Energy Consumption in Downlink MIMO Relay Systems with Multiple Users

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Abstract—This paper focuses on the energy consumption problem in the downlink MIMO relay systems with multiple users. Power consumption under the target sum capacity is used as the energy efficient performance metric. Three transmission schemes, i.e. regenerate decode-and-forward (DF) relaying, linear non-regenerate relaying (SVD-ZFBF) and direct transmission with ZFBF are considered. The power model is developed at first, in which the power amplifier (PA) power, transmit circuit power at the base station (BS) and relay station (RS) and the receive circuit power at RS are taken into consideration. Then the power consumption expression for each scheme is derived. In order to optimize the power consumption, optimal rate allocation among different users is proposed and the energy efficient time allocation between the first and second phase for regenerate relaying is discussed. Simulation results show that optimal rate allocation can improve the energy efficiency significantly. Optimal time resource allocation of the DF scheme can further decrease the power consumption and it is the most promising scheme with the highest complexity. Furthermore, direct transmission benefits in the short distance scenario while relaying transmission benefits in the long distance scenario. Finally, the performance under different target sum capacity is discussed.

Index Terms—Energy Consumption, MIMO, Relay, Multiple Users.

I. INTRODUCTION

As global warming has been acknowledged these days, reducing the energy usage and CO₂ emissions has attracted a lot of attentions recently [1]–[4]. As shown in [3], mobile radio networks account for about 0.5% of the global electric energy consumption and over 80% of the power in telecommunications, more specifically in the base station (BS). In order to decrease the energy consumption, energy efficient architecture deployments need to make the access point closer to the users [3], [4]. Deploying relays is an efficient way to improve energy efficiency [7]. Meanwhile, MIMO technology has been the key technology in the future wireless communication systems and multi-user (MU) MIMO relaying is a promising technology to improve the spectral efficiency [8]. However, there are few works discussing the energy efficiency problem. We will consider the downlink MIMO relay systems with multiple users from energy efficiency point of view.

Relays are mainly divided into two types, i.e. the regenerate relay also called decode-and-forward (DF) relay and the nonregenerate relay. Compared with the regenerate relay, the nonregenerate relay needs higher transmit power to get the same spectral efficiency due to the noise interference amplification at relay side [8], [9]. The energy tradeoff here is an interesting problem.

There are two main options to evaluate the energy efficiency of wireless communication systems [7]: compare the performance with constant energy consumption or compare the energy consumption with constant performance measure. The later one is applied in this paper. Ericsson and Huawei reported that most energy in consumed during the ‘use phase’ or ‘operation period’ [5], [6], so considering the energy consumed during transmission period is important. The power consumption under a target sum capacity is used as the performance metric in this paper.

For the MU-MIMO, dirty paper coding (DPC) is the capacity optimal scheme [10], but it is too complex to implement. Linear processing is promising in the practical systems and is considered in this paper. Zero-forcing beamforming (ZFBF) [11] is considered as the precoding scheme in the direct transmission and the second phase of regenerate relaying. In the first phase of DF transmission, it is a point to point MIMO transmission for which the singular value decomposition (SVD) with waterfilling is the capacity optimal scheme [12], so SVD is applied here. For the nonregenerate relaying, our previous proposed SVD-ZFBF scheme [9] would be considered.

The main contributions can be summarized as follows.

1) A more general power model for the MIMO relay systems is developed, in which the power amplifier (PA) power, circuit power at the transmitter including base station (BS) and relay station (RS) and the receive circuit power at RS are taken into consideration.

2) The power consumption expressions for different schemes are derived under the target sum capacity constraint. Optimal rate allocation among different users is proposed and the energy efficient time allocation between the first and second phase for regenerate relaying
is discussed.

3) Through simulations, we show that optimal rate allocation can improve the energy efficiency significantly. Optimal time resource allocation of the DF scheme can further decrease the power consumption and it is the most promising scheme with the highest complexity. Furthermore, Direct transmission benefits in the short distance scenario while relaying transmission benefits in the long distance scenario. Finally, the effect of target sum capacity is also discussed.

The rest of the paper is organized as follows. Section II introduces the system model and develop the energy model of MIMO relay systems. Section III introduces different transmission schemes. In section IV, power consumption of different schemes with the target sum capacity is derived and optimal rate allocation is proposed. In section V, we show the simulation results. Finally, we conclude this paper in VI.

Regarding the notation, bold face letters refer to vectors (lower case) or matrices (upper case). Notation $E(A)$ and $Tr(A)$ denote the expectation and trace operation of matrix $A$, respectively. The superscript $H$ and $T$ represent the conjugate transpose and transpose operation, respectively.

II. SYSTEM AND ENERGY MODEL

The downlink MIMO relay systems with multiple users are considered here. As depicted in Fig. 1, there are a single BS deployed with $M_B$ antennas, a single relay station (RS) deployed with $M_R$ antennas and $K$ users each with $M_U$ antennas. We assume that $M_U = 1$ and $M_B \geq M_R \geq K$ here.

For the MIMO relaying transmission, the direct link from BS to users is omitted [8], [9]. The transmission is divided into two phases. In the first phase, the BS transmits to the RS. The received signal at RS can be denoted as

$$r = HF{s} + n_R, \quad (2)$$

in which $n_R \in \mathbb{C}^{N_R \times 1}$ is the noise at the RS. The variance of each element of $n_R$ can be denoted as $\sigma_R^2$. Then in the second phase, the RS transmit to the users, the received signal at the users are denoted as

$$y = Gt + n_U, \quad (3)$$

in which $t$ is the transmit data of the RS. For the regenerate case, $t = s$ after the RS decodes the data. And for the nonregenerate case, we have $t = W(HF{s} + n_R)$. The detail of the processing matrices design will be introduced in the next section.

About the energy consumption, the following model is applied. Only RF related power is considered [13] and the baseband processing related power is omitted.

The power model of a MIMO transceiver is introduced in [13]. We would use the same model for the transmitter of BS and the transceiver of RS during the transmission period. As in the relaying transmission, the BS would be silent in the second phase. We introduce the idling power [14] for this phase.

The channel from the BS to the RS is denoted as $H \in \mathbb{C}^{M_R \times M_B}$ and the channel from the RS to users is denoted as $G = [g_1^T, \ldots, g_K^T]^T \in \mathbb{C}^{K \times M_R}$, in which $g_i \in \mathbb{C}^{1 \times M_R}$ is the channel matrix from the RS to the $i$th user. The direct channel from BS to users is $H_{BU} = [h_{BU,1}^T, \ldots, h_{BU,K}^T]^T \in \mathbb{C}^{K \times M_B}$, in which $h_{BU,i} \in \mathbb{C}^{1 \times M_B}$ is the channel matrix from the RS to the $i$th user. And the precoding matrix at BS and processing matrices are denoted as $F$ and $W$, respectively.

Linear processing is considered in this paper. For the direct transmission, the received single at users can be denoted as

$$y = H_{BU}Fs + n_U, \quad (1)$$

in which $s$ is the desired signal and $n_U \in \mathbb{C}^{K \times 1}$. The variance of each element of $n_U$ can be denoted as $\sigma_U^2$.

The transmitted and receiver structure can be denoted as Fig. 2 and Fig. 3. The total power consumed during RF transmission is divided into two parts. The first part is PA power which is related to the radiation power. The second part is circuit power including digital-to-analog converter power $P_{DAC}$, mixer power $P_{Mix}$, filter power $P_{Filter}$ and frequency synthesizer power $P_{syn}$, i.e., local oscillator (LO). And during the receiving, the power consumed includes low noise amplifier (LNA) power $P_{LNA}$, $P_{Mix}$, intermediate frequency
amplifier (IFA) power $P_{\text{IFA}}$, $P_{\text{Filter}}$, analog-to-digital converter (ADC) power $P_{\text{ADC}}$ and $P_{\text{syn}}$. $\eta$ denotes the efficiency of the RF chains. Except PA power, other parts are called circuit power [13] totally. We use $P_{\text{BS,DC}}$ to denote the circuit power consumed for BS transmitting and $P_{\text{BS,rec}}$ to denote the circuit power consumed for RS receiving. Therefore, the power consumed when BS is transmitting can be denoted as

$$P_{\text{BS,trans}} = P_{\text{BS,PA}} + P_{\text{BS,DC}};$$

$$P_{\text{BS,PA}} = \frac{P_{\text{BS}}}{\eta};$$

$$P_{\text{BS,DC}} = M_B(P_{\text{DAC}} + P_{\text{Mix}} + P_{\text{Filter}}) + P_{\text{sync}}.$$  \hfill (4)

When the BS is transmitting, the RS is receiving. So the power consumed for RS receiving is denoted as

$$P_{\text{RS,rec}} = M_R(P_{\text{LNA}} + P_{\text{Mix}} + P_{\text{FA}} + P_{\text{Filter}} + P_{\text{ADC}}) + P_{\text{sync}}.$$  \hfill (5)

When the RS is transmitting, a similar model is used.

$$P_{\text{RS,trans}} = P_{\text{RS,PA}} + P_{\text{RS,DC}};$$

$$P_{\text{RS,PA}} = \frac{P_{\text{RS}}}{\eta};$$

$$P_{\text{RS,DC}} = M_R(P_{\text{DAC}} + P_{\text{Mix}} + P_{\text{Filter}}) + P_{\text{sync}}.$$  \hfill (6)

$P_{\text{BS,idle}}$ denotes the power consumed when the BS is scient in the second phase.

Therefore, the power consumed for different transmission schemes can be denoted as follows. When direct MU-MIMO with ZFBF is applied,

$$P_{\text{ZFBF}} = P_{\text{BS,trans}}.$$  \hfill (7)

For regenerate relaying, if the length of the first phase is $t$, the second is $1-t$, then

$$P_{\text{regenerate}} = tP_{\text{BS,trans}} + tP_{\text{RS,rec}} + (1-t)P_{\text{RS,trans}} + (1-t)P_{\text{BS,idle}}.$$  \hfill (8)

For nonregenerate relaying with SVD-ZFBF, we have $t = \frac{1}{2}$, and then

$$P_{\text{SVD-ZFBF}} = \frac{1}{2}(P_{\text{BS,trans}} + P_{\text{RS,rec}} + P_{\text{RS,trans}} + P_{\text{BS,idle}}).$$  \hfill (9)

### III. TRANSMISSION SCHEMES

We will shortly review the transmission schemes in this section and give the achievable capacity for each scheme.

#### A. MU-MIMO with ZFBF

For ZFBF, the precoding matrix at the BS can be denoted as [11]

$$\mathbf{F} = \mathbf{H}_{\text{BU}}^H(\mathbf{H}_{\text{BU}}\mathbf{H}_{\text{BU}}^H)^{-1}.$$  \hfill (10)

And then the achievable capacity can be denoted as

$$C_{\text{ZFBF}} = \sum_{k=1}^{K} C_{\text{ZFBF},k} = \sum_{k=1}^{K} \log(1 + \frac{P_{\text{BS},k}\xi_k}{\sigma_k^2});$$  \hfill (11)

in which $C_{\text{ZFBF},k} = \log(1 + \frac{P_{\text{BS},k}\xi_k}{\sigma_k^2})$ is the achievable capacity for user $k$ and $\xi_k = \frac{(\mathbf{H}_{\text{BU}}\mathbf{H}_{\text{BU}}^H)^{-1}H_{BU,k}}{\sigma_k^2}$ is the equivalent channel gain for user $k$. $P_{\text{BS},k}$ is the transmit power for each data stream and we have that $P_{\text{BS}} = \sum_{k=1}^{K} P_{\text{BS},k}$.

#### B. Regenerate MIMO Relaying

The first phase of the regenerate relaying is a point to point MIMO channel. Through SVD the channel can be decomposed into several parallel SISO channels as [12]

$$\mathbf{H} = \mathbf{U}\Lambda\mathbf{V}^H,$$

in which $\mathbf{A} = \text{diag}(\Lambda_1, \ldots, \Lambda_M)$. And then the capacity can be denoted as

$$C_{\text{regen},1} = \sum_{k=1}^{M_k} \log(1 + \frac{P_{\text{BS},k}^2\xi_k}{\sigma_k^2}).$$  \hfill (12)

For the second phase, it is a MU-MIMO transmission from RS to users. ZFBF is applied here and

$$\mathbf{W} = \mathbf{G}^H(\mathbf{G}\mathbf{G}^H)^{-1}.$$

Then the capacity of the second phase can be denoted as

$$C_{\text{regen},2} = \sum_{k=1}^{K} \log(1 + \frac{P_{\text{RS},k}\gamma_k}{\sigma_k^2});$$  \hfill (13)

in which $\gamma_k = \frac{1}{(\mathbf{G}\mathbf{G}^H)^{-1}H_{BU,k}}$ and $P_{\text{RS}} = \sum_{k=1}^{K} P_{\text{RS},k}$. And $C_{\text{regen},2,k} = \log(1 + \frac{P_{\text{RS},k}\gamma_k}{\sigma_k^2})$ is the capacity of the $k$th user for the second phase. Finally, the achievable capacity of the regenerate MIMO relaying can be denoted as

$$C_{\text{regen}} = \min(tC_{\text{regen},1}, (1-t)C_{\text{regen},2}), t \in [0, 1].$$  \hfill (14)

#### C. Nonregenerate MIMO Relaying with SVD-ZFBF

The SVD-ZFBF is proposed by us in [9] and it is proved to be a asymptotic optimal scheme. We will only introduce the processing matrix design and the achievable capacity here.

It is designed as

$$\mathbf{F} = \mathbf{U}^H,$$

$$\mathbf{W} = \mathbf{V}\mathbf{G}^H(\mathbf{G}\mathbf{G}^H)^{-1}.$$  \hfill (15)

The achievable capacity is

$$C_{\text{SVD-ZFBF}} = \frac{1}{2} \sum_{k=1}^{K} \log \left(1 + \left(\frac{Q_k\gamma_k}{\sigma_k^2}\right)\Lambda_k^2P_{\text{BS},k}\right),$$  \hfill (16)

in which

$$Q_k = \frac{P_{\text{BS},k}}{\sigma_k^2 + \Lambda_k^2P_{\text{BS},k}}.$$  \hfill (17)

And

$$C_{\text{SVD-ZFBF},k} = \frac{1}{2} \log \left(1 + \left(\frac{Q_k\gamma_k}{\sigma_k^2 + Q_k\gamma_k\sigma_k^2}\right)\Lambda_k^2P_{\text{BS},k}\right)$$  \hfill (18)
IV. POWER CONSUMPTION WITH CONSTANT TARGET SUM CAPACITY

In this section, we will derive the power consumption under the target sum capacity \( C_T \) for different transmission schemes. Assume that the capacity of the \( k \)th user is \( C_k \) and then the constraint can be denoted as \( \sum_{k=1}^{K} C_k \geq C_T \).

The minimum power consumption problem can be denoted as
\[
\min P_{\text{total}} \quad \text{s.t.} \quad \sum_{k=1}^{K} C_k \geq C_T.
\] (17)

Here \( P_{\text{total}} \) denotes the total energy consumption for each transmission scheme which can be \( P_{ZFBF} \) in (7), \( P_{\text{regenerate}} \) in (8) or \( P_{SVD-ZFBF} \) in (9). Therefore, solving the minimization problem is to find the optimal rate allocation \( C_k \). For the two relaying schemes, the optimization is solved at the BS side and the channel state information from the RS to users is needed. We assume that the BS can gather all the needed information and omit the cost of getting these information.

A. MU-MIMO with ZFBF

In order to get the optimal power consumption of ZFBF, the transmit power of ZFBF need to be derived at first, here \( C_{ZFBF,k} = C_k \). From (10), we have
\[
P_{\text{BS,k}} = \frac{\sigma_k^2 (2^{C_k} - 1)}{\xi_k}.
\] (18)

And from (4)(7) and (15), minimizing \( P_{ZFBF} \) is minimizing \( P_{\text{BS}} \), the optimization problem can be changed as
\[
\min P_{\text{BS}} = \sum_{k=1}^{K} \frac{\sigma_k^2 (2^{C_k} - 1)}{\xi_k} \quad \text{s.t.} \quad \sum_{k=1}^{K} C_k \geq C_T.
\] (19)

After some calculation through Lagrange multiplier method, we have the optimal rate allocation is
\[
C_{ZFBF,k} = (\mu + \log_2 \xi_k)^+,
\] (20)

in which \( (x)^+ = \max(x, 0) \) and \( \mu \) should satisfy that \( \sum_{k=1}^{K} (\mu + \log_2 \xi_k)^+ = C_T \). Then the power consumption for ZFBF with MU-MIMO can be denoted as
\[
P_{ZFBF} = \sum_{k=1}^{K} \frac{\sigma_k^2 (2^{C_{ZFBF,k}} - 1)}{\eta_k} + M_B (P_{DAC} + P_{Mix} + P_{Filter}) + P_{\text{syn}}.
\] (21)

B. Regenerate MIMO Relaying

From (13), under the target sum capacity constraint, we can have
\[
C_{\text{regge},1} \geq \frac{C_T}{K}, \quad C_{\text{regge},2} \geq \frac{C_T}{2K}.
\] (22)

We denote the capacity for each data stream in phase one as \( C_{\text{regge},1,k}, k = 1, \ldots, M_R \) and the capacity of each user in phase two as \( C_{\text{regge},2,k}, k = 1, \ldots, K \) which is also the end to end capacity from BS to the dedicated user. According to (11) and (12), the transmit power for each data stream in phase one and for each user in phase two can be denoted as \( P_{\text{BS},k} = \frac{\sigma_k^2 (2^{C_{\text{regge},1,k}} - 1)}{\gamma_k} \) and \( P_{\text{RS},k} = \frac{\sigma_k^2 (2^{C_{\text{regge},2,k}} - 1)}{\gamma_k} \). Taking the above expression to (8), the optimization problem can be denoted as

\[
\min P_{\text{regenerate}} = t \sum_{k=1}^{M_R} \frac{\sigma_k^2 (2^{C_{\text{regge},1,k}} - 1)}{\Lambda_k^2} + (1 - t) \sum_{k=1}^{M_S} \frac{\sigma_k^2 (2^{C_{\text{regge},2,k}} - 1)}{\gamma_k} + t (M_B (P_{DAC} + P_{Mix} + P_{Filter}) + P_{\text{syn}}) + (1 - t) (M_R (P_{DAC} + P_{Mix} + P_{Filter} + P_{ADC}) + P_{\text{syn}}) + (1 - t) P_{\text{BS, idle}}
\]

\[
\text{s.t.} \quad \sum_{k=1}^{K} C_{\text{regge},1,k} \geq \frac{C_T}{t}, \quad \sum_{k=1}^{K} C_{\text{regge},2,k} \geq \frac{C_T}{2t}.
\] (23)

These parameters \( t, C_{\text{regge},1,k} \) and \( C_{\text{regge},2,k} \) to be optimized. We will find the close-form expression of \( C_{\text{regge},1,k} \) and \( C_{\text{regge},2,k} \) with fixed \( t \). And then through searching the optimal \( t \), we could solve this problem. For a constant \( t \), the optimal \( C_{\text{regge},1,k} \) and \( C_{\text{regge},2,k} \) can get with the same methods as (20), and we have
\[
C_{\text{regge},1,k} = (\mu_1 + \log_2 A_{\text{syn}}^2), \quad C_{\text{regge},2,k} = (\mu_2 + \log_2 \gamma_k)^+.
\] (24)

\( \mu_1 \) and \( \mu_2 \) should satisfy \( \sum_{k=1}^{K} (\mu_1 + \log_2 A_{\text{syn}}^2) = \frac{C_T}{t} \) and \( \sum_{k=1}^{K} (\mu_2 + \log_2 \gamma_k)^+ = \frac{C_T}{2t} \). Taking (24) and (25) into ((23)), the optimization problem degenerates to search the optimal \( t \). Calculating the first and second order derivative of the function, the optimal \( t \in [0, 1] \) can be get. However, the equation is hard to solve to get a close-form expression of \( t \). We omit the detail of the calculation here. And in the simulation, we search \( t \in [0, 1] \) through numeral search to get the minimum power consumption value.

C. Nonregenerate MIMO Relaying with SVD-ZFBF

From (9), \( P_{SVD-ZFBF} \) is a linear function of \( P_{\text{BS}} + P_{\text{RS}} \), so minimizing \( P_{SVD-ZFBF} \) is the same as minimizing \( P_{\text{BS}} + P_{\text{RS}} \). As SVD-ZFBF have separated the channel into \( K \) parallel SISO channels \( [9] \), we will find the relationship between the total energy consumption for the \( k \)th user \( P_{\text{total,k}} = P_{\text{BS},k} + P_{\text{RS},k} \) and the capacity for the \( k \)th user \( C_k \). According to (15) and (16), we can get the following expression with some simple calculation.
\[
P_{\text{RS},k} = \frac{(2^{C_{\text{regge}}}-1)\sigma_k^2}{\gamma_k} \left( \frac{\Lambda_k^2}{P_{\text{BS,k}}} - \frac{\Lambda_k^2}{(P_{\text{BS,k}} - 1)\gamma_k} \right)
\] (26)

According to (26), we can have the first derivative of \( P_{\text{total,k}} \) as a function of \( P_{\text{BS},k} \),
\[
\frac{\text{d}P_{\text{total,k}}}{\text{d}P_{\text{BS},k}} = 1 - \frac{(2^{C_{\text{regge}}}-1)\sigma_k^2}{\gamma_k} \left( \frac{\Lambda_k^2}{(P_{\text{BS,k}} - 1)\gamma_k} \right)
\] (27)
Let \( \frac{dP_{\text{total},k}}{dr_{\text{BS},k}} = 0 \), we can have that for a dedicated \( C_k \), the optimal \( P_{\text{BS},k} \) can be denoted as

\[
P_{\text{BS},k} = \sqrt{(2^{2C_k} - 1)\sigma_U^2 2^{2C_k} \sigma_R^2 (\sqrt{\gamma_k} \Lambda_k^2 + \frac{1}{\sqrt{\gamma_k} \Lambda_k^2})}.
\]

(28)

After some calculations, we have

\[
P_{\text{total},k} = \sqrt{(2^{2C_k} - 1)\sigma_U^2 2^{2C_k} \sigma_R^2 (\sqrt{\gamma_k} \Lambda_k^2 + \frac{1}{\sqrt{\gamma_k} \Lambda_k^2})} + (2^{2C_k} - 1)(\sigma_U^2 \frac{1}{\gamma_k} + \sigma_R^2 \frac{1}{\Lambda_k^2})
\]

(29)

and the optimization problem is

\[
\min P_{\text{BS}} + P_{\text{RS}} = \sum_{k=1}^{K} \left( \sqrt{(2^{2C_k} - 1)\sigma_U^2 2^{2C_k} \sigma_R^2 (\sqrt{\gamma_k} \Lambda_k^2 + \frac{1}{\sqrt{\gamma_k} \Lambda_k^2})} + (2^{2C_k} - 1)(\sigma_U^2 \frac{1}{\gamma_k} + \sigma_R^2 \frac{1}{\Lambda_k^2}) \right)
\]

s.t. \( \sum_{k=1}^{K} C_k \geq C_T \).

(30)

In order to have some similar expression as the previous subsection, we will develop a lower bound to optimize. We have

\[
P_{\text{BS}} + P_{\text{RS}} > \sum_{k=1}^{K} (2^{2C_k} - 1)(\sigma_U^2 \frac{1}{\gamma_k} + \sigma_R^2 \frac{1}{\Lambda_k^2}) + \sqrt{\sigma_U^2 \sigma_R^2 \gamma_k \Lambda_k^2} + \sqrt{\sigma_U^2 \sigma_R^2 \gamma_k \Lambda_k^2}
\]

(31)

Denote \( \beta = \frac{\sigma_U^2}{\gamma_k} + \frac{\sigma_R^2}{\Lambda_k^2} + \sqrt{\sigma_U^2 \sigma_R^2 \gamma_k \Lambda_k^2} + \sqrt{\sigma_U^2 \sigma_R^2 \gamma_k \Lambda_k^2} \). Then the rate allocation can be denoted as

\[
C_k = \left( \mu_3 + \log_2 \frac{1}{\beta} \right)^+,
\]

(32)

in which \( \mu_3 \) should satisfy \( \sum_{k=1}^{K} (\mu_3 + \log_2 \frac{1}{\beta})^+ = C_T \).

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, different transmission schemes are compared through simulations. The simulation parameters are set as reference [8], [13], [14]. We list it in table I. For the channel model, a Okumura-Hata pathloss model with a small scale Rayleigh fading is considered. The three transmission schemes in last section are all evaluated here and both optimal rate allocation in the last section and equally rate allocation between each users are considered. In the simulation, 'ZFBF' denotes the direct MU-MIMO with ZFBF, 'DF' denotes the regenerate transmission and 'SVD-ZFBF' denotes the nonregenerate transmission with SVD-ZFBF. Meanwhile, 'opt' denotes the rate \( C_k, k = 1, \ldots, K \) are optimally allocated as calculated in the last section. And 'equ' denotes that \( C_i = C_j, i, j = 1, \ldots, K \) which means that different users are fairly served here. As time allocation \( t \) between the two phases in regenerate transmission would affect the performance significantly, we denote the power consumption with optimal \( t \) as 'w opt t' and denote equal time allocation \( t = \frac{1}{2} \) as 'w t = 1/2'. In the simulation, we assume that the distance between the BS and all users are the same and the RS is located at the middle position between the BS and the users.

![Fig. 4. Power Consumption versus distance between BS and users, \( M_B = M_R = K = 4 \) and \( C_T = 5 \text{bps/Hz} \).](image)

![Fig. 5. Power Consumption versus target sum capacity, \( M_B = M_R = K = 4 \) and the distance between BS and users is 1km.](image)
smaller than the circuit power and then the circuit power of both transmitting and receiving takes the significant part of the total power consumption. And from (7)(8) and (9), using relay would consume more circuit power. In the long distance scenario, the relay transmission benefits significantly. That is because when the distance gets longer, the consumed PA power would increase and the circuit power would be constant, the PA power would be more significant than the circuit power. Another observation is that we can also see the performance gain between the optimal rate allocation and the equally rate allocation. The power consumed with optimal rate allocation is much less than that with equally allocation. However, the fairness problem of rate allocation among different users is not considered here. In the real systems we need to find a trade-off between the minimum power consumption and fairness. Compared 'SVD-ZFBI' and 'DF w \( t = 1/2 \)', the power gap comes from the noise enhancement of nonregenerate relaying. And the power gap between 'DF w \( t = 1/2 \)' and 'DF w Opt \( t' \) can indicates the performance gain coming from the time allocation between different time phases. Above all, 'DF-Opt w Opt \( t' \) performs best when the distance is longer than 0.4km. It is most promising method for energy efficiency, however, with highest complexity.

Fig. 5 shows the power consumption versus the target sum capacity when the distance between the BS and the users is 1km. The power consumption is exponentially increasing as a function of each users’ target capacity and the performance difference among different schemes is similar as Fig. 4. Compared with the Fig. 4, we should notice that the power gap between direct MU-MIMO and relay transmission is getting smaller as \( C_T \) gets larger when \( C_T \) is larger than 10bps/Hz. The reason is that the exponent factor of relaying is greater than the direct transmission. For example, the power of relaying is increasing as a function of \( 2^{C_T} \), while the power is increasing as a function of \( 2^{C_T} \) with direct transmission. Therefore, the transmission mode should be changed adaptively between direct transmission and relaying transmission under different target sum capacity.

From the previous figures, we have seen that the regenerative transmission is superior to the nonregenerative transmission, because the noise would be enhanced during nonregenerate transmission. However, we should emphasize again that only RF related power is considered here. As nonregenerate relays need not decode the signal, the energy consumed doing MIMO detection, demodulation and channel codes decoding can be saved and meanwhile the hardware cost can be significantly decreased. If we denote these energy as signal processing energy of the relay during the whole life cycle makes sense for the real system design.

VI. CONCLUSION

The energy consumption problem of MIMO relay systems with multiple users is considered in this paper. Optimal rate allocation between different users is proposed and can improve the energy efficiency significantly. Moreover, optimal time resource allocation of the DF scheme can further decrease the power consumption and it is the most promising scheme with the highest complexity. Through simulation, we show that direct transmission benefits in the short distance scenario while relaying transmission benefits in the long distance scenario. Furthermore, The performance under different target sum capacity is discussed. Finally, a simple discussion about the RF related power and signal processing power tradeoff between nonregenerate relays and regenerate relays are given to provide some insights about the chosen between different type of relays.

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