On the energy efficiency of MIMO cooperative relaying networks

HUANG Jing\textsuperscript{1,2} (✉), WANG Ying\textsuperscript{1,2}, WU Tong\textsuperscript{1}, YU Xin-min\textsuperscript{1}

1. Wireless Technology Innovation Institute, Beijing University of Posts and Telecommunications, Beijing 100876, China
2. Key Laboratory of Universal Wireless Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, China

Abstract

Cooperative relaying techniques can greatly improve the capacity of the multiple input and multiple output (MIMO) wireless system. The transmit power allocation (TPA) strategies for various relaying protocols have become very important for improving the energy efficiency. This article proposes novel TPA schemes in the MIMO cooperative relaying system. Two different scenarios are considered. One is the hybrid decode-and-forward (HDF) protocol in which the zero-forcing (ZF) process is operated on relays, and the other is the decode-and-forward (DF) protocol with relay node and antenna selection strategies. The simulation results indicate that the proposed schemes can bring about significant capacity gain by exploiting the nature of the relay link. Additionally, the proposed TPA scheme in the HDF system can achieve the same capacity as the equal TPA with fewer relay nodes used. Finally, the capacity gain with the proposed schemes increases when the distribution range of relay nodes expands.

Keywords: cooperative relaying, transmit power allocation, hybrid amplify-and-forward, zero-forcing

1 Introduction

Ubiquitous high-data rate coverage in large areas is envisioned to be supported in future wireless communication systems. To meet such requirements, diverse fundamental changes in transmission technologies and network architectures are developed. MIMO techniques are well studied to promise significant improvements in terms of spectral efficiency and link reliability. However, the application of such system often requires relatively more implementation complexity. For instance, the elements spacing needs to be large enough to ensure uncorrelated channels, and a large number of antennas should be equipped on wireless terminals, which is rather infeasible in future networks. Therefore, a novel network architecture known as the relaying technology or cooperation transmission is taken into consideration, for exploiting system resources through the cooperation of relay nodes [1]. The application of relays in the MIMO system can increase the cooperative diversity [2] and is also regarded as a rank-improvement strategy for the traditional point-to-point multi-antenna link [3]. Relay-enabled standards have already been considered in the IEEE 802 family and the WINNER project as well [4].

Various protocols have been developed to accommodate the relay-based wireless access network. Laneman and Wornell present DF protocols for increasing the network reliability in Ref. [5], whereas in Refs. [2,6], the performance of an amplify-and-forward (AF) protocol is studied. Ref. [7] discusses the outage capacity of the HDF protocol. Meanwhile, the corresponding TPA strategies for the above protocols are investigated in numerous works. Ref. [8] discusses the optimal TPA for the MIMO relaying system in the AF mode, where the single-antenna relay is assumed. In Ref. [9], the power assignment for the AF MIMO relaying with a single relay node is investigated. Ref. [10] studies the joint power allocation in the DF system where each node in the network is equipped with only a single antenna.

However, the above works only consider scenarios of single-antenna relays or single relay with multiple antennas. Besides, none of them involves the TPA schemes for the HDF system. To solve this problem, this article studies the energy efficiency in the MIMO cooperative relaying scenario where multiple relay nodes are used and each relay is equipped with multiple antennas. Both the HDF and DF protocols are involved and the research focuses on a spatial multiplexing system where streams of independent data are transmitted.
The remainder of the article is organized as follows: in Sect. 2, the MIMO cooperative relaying system model with corresponding transmission mechanism is described. Sect. 3 proposes the transmit power allocation schemes in the HDF and DF systems. The simulation results and analysis are presented in Sect. 4. Finally, conclusions are drawn in Sect. 5.

2 System model

This article focuses on a two-hop relaying network, which consists of a single source and a single destination node with \( M \) antennas and \( K \) relay nodes each carrying \( N \) antennas, as shown in Fig. 1.

![Two-hop MIMO cooperative relaying network](image)

The \( K \) relay nodes are assumed to be randomly distributed in the middle region between the source and the destination. The direct link between the source and the destination node is ignored, which means that the destination node relies only on the signals from the relays.

In this model, a symmetric network is considered. A half-duplex constraint is imposed on the relay nodes; thus, the two hops are implemented in two separate slots, respectively (i.e., in the first slot, the relays receive the broadcast signals from the source and then forward them to the destination in the second slot). The channels between all the nodes are assumed to be stochastic, independent, frequency-flat, and constant for the signaling duration. Besides, a power constraint is imposed on both the source and relays, and it is also assumed that \( N = M \) throughout this article for simplicity.

According to the system model, the source broadcasts an \( M \times 1 \) data vector \( s \) to all relays in the first slot, and the \( M \times 1 \) received data vector \( y_i \) at the \( k \)th relay can be expressed as

\[
y_i = \sqrt{\alpha_k} H_k s + n_i = \tilde{H}_k s + n_i
\]

where \( H_k \) is an \( M \times M \) channel matrix between the source and the \( k \)th relay, with each entry set as an identically independent distributed (i.i.d.) complex Gaussian random variable with unit variance. The total transmit power \( P_s \) is equally distributed among the \( M \) antennas on the source and the covariance matrix of \( s \) is \( (P_s/M)I_M \). \( n_i \) is an \( M \times 1 \) zero-mean mutually independent, circularly symmetric, complex Gaussian random vector at the \( k \)th relay with covariance matrix \( \sigma_{\alpha_k} I_M \), where \( I_M \) is the \( M \times M \) identity matrix. Throughout this article, we assume that \( \sigma_{\alpha_k}(k=1, 2, \ldots, K) = \sigma_\alpha \) for simplicity.

Factor \( \alpha_k \) captures the large-scale pathloss between the source and the \( k \)th relay. According to the transmission model in the system, this large-scale pathloss factor can be written as

\[
\alpha_k = \left( \frac{4 \pi \lambda}{d_0} \right)^2 \left( \frac{d_0}{d_{k-w}} \right)^\gamma 10^{6/10}
\]

where \( \lambda \) represents the wavelength of the carrier, and \( d_0 \) is the reference distance that is assumed to be 1 m in this model. The scalar \( \eta \) denotes the pathloss exponent and is set to be 4. The shadowing fading coefficient \( \zeta_k \) is a zero-mean lognormal random variable with standard deviation \( \delta \), and \( \delta = 8 \text{ dB} \) is used in urban cellular environments. The distance parameter \( d_{k-w} \) denotes the distance between the source and the \( k \)th relay.

In the second slot, the \( k \)th relay processes the received data vector and forwards the corresponding transmit vector \( x_k \) to the destination. The signal vector received at the destination, as well as the total power constraint at the relays are expressed as

\[
r = \sum_{k=1}^K \sqrt{\beta_k} A_k x_k + z = \sum_{k=1}^K A_k x_k + z
\]

\[
\sum_{k=1}^K E[x_k^H x_k] = P_{EN}
\]

where \( A_k \) is an \( M \times M \) channel matrix between the \( k \)th relay and the destination, with each entry set as an i.i.d. complex Gaussian random variable with unit variance. \( z \) is an \( M \times 1 \) zero-mean mutually independent, circularly symmetric, complex Gaussian random vector at the destination with covariance matrix \( \sigma_z I_M \). \( E(\cdot) \) denotes the expectation, and \( (\cdot)^H \) is the conjugate transpose. \( P_{EN} \) denotes the total transmit power on all the relays. Analogous to \( \alpha_k \), the factor of \( \beta_k \) captures the large-scale pathloss from the \( k \)th relay to the destination and is given by

\[
\beta_k = \left( \frac{4 \pi \lambda}{d_0} \right)^2 \left( \frac{d_0}{d_{k-w}} \right)^\gamma 10^{6/10}
\]

where \( d_{k-w} \) is the distances between the \( k \)th relay and the destination.

3 Power allocation for relaying

Efficient power allocation strategies can further improve the benefits brought by cooperative relays and increase the efficiency of the system.
system capacity with the same amount of transmission power. Based on the criterion of maximum channel capacity, the power assignment strategies in the MIMO relaying network with HDF and DF protocols are discussed in this section. The transmit power is assumed to be equally distributed to the antennas on the source node. Furthermore, the channel state information (CSI) is assumed to be available to transmitters of both the first hop (source) and the second hop (relay) by using training sequence periodically.

3.1 Power allocation on HDF relaying

In the hybrid decode-and-forward relaying scheme, relays only filter the received signals without decoding them. The filtering matrix on the kth relay $W_k$ may comprise the first hop CSI obtained from the training sequence of the received signals, as well as the second hop CSI fed back from the training sequence periodically. The received signal vector at the destination can be written as $y = W_k y_k$. This article focuses on the ZF based HDF, where the kth relay first separates the multiple data streams from the source with the pseudoinverse of $\hat{H}_k$ (denoted by $\hat{H}_k^+$) and then implements the transmitted ZF with $\hat{A}_i$. Hence, the weight matrix to be multiplied by the received signal vector $y_k$ can be written as $W_k = \rho_k \hat{A}_i \hat{H}_k^+$, where $\rho_k$ is the power coefficient, which helps implement the power allocation on the kth relay. From Eqs. (3) and (6), the received signal vector at the destination can be written as

$$ r = \sum_{k=1}^{K} \rho_k s + \sum_{k=1}^{K} \rho_k \hat{H}_k n_k + z $$

According to Eq. (7), the signal to noise ratio (SNR) of the nth data steam at the destination is

$$ \Gamma_n = \frac{P}{\sigma^2 \sum_{k=1}^{K} \rho_k + \sigma_d^2}; \quad m=1,2,...,M $$

where $(\cdot)_m$ denotes the mth row of the matrix, and $\|\|$ stands for the Frobenius-norm. Consequently, the capacity with such scheme is

$$ C = \frac{1}{2} \sum_{m=1}^{M} \log_2 (1 + \Gamma_m) $$

where the constant 1/2 denotes the half channel resource occupied by the relay link compared with the traditional direct link.

Therefore, taking the capacity as the optimization criterion, the optimization issue can be determined from Eqs. (4), (8), and (9) as

$$ \max \quad \frac{1}{2} \sum_{m=1}^{M} \log_2 \left( 1 + \frac{P}{\sigma^2 \sum_{k=1}^{K} \rho_k + \sigma_d^2} \right) $$

s.t. $\sum_{k=1}^{K} \rho_k \| \hat{H}_k \|_F^2 + \sigma_d^2 \| \hat{H}_k \|_F^2 = P_{RN}$

where the power allocation among relay nodes depends on the factor of $\rho_k$.

The Lagrange cost function can be written as

$$ L(\rho, \lambda) = \frac{1}{2} \sum_{m=1}^{M} \log_2 \left( 1 + \frac{P}{\sigma^2 \sum_{k=1}^{K} \rho_k + \sigma_d^2} \right) $$

$$ + \lambda \left( \sum_{k=1}^{K} \rho_k \| \hat{H}_k \|_F^2 + \sigma_d^2 \| \hat{H}_k \|_F^2 - P_{RN} \right) $$

where the power coefficient vector is denoted by $\rho = [\rho_1, \rho_2, ..., \rho_K]$ and $\lambda$ is the Lagrange parameter. Upon setting the derivatives of $L(\rho, \lambda)$ with respect to $\rho_i (i=1,2,...,K)$ to zero, the result is given by:

$$ \frac{1}{2} \sum_{m=1}^{M} \left( 1 + \frac{P}{\sigma^2 \sum_{k=1}^{K} \rho_k + \sigma_d^2} \right) \left( \sum_{k=1}^{K} \rho_k \| \hat{H}_k \|_F^2 + \sigma_d^2 \| \hat{H}_k \|_F^2 \right)^{-1} \left( \sum_{k=1}^{K} \rho_k \hat{H}_k n_k + z \right) $$

$$ \frac{1}{2} \rho \sum_{k=1}^{K} \rho_k \| \hat{H}_k \|_F^2 + \sigma_d^2 \| \hat{H}_k \|_F^2 $$

$$ + 2\lambda \rho \| \hat{H}_k \|_F^2 $$

$$ - 2 \lambda \rho \| \hat{H}_k \|_F^2 = 0 $$

Without loss of generality, $\sigma$ and $\sigma_d$ are both assumed to equal 1. Utilizing some further manipulations, Eq. (11) can be rewritten as

$$ \frac{1}{2} \sum_{m=1}^{M} \left( 1 + \frac{P}{\sigma^2 \sum_{k=1}^{K} \rho_k + \sigma_d^2} \right) \left( \sum_{k=1}^{K} \rho_k \| \hat{H}_k \|_F^2 + \sigma_d^2 \| \hat{H}_k \|_F^2 \right)^{-1} \left( \sum_{k=1}^{K} \rho_k \hat{H}_k n_k + z \right) $$

$$ + 2\lambda \rho \| \hat{H}_k \|_F^2 = 0 $$

where

$$ q_m = \left( \sum_{k=1}^{K} \rho_k \| \hat{H}_k \|_F^2 \right)^{-1} + \gamma $$
The form of the solution in Eq. (13) makes it suitable to be solved by the successive approximation method [11] in which a few iterations are enough to reach an accuracy of $10^{-3}$ in power assignment by beginning with an initial solution vector $\mathbf{\hat{P}}^*$. In this case, the solution by the equal TPA scheme is set as the initial vector of the iteration.

3.2 Power allocation on DF relaying

Power allocation for the DF protocol is studied in this subsection. Since signals are decoded on the relay before they are forwarded to the destination, the channel capacity depends on the inferior hop of the relaying link with the DF protocol [5]. The relay and antenna selection algorithm developed in Ref. [7] is adopted. In such scheme, the source chooses the best relay for each data stream in the first hop and then forwards the signals with the best antenna on the corresponding relay node.

In the first hop, assume that the SNR of the $m$th data stream decoded by the $k$th relay is $\Gamma_{m,k-r}$. Then, the SNR of the $m$th data stream and the selected relay node can be determined as $\Gamma_{m,r} = \max_k \{ \Gamma_{m,k-r} \}$, $R_m = \arg \max_k \{ \Gamma_{m,k-r} \}$

Thus, the capacity of the $m$th channel in the first hop is $C_{m,a-d} = \frac{1}{2} \log_2 \left( 1 + \Gamma_{m,a-d} \right)$

Here, the best-select-one [10] relay selection scheme is implemented in the first hop for the following two reasons:

1) The selection combining (SC) relaying is an excellent candidate in terms of performance-complexity tradeoff [12]. Besides, the switch-and-stay combining (SSC) can be used in it for a quasistatic fading channel.

2) Since the channel capacity in the DF relaying depends on the inferior link of the two hops, the research can focus on the power allocation problem of the second hop (i.e., the power assignment among relays) with this scheme applied.

For the $m$th data stream in the second hop, the antenna that has the maximum column norm is chosen from the corresponding channel matrix $A_{m,a}$, and the antenna is denoted by $L_m$. The number of selected antennas equals $M$ when all data streams have been assigned proper transmitting antennas in the second slot. Therefore, the received signal vector in Eq. (3) should be rewritten as

$$r = ABx + z = Ax + z$$

where $B = \text{diag}(\sqrt{\beta_{m1}}, \sqrt{\beta_{m2}}, ..., \sqrt{\beta_{mM}})$ and $A$ is an $M \times M$ channel matrix between the $M$ antennas selected from the relays and the $M$ antennas at the destination. $\beta_{m1}$ is the large-scale pathloss factor between relay $R_m$ and the destination. $x$ is the encoded signal vector to be transmitted from selected antennas.

Analogous to the transmission in the first hop, assume that the SNR of the $m$th data stream to the destination is $\Gamma_{m,a-d}$ and $P_m$ is the power allocated to $L_m$. Then, the capacity of the $m$th channel in the second hop is $C_{m,a-d} = \frac{1}{2} \log_2 \left( 1 + \Gamma_{m,a-d} \right)$ and the capacity of the $M \times M$ spatial multiplexing relaying link can be written as

$$C = \sum_{m=1}^{M} C_m$$

where the capacity of each transmitted signal $s_m$ through the two hops is $C_m = \min \{C_{m,a-w}, C_{m,a-d} \}$.

Since the channel capacity in such MIMO relaying system depends on the channel quality of both the two hop links instead of a single hop link, the traditional water filling algorithm (WFA) may lead to a waste of transmit power and degradation of system throughput (e.g. when the channel quality of the first hop is far worse than that of the second hop, the large amount of power assigned to the relay only makes minor contribution to the whole relay link). Therefore, a novel WFA-based TPA scheme for the DF MIMO relaying system is proposed. This scheme is implemented primarily by two stages. In stage one, allocate the transmit power of relays through water filling algorithm according to the CSIs feedback by the destination; in stage two, adjust the allocated power to maximize the system capacity by taking into account the integrated CSIs of both the two hops.

Assume that $P_m^0$ denotes the initial allocation power calculated by the WFA, and $P_m^*$ represents the maximum efficient power, which can be allotted to the $m$th stream without any waste of energy (i.e., to ensure $\Gamma_{m,a-d} = \Gamma_{m,a-w}$).

The detailed steps are described as follows:

1) Calc. $P_m^0$ for each data stream according to the WFA.

2) Initialize stream set $\mathcal{Q}$ and $\Phi$

   s.t. $\forall m \in \mathcal{Q}$, $P_m^0 \geq P_m^*$,

   $\forall m \in \Phi$, $P_m^0 < P_m^*$

3) For $m \in \mathcal{Q}$

   set $P_m = P_m^*$,

   calc. the residual power $P_m = \sum_{\forall m \in \mathcal{Q}} (P_m^0 - P_m)$.

4) Sort $\Phi$ in ascending order of $P_m^0$.

5) For $m \in \Phi$

   allot $P_m$ to $m$, until $P_m = 0$ or $P_m^* = P_m^*$. 

Here, $\Phi$ is sorted in ascending order of $P_m^0$ in step 4 for
the reason that the spatial subchannel with lower $P_m^p$ has lower SNR according to the nature of the WFA and the channel with worse SNR is power-limited; thus, allocating energy resource to such channel is more power efficient.

4 Simulation results

The 10% outage capacities of different schemes studied in this article is evaluated in frequency flat fading environment. In this simulation model, a total power constraint is imposed on the relay nodes, and the power resource is allocated among these nodes according to the proposed schemes. Note that for the AF scenario, equal power allocation is implemented as the first step of iterations, whereas the conventional water filling algorithm is the initialization of power assignment in the DF case. The source, relay nodes, and destination are all equipped with multiple antennas. The fading distributions between the tripartite (source to relays and relays to destination) are identical. The distance between the source and destination is assumed to be 1 km. The transmit power constraints of the source and relays are the same, i.e., $P_s = P_{kn}$. The AF relaying scheme with equal power allocation is also simulated for performance comparison.

Fig. 2 illustrates the 10% outage capacity in the AF, HDF, and DF systems with different TPA schemes. Six relay nodes are used in this figure. It can be observed that the capacity of the DF system is higher than that of the HDF system in the whole range of the various SNR, and the two proposed TPA schemes outperform the equal TPA scheme in either of these two relaying protocols. Additionally, when SNR is less than 9 dB, the capacity of the HDF is slightly inferior to that of the AF approach and the performance gain between the proposed scheme and the equal TPA scheme is not obvious. This is because the ZF operation in the HDF reduces the receive array gain because of the nulling of multiple data stream at relays and amplifies the noise at the same time when SNR is low.

The capacity behavior versus the number of relay nodes when SNR equals 9 dB is shown in Fig. 3. The capacity of the HDF increases with the growth of relay number by obtaining the received array gain and distributed array gain when signals are coherently combined at receivers. It is found that the capacity gain between the two power allocation schemes reaches around 5%. On the other hand, capacity of the AF scheme tends to saturate when the number of relay nodes increases since the simple amplify-and-forward operation at relays could hardly obtain any diversity gain from the relaying transmission. From this figure, it can also be observed that the capacity of the HDF with the equal TPA surpasses that of the AF when more than six relays are used, whereas the proposed scheme only needs five relays, which means that similar performance can be achieved when fewer relay nodes are equipped by utilizing the proposed TPA scheme.

Fig. 3 Outage capacity with $M = 4$, SNR = 9 dB

Figs. 4 and 5 show the capacity performance under different relay distribution configurations when SNR equals 9 dB. The relays are assumed to locate around the middle point of the source and destination node, and the distribution range is defined as the largest horizontal distance among all the relay nodes and is normalized by the distance between the source and the destination. Seen from these two figures, the performance gain of the proposed TPA rises when the relay distribution range expands. The reason is that the proposed TPA schemes can improve the performance by utilizing the link quality fluctuation among different streams when relays are widely located. In Fig. 4, the capacity achieves the peak point when normalized relay distribution range is around 0.6. This is because the HDF protocol only filters the receiving
signals instead of decoding them, thus the capacity degrades when some relays are quite far from the source. Contrarily, in Fig. 5, the capacity decreases with the increase of relay distribution range in the DF for the reason that the channel capacity depends on the inferior hop of the two links with the DF protocol and the widely located relays introduce the imbalance of relay links.

Acknowledgements

This work was supported by Ericsson Company, the National Natural Science Foundation of China (60496312), the Hi-Tech Research and Development Programm of China (2006AA01Z260).

References


5 Conclusions

This article has proposed the novel transmit power allocation schemes based on the criterion of maximum channel capacity, for different MIMO cooperative relaying protocols in which all terminals are equipped with multiple antennas and a power constraint is imposed on the source and relays. From the evaluation on outage capacities of different TPA schemes, it can be concluded that an average capacity gain of 5% is achieved when the proposed TPA algorithms are used in both HDF and DF systems. For the HDF system particularly, the proposed TPA scheme can provide the same capacity as the equal TPA with fewer relay nodes used, which means that the cost of relays in the network can be saved. Furthermore, the performance gain of the proposed TPA schemes increases with the increase of the relay distribution range.