpart. For example, a bidirectional dual-relay network with the finite-sized battery was considered in [1] for space-time transmission protocol. A user pair, subcarrier pairing permutation and power allocation problem was proposed in [2] for multuser bidirectional regenerative relay networks. A linear minimum mean square error approach was studied in the spatially correlated fading environment for multiple input multiple output bidirectional relay networks [3]. While a beamforming technology [4] was assumed in asynchronous single carrier bidirectional networks [5], where different relays caused different propagation delays.

Meanwhile, the three-phase transmission scheme receives a lot of attention due to the extra phase. A three-phase bidirectional decode and forward energy harvesting scheme were studied in [6] under $\kappa - \mu$ shadowed fading. Short packet communications of finite block length were applied in a three-phase scheme [7]. Two clusters architecture was proposed in the three-phase relaying scheme [8]. Three-phase analogue network coding and opportunistic relay selection were employed in [9].

However, there are still some shortcomings in the previous works. First, the study of three-phase transmission is relatively small compared to traditional two-phase one. A careful survey of the relevant literature reveals that the traditional two-phase bidirectional relaying has attracted the attention of many researchers. For example, the subjects of [1–3, 5] are typical two-phase bidirectional transmissions.

Then, in a small amount of three-phase research works, a large proportion contributes to the complex derivation of performance expressions. Common to these expressions is that there is no power distribution in these derivations. In this way, the power can be regarded as a constant, which is independent of the channel coefficient variable. Obviously, this method is easier for mathematical calculation due to fixed power allocation. For example, an end to end intercept probability was derived in [6] while power allocation technique is neither used on the source node nor used on the relay station. Similarly, an average bit error rate was provided in [10] for Alamouti space-time block code in three-phase xor relaying while transmission power is assumed to be a fixed value independent of channel state changes.

Finally, the rate of maximisation and power minimisation issues dominate the remaining small part. The reason maybe is that it is easier to deal with logarithmic function in data rates than with Gaussian $Q$ function in the error probability. The logarithmic function is a simple mathematical formula, while Gaussian $Q$ function is a complex integral formula, which cannot be expressed by an elementary mathematical formula. For example, a signal to noise ratio (SNR) maximisation problem was proposed in [8] for three-phase relaying systems equipped with multiple input multiple output antenna arrays.

In light of the preceding observation and discussion, little attention has been devoted to the symbol error probability (SEP) optimisation problem of bidirectional cooperative systems, especially for three-phase transmission. Although a few power distribution schemes are proposed for two-phase transmission, the two-phase method cannot be directly applied to the three-phase counterpart. So it is meaningful to explore the open problem for three-phase bidirectional relaying.

This paper studies the SEP optimisation problem in the three-phase bidirectional relaying systems. First, a unified error probability optimisation problem is formulated in terms of the exact expression and its tight upper bound. Then, according to the dual decomposition rule, two standard quadratic equations with one unknown variable are obtained for power allocation, each for different terminals. Thus the power of each terminal has two closed form solutions. Although there may be four different possibilities due to the existence of the quadratic equation for each terminal's power, rigorous mathematical proofs tell us that the optimal power distribution is unique. The remainder of this paper is organised as follows. In Section 2 the system model is given, followed by Section 3 that contains SEP optimisation. In Section 4 simulation results are provided. Finally, Section 5 concludes this work.

2 System model

Consider a bidirectional relay system where two terminals $S_1$ and $S_2$, exchange their own information via a neighbouring bidirectional amplify and forward (AF) relay $R$, as shown in Fig. 1. The channel coefficients of the relayed link between $S_1$ and $R$ and between $S_2$ and $R$ are denoted by $h_1$ and $h_2$, respectively. The transmit powers of $S_1$, $S_2$, and $R$ are assumed as $P_s$, $P_s$ and $P_r$, respectively. Employing the three-phase relaying protocol, the equivalent SNRs...
received at two terminals $S_i$ and $S_i$ node are, respectively, denoted by [11]

\[
\gamma_i = \frac{\beta_i p_i a b}{p_i a + \beta_i p_i b + p_i b + c} \quad (1)
\]

\[
\gamma_i = \frac{\beta_i p_i a b}{p_i a + \beta_i p_i b + p_i b + c} \quad (2)
\]

where $a = |h_i|^2/N_0$, $b = |h_i|^2/N_0$ and $N_0$ is noise variance. $\beta_i$ and $\beta_j$ are the relay power factor split to the two terminals $S_i$ and $S_j$, respectively. Obviously, $\beta_i$ and $\beta_j$ satisfy $\beta_i + \beta_j = 1$. $c \in [0, 1]$ indicates whether the influence of noise is ignored or not. If the effect of noise is considered, then $c$ takes a value of 1, otherwise $c = 0$. On the other hand, when $c = 0$, $\gamma_1$ and $\gamma_2$ can be regarded as the upper bound of the received SNRs at two terminals, which has been used in many works for analytical simplicity [12].

Fig. 1 System model

For the three-phase bidirectional AF protocol under consideration, the overall system performance is characterised in terms of the total SEP of both directions. Our goal is to minimise the total SEP of both transmission directions. Mathematically, this problem is formulated by

\[
\min_{\{p_1, p_2, p_3, p_3\}} \ u(Q(\sqrt{\gamma_1})) + u(Q(\sqrt{\gamma_2}))
\]

s.t. $p_1 + p_2 + p_3 = P_T$, $p_i \geq 0$, $p_1 \geq 0$

$\beta_i + \beta_j = 1$, $\beta_i \geq 0$, $\beta_j \geq 0$

$\gamma_i = \tau\gamma_2$  

where $Q(\cdot)$ is Gaussian $Q$ function and $u$ and $v$ are constants dependent on specific modulation constellation. $P_T$ is the total power budget. The last constraint is the introduction of traffic control and $\tau$ is traffic pattern indicator [13]. Through the traffic factor $\tau$, the flow in both directions can be artificially modulated. In particular, when $\tau = 1$, the original problem is equivalent to minimising the maximum SEP of the two directions. It is worth noting that many previous works used the average SEP as an optimisation goal [1, 14, 15]. However, the average SEP formula is often very complicated and cumbersome due to the complex channel fading model. It is very difficult and mathematically intractable to find the optimal value of the complex SEP formula. That way, most researchers have to take the second-best and choose the asymmetric value of average SEP as the optimisation target instead of the exact one. The power allocation obtained in this asymmetric case may be useful for the average SEP reduction in high SNR region. However, for low or medium SNR, there are some deviations between the optimal value of the average SEP and the asymmetric one. The reason is that the asymmetric value is often relatively simple, predicting the trend of the average SEP in the high SNR region so that it eliminates many complicated mathematical expression. So there is a certain gap between the exact expression and the asymmetric one. This power allocation in the asymmetric case often sacrifices the average SEP level in the low and medium SNR regions. It is clear from the fact that the SEP maximum is equivalent to the corresponding SNR minimum due to the monotonicity of Gaussian $Q$ function. The original problem (3) is converted to a new one below

\[
\begin{align*}
\max_{\{p_1, p_2, p_3, p_3\}} & \quad \gamma_i \\
\text{s.t.} & \quad p_1 + p_2 + p_3 = P_T, p_i \geq 0, p_2 \geq 0, p_3 \geq 0 \\
& \quad \beta_i + \beta_j = 1, \beta_i \geq 0, \beta_j \geq 0 \\
& \quad \gamma_i = \tau\gamma_2 \\
\end{align*}
\]

3 SEP optimisation of three-phase protocol

This section deals with the SEP optimisation problem of the three-phase protocol. The optimisation problem has to be divided into two steps due to the complexity. The first step is to find the optimal powers of the two terminals $S_i$, $S_j$ and the relay $R$ at given the split factors $\beta_i$ and $\beta_j$. The second step is to conduct a one-dimensional search for the split factor at given power allocation.

3.1 Power allocation

The dual function of problem (4) is constructed by

\[
L = \gamma_1 + \lambda_1 (P_T - p_1 - p_2 - p_3) + \lambda_2 (\gamma_1 - \tau\gamma_2)
\]

where $\lambda_1$ and $\lambda_2$ are dual variables. Differentiating $L$ with respect to $p_1$, $p_2$, and $p_3$, respectively, we get

\[
\frac{\partial L}{\partial p_1} = \frac{\beta_1 p_1 a b [(p_1 b + \beta_1 p_1 b + c)(1 + \lambda_1)]}{(p_1 a + \beta_1 p_1 b + p_1 b + c)} + \frac{\beta_2 \beta_1 p_1 a b c (1 + \lambda_1)}{(p_1 a + \beta_1 p_1 b + p_1 b + c)} - \lambda_1 (6)
\]

\[
\frac{\partial L}{\partial p_2} = \frac{-\beta_1 p_2 a b (1 + \lambda_1)}{(p_1 a + \beta_1 p_1 b + p_1 b + c)} - \lambda_1 (7)
\]

\[
\frac{\partial L}{\partial p_3} = ab (p_1 a + \beta_1 p_1 b + c)
\]

\[
\times \frac{\beta_1 p_1 (1 + \lambda_1)}{(p_1 a + \beta_1 p_1 b + p_1 b + c)} - \frac{\beta_2 \lambda p_2}{(p_1 a + \beta_1 p_1 b + p_1 b + c)} - \lambda_1 (8)
\]

Setting (6)–(8) equal to zero yields two standard quadratic equations with one unknown variable with respect to $p_1$ and $p_2$

\[
p_1^2 + \alpha_1 p_1 + \alpha_0 = 0
\]

where

\[
\alpha_1 = 2\beta_1 \tau (\beta_1 a (b + \beta_1 a) + \beta_2 b (b - \beta_1 a) + \beta_2 b (b - \beta_1 a) + \beta_2 b (b - \beta_1 a))
\]

\[
+ \beta_2 \tau (c + b P_T) (\alpha_2 (1 + \beta_1 \tau) + \beta_2 \tau + \beta_1 + \tau)
\]

\[
- 2\beta_1 b (\beta_1 \tau + \beta_2 \tau + \beta_1 + \tau)
\]

\[
+ \beta_2 b (\tau + \beta_1 \tau)
\]

\[
\alpha_0 = \beta_2 \tau P_T (\beta_1 \tau (c + b P_T) + \beta_2 (b - \beta_1 a) + \beta_2 (b - \beta_1 a) + \beta_2 (b - \beta_1 a))
\]

\[
- \beta_2 a (c + b P_T) (\alpha_2 (1 + \beta_1 \tau) + \beta_2 \tau + \beta_1 + \tau)
\]

\[
- 2\beta_1 b (\beta_1 \tau + \beta_2 \tau + \beta_1 + \tau)
\]

\[
+ \beta_2 b (\tau + \beta_1 \tau)
\]

Thus, the power $p_1$ of the terminal $S_i$ has two solutions given by
\[ p_{1,1} = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T + c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) + \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T + c) (\beta a P_T + c) + \beta a P_T + b P_T + c)) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1)) \frac{1}{\beta + \beta \tau}) (\beta (a + \beta \tau) - \beta b (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

Similarly, the quadratic equation of one unknown variable with respect to \( p_2 \) is written by

\[ p_2^2 + b p_2 + b_2 = 0 \]

where

\[ b_2 = 2 \beta \beta \beta \beta (a P_T (\beta - \beta c) + c) - \beta \tau a (a \beta a P_T + \beta c + c) + \beta a (c + a P_T) (\beta a (\beta - \beta c) + c) + \beta a (a P_T + c) (a \beta a P_T + c) - \beta \tau a (\beta a P_T + c) \frac{1}{\beta + \beta \tau}) (\beta (a + \beta \tau) - \beta b (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

Thus, the power \( p_2 \) of the terminal \( S_2 \) has two solutions given by

\[ p_{2,1} = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T (\beta - \beta c) + c) + \beta a (a P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (a (\beta a (1 + \beta \tau) + \beta)) - \beta b (a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

\[ p_{2,2} = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T (\beta - \beta c) + c) + \beta a (a P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (a (\beta a (1 + \beta \tau) + \beta)) - \beta b (a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

Finally, the relay power \( p_1 \) is given by \( P_T - p_1 - p_2 \) when the powers of the terminals have been worked out. A closer observation reveals that there is an annoying problem here. There seem to be four possible optimal power allocations due to two different solutions for each power \( p_2 \) and \( p_2 \). However, intuitively, the optimal power allocation should be unique and there are no different possibilities. Substituting the four cases \( \{ p_1, p_2, P_T - p_1 - p_2 \}, \{ p_1, p_2, P_T - p_1 - p_2 \}, \{ p_2, p_2, P_T - p_2 - p_2 \}, \{ p_2, p_2, P_T - p_2 - p_2 \} \) into (4), we find that only two of them \( \{ p_1, p_2, P_T - p_1 - p_2 \}, \{ p_2, p_2, P_T - p_2 - p_2 \} \) satisfy the constraint \( \gamma = \tau \gamma \). However, the former cannot guarantee that all powers are greater than or equal to zero at the same time, while the latter can ensure this condition. In other words, when \( a > 0, b > 0, c > 0, \tau > 0, c > 0, \beta < 1 \) and \( P_T > 0 \), \( \{ p_1, p_2, P_T - p_1 - p_2 \} \) and \( \{ p_2, p_2, P_T - p_2 - p_2 \} \) are simplified to

\[ p_1^* = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T (c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

\[ p_2^* = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T (c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

Case III: The upper bound of the SNR in symmetric bidirectional relaying systems.

Under the assumption of a small noise component, the upper bound of the SNR can be used, i.e. \( c = 0 \). Thus, (13) and (18) are rewritten as

\[ p_1^* = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T (c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

\[ p_2^* = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T (c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

Case VI: Symmetric bidirectional relaying systems.

In the symmetric network, \( \tau = 1 \), (13) and (18) can be simplified to

\[ p_1^* = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T + c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

\[ p_2^* = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T + c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

Case II: The upper bound of the SNR.

Under the assumption of a small noise component, the upper bound of the SNR can be used, i.e. \( c = 0 \). Thus, (13) and (18) are rewritten as

\[ p_1^* = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T (c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]

\[ p_2^* = \beta \tau (\beta + \beta \tau) (\beta \tau (b P_T (c) (b - \beta a) + \beta a (b P_T (\beta - \beta c) - c) + \beta b (b \beta P_T + \beta c + c)) \times (b (\beta^2 \beta P_T + 1) - \beta a (\beta \tau + 1))^2 + 4 \beta \beta^2 \beta \tau a b \beta \]
$$p_i^* = \left[ \beta_i b P_i (\beta_i b - 2 b_1 \beta_i a + \beta_i b) - \beta_i P_i (2 \beta_i b a - (1 - \beta_i a) + 1) \right]$$

$$+ 4 \beta_i^2 b a$$

$$l_i = (\beta_i b - 1 - (1 - \beta_i a) + 1)$$

$$+ 4 \beta_i^2 b a$$

(23)

$$p_i^* = \left[ \beta_i a P_i (\beta_i b - 2 b_1 \beta_i a + \beta_i b) - \beta_i P_i (2 \beta_i b a - (1 - \beta_i a) + 1) \right]$$

$$+ 4 \beta_i^2 b a$$

(24)

3.2 Split factor optimisation

Given the optimal power allocation, only the split factor variable is left in the problem given by

$$\max y_1$$

$$\text{s.t. } 0 \leq \beta_i \leq 1,$$

$$y_1 = \tau y_2,$$

where $\beta_i = 1 - \beta_i$ has been applied in problem (25). As there is only one variable $\beta_i$ in problem (25), some prevailing one-dimensional searches can be used to solve problem (25), such as the golden section method and the Fibonacci method [16].

By now, the power variables of the two terminals and the relay and the splitting factors have been separately optimised. Finally, the complete SEP optimisation algorithm is summarised as follows.

Algorithm 1: The SEP optimisation of three-phase bidirectional AF relaying

1. Determine accuracy requirement $\xi$ and initialise $\beta_0^0 \in [0, 1]$.
2. Calculate the unique optimal power allocation $p_i^{(t)}$, $p_j^{(t)}$ and $p_k^{(t)}$ based on the given $\beta_0^0$ in (13) and (18) and update $t = t + 1$, where $t$ is the number of iteration.
3. Update $\beta_0^{t+1}$ according to the golden section method or the Fibonacci method. If $|\beta_0^t - \beta_0^{t+1}| < \xi$, stop the calculation and exit the iteration. Otherwise, return to step 2.

4 Simulation results

The simulation results are stated in this section to confirm our previous theoretical analysis. The channel gains are normalised to unity and the golden section search method is adopted due to its simplicity. We use quaternary quadrature amplitude modulation constellation in this system and other modulations can be employed in a similar way. All SEP results are averaged from 10,000 independent trials.

The impact of average SNR on the SEP is shown in Fig. 2, where the average SNR is defined as $P_t/N_0$. From Fig. 2, the case with $\tau = 1/5$ and the case with $\tau = 5$ behave almost identically due to the symmetry of the link $S_i \leftrightarrow R$ and the link $S_i \leftrightarrow R$. In fact, the effects of $\gamma_i = \gamma_2$ and $\gamma_2 = \gamma_1$ are the same because the objective function is a summation of the SEP of the two links. Meanwhile, there is always a SEP gap between the case with $\tau = 1$ and the case with $\tau = 1/5$ or $\tau = 5$. The reason is that when $\tau = 1$, the two links are balanced. From Fig. 2, the exact SEP curve is very close to its upper bound by observation of solid line $c = 1$ and dotted line $c = 0$. This means that the upper bound is very tight without much precision loss.

The effect of the relay position on the SEP is shown in Fig. 3, where the two terminals and the relay node are deployed in a straight line. $d_1$ and $d_2$ are the distances between $S_i$ and $R$ and between $S_i$ and $S_2$, respectively. The path loss exponent is set to three. Owing to the symmetry of the two links, in all cases, the SEP reaches the minimum when $d_1/d_2 = 0.5$ in the sense of the system balance. The relay node closer to either terminal is not the best option. So the relay prefers the midpoint from the perspective of SEP optimisation.

Finally, the impact of the traffic factor is illustrated in Fig. 4. It is observed that when $\tau$ changes from 0.1 to 1, the SEP continues to decrease. Conversely, when $\tau$ changes from 1 to 5, the SEP increases slowly. The SEP always reaches its minimum at $\tau = 1$ regardless of the total power $P_t$ supplied. This phenomenon further confirms that the balanced state of the two links guarantees the minimum SEP. Too much traffic factor on one link increases the asymmetry of the two links and leads to performance degradation.
5 Conclusion
The SEP minimisation problem has been investigated in three-phase bidirectional AF relaying protocol. Although each power has two different possibilities due to the existence of the quadratic equation of one unknown variable, the uniqueness of power allocation has been proved. Then the splitting factor is optimised by the golden section method or the Fibonacci method. Simulation results show that the balance state of the two links and the middle position of the relay can reduce the SEP. In future, we will expand the single antenna case into the multiple antennas scenario and integrate beamforming technology into our model. By using beamforming techniques, the transmission power is concentrated in a particular direction and the SEP is expected to be further reduced.

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