

Energy-Efficient Power Allocation for Decode-and-Forward OFDM Relay Links

Guangli Zhou¹, Tao Wang², Yating Wu³, Guoxin Zheng⁴, and Guangli Yang⁵

Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai University,
149 Yanchang Road, Shanghai, China

¹mugua@shu.edu.cn, ²twang@shu.edu.cn, ³ytwu@shu.edu.cn, ⁴gxzheng@staff.shu.edu.cn,
⁵guangli.yang@shu.edu.cn

Abstract. This paper investigates the power allocation aiming to optimize the energy efficiency for an OFDM two-hop relay link based on DF protocol. First, an equivalent single-hop link is used to replace the two-hop link, and the model of the energy efficiency is established. When modeling the energy efficiency of the link, the circuit power consumption is not only taken into account, but also modeled as a linear increasing function of the rate. Subsequently, the energy efficiency optimization problem is solved by convex optimization, and the optimal power allocation is obtained under rate constraint. After that, the energy efficiency performance is also analyzed. Finally, the correctness of the theoretical analysis is verified by simulation results which adopt the spatial channel model conforming to the 3GPP standard, and the influence of circuit parameters on the performance of the system is also studied.

1 Introduction

Due to the sharp increase of the carbon emission and operating cost of wireless communication systems, energy efficiency (EE) has become a new design goal^[1]. For a communication system, its EE can be evaluated by either the total energy consumption for transmitting per message bit (TEPB), or the number of message bits transmitted with per-Joule total energy consumption (NBPE). A higher EE is represented by either a smaller TEPB or a greater NBPE.

Relaying was expected as an energy saving strategy by breaking a long distance transmission into several short distance transmissions. Cooperative relay transmission can expand the coverage of the network, improve the throughput and enhance the reliability of communication link. With the combination of relay and OFDM technology, optimal performance can be achieved via a reasonable allocation of subcarriers and power. In [2], under the premise of the optimal subcarrier pairing and the total rate constraint, the resource allocation algorithm is designed for the selective decode-and-forward (DF) relay OFDM link, which makes the total power consumption minimum. However, most of current studies don't take the circuit power consumption into account.

In practical systems, the energy is not only consumed by transmitting data, but also by various circuits and signaling. Nevertheless, early works studying the EE of communication systems only considered transmission energy but ignored circuit energy consumption. For instance, weighted sum power minimization problems were addressed for a source-relay-destination communication link subject to a minimum rate requirement in [3]. For high-EE design of short-distance communication systems, the circuit energy consumption cannot be ignored, because the small transmission energy consumption is comparable to the circuit energy consumption^[4]. Thus, the circuit energy must be taken into account especially for short-distance communication systems.

In view of the above fact, the circuit energy was taken into account to optimize the EE of communication systems in recent works. For instance, modulation schemes were optimized in [5] for communication links operating over flat-fading channels, and link adaptation algorithms were developed in [6]-[9] for multi-carrier systems transmitting over frequency-selective channels. In [6]-[12], the circuit power was assumed to remain fixed independently of the bit transmission rate. In [4] and [5], the circuit power was assumed to be linear with the transmission rate. In general, the circuit power is an increasing function of the transmission rate, since a greater bit rate indicates that a bigger codebook is used which usually incurs higher power for encoding and decoding on baseband circuit boards.

In this paper, we investigate the power allocation for high-EE in DF three-node OFDM relay link in order to optimize the system performance. The EE is evaluated by TEPB. Both the transmit power and various circuit power consumption are taken into account, where the circuit power is modeled as a linear increasing function of the bit transmission rate.

The rest of this paper is organized as follows. The system model is described in the next Section. After that, the power optimization function is formulated and the theoretical analysis is made in Section 3. The simulation results are shown in Section 4 to illustrate the obtained insight. Finally, we conclude the paper in Section 5.

2 System Models and Problem Formulation

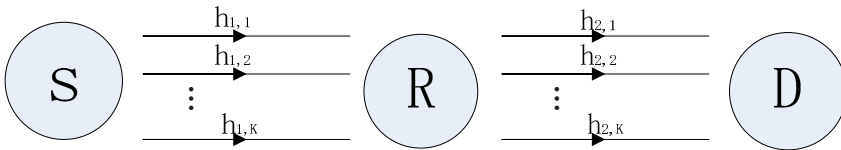


Fig. 1. Two-hop OFDM relay link

2.1 System Models

Consider a simple two-hop OFDM relay link with K orthogonal sub-carriers in each hop link, as shown in Figure 1. Each of the subcarriers can be approximated as flat-fading and quasi-static channel, so the channel gain of individual link is kept constant within each frame. Assume that the destination (D) is out of reach of the source (S) and therefore does not listen when the source is transmitting, such that direct link is ignored in our model, and the signal must be transmitted with the help of the relay (R). The relay is also supposed to be half-duplex and work in time division duplex (TDD) mode. Specifically, every data-transmission session takes two consecutive equal-duration time slots. During the first slot, the source emits signals to the relay node. The relay decodes and reencodes those message bits, then forwards the symbols (same as those emitted by the source) to the destination at every subchannel during the second slot. Actual circuit diagram of DF relay is shown in figure 2 in detail.

The channel coefficients of the k th subcarrier on the two hops are denoted by $h_{1,k}$ and $h_{2,k}$, respectively. Moreover, the power allocated for the k th subcarrier on the two hops is $P_{s,k}$ and $P_{r,k}$, respectively. Therefore, in the two time slots, the signals received by the relay node and the destination node are expressed as:

$$y_r = \sum_{k=1}^K \sqrt{P_{s,k}} h_{1,k} x_s + n_{sr}, \quad (1a)$$

$$y_d = \sum_{k=1}^K \sqrt{P_{r,k}} h_{2,k} x_r + n_{rd}, \quad (1b)$$

where x_s and x_r are the transmitted symbols by the source and relay node, respectively, and that n_{sr} and n_{rd} denote additive white Gauss noise (AWGN) with zero mean and variance σ^2 in the S-R and R-D link, respectively. Therefore, the received SNR for the k th subcarrier on the two hops can be given by $\Gamma_{1,k} = P_{s,k} g_{1,k}$ and $\Gamma_{2,k} = P_{r,k} g_{2,k}$, where

$$g_{1,k} = \frac{|h_{1,k}|^2}{\sigma^2} \text{ and } g_{2,k} = \frac{|h_{2,k}|^2}{\sigma^2}, \text{ respectively.}$$

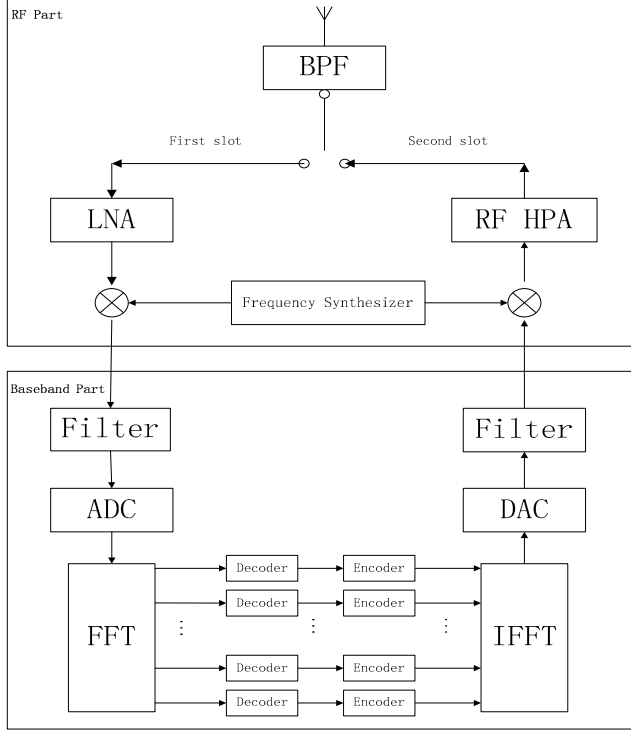


Fig. 2. Actual circuit diagram of DF relay

2.2 Power Allocation of a Single Link

Because the rate on the k th subcarrier depends on the small rate between the two hop links, the instantaneous rate of the k th subcarrier pair in the DF OFDM relay link is expressed as:

$$\begin{aligned}
 R_k &= \frac{1}{2} \log_2(1 + \min\{\Gamma_{1,k}, \Gamma_{2,k}\}) \\
 &= \frac{1}{2} \log_2(1 + \min\{P_{s,k} g_{1,k}, P_{r,k} g_{2,k}\}), \quad (2)
 \end{aligned}$$

Given the instantaneous rate of the k th link r_k , the optimal power allocation of this link must be obtained under the condition of known rate in order to minimize the power consumption and to save energy of the communication system. Therefore, the problem can be formulated as(P1):

$$\begin{aligned}
& \min_{\{P_{s,k}, P_{r,k}\}} P_{s,k} + P_{r,k} \\
& \text{s.t.} \quad \frac{1}{2} \log_2(1 + \min\{P_{s,k}g_{1,k}, P_{r,k}g_{2,k}\}) = r_k, \\
& \quad P_{s,k}, P_{r,k} \geq 0
\end{aligned} \tag{3}$$

We can get the optimal solution of (P1) if and only if $P_{s,k}g_{1,k} = P_{r,k}g_{2,k} = 2^{2r_k} - 1$, which indicates that the optimal power allocation of the k th link can be obtained when the rates of the two hops are the same. Assume that the optimal power of the k th link is P_k , namely $P_{s,k} + P_{r,k} = P_k$, then

$$P_k = \frac{(g_{1,k} + g_{2,k})}{g_{1,k}g_{2,k}} \cdot (2^{2r_k} - 1). \tag{4}$$

Let $G_k = \frac{g_{1,k}g_{2,k}}{g_{1,k} + g_{2,k}}$ denotes the equivalent channel gain. At this time, the two-hop relay link can be seen as a one-to-one paired single hop link^[13], as shown in Figure 3. Then, the optimal power in the k th link can be expressed as:

$$P_k = \frac{2^{2r_k} - 1}{G_k}. \tag{5}$$

Furthermore, the power allocation of each hop is

$$P_{s,k} = \frac{g_{2,k}}{g_{1,k} + g_{2,k}} P_k, \quad P_{r,k} = \frac{g_{1,k}}{g_{1,k} + g_{2,k}} P_k, \tag{6}$$

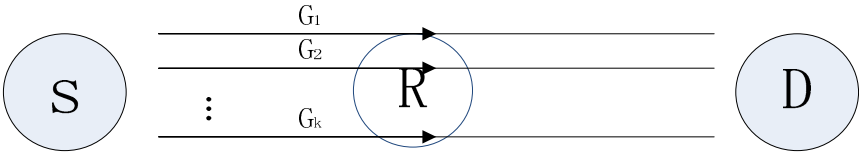


Fig. 3. Equivalent single hop link

2.3 EE Formulation

In last part, we analysis the power of a single link. Therefore, the total power of communication system can easily be expressed as:

$$\begin{aligned}
P_{total} &= \sum_{k=1}^K P_k + P_c \\
&= \sum_{k=1}^K \frac{2^{2r_k} - 1}{G_k} + \beta \sum_{k=1}^K r_k + \alpha,
\end{aligned} \tag{7}$$

where P_c denotes the circuit power, including the relay and the base station circuit consumption. moreover, P_c is related to the rate instead of a simple constant, and can be modeled as linear increasing function of the rate [4][5], namely $P_c = \beta \sum_{k=1}^K r_k + \alpha$, where α, β are constants depending on the circuit properties.

In this paper, the EE of the system is defined as the total energy consumption for transmitting per message bit(TEPB).The smaller the EE is, the better the performance will be. We can express the EE as:

$$\eta(\mathbf{r}) = \frac{P_{total}}{R_{total}} = \frac{\sum_{k=1}^K \frac{2^{2r_k} - 1}{G_k} + \beta \sum_{k=1}^K r_k + \alpha}{\sum_{k=1}^K r_k} (J / bit), \tag{8}$$

where $\mathbf{r} = [r_1, r_2, \dots, r_K]$ represents a set of link rates. In order to enable the system to achieve the best performance, the best EE must be obtained.

3 Power Allocation and Theoretical Analysis

3.1 Power Allocation Based on EE Optimization

As can be seen from the previous analysis, we can minimize the power consumption under the premise that the total rate is equal to a fixed value in order to reach the best EE. Therefore, we can draw the following problem(P2):

$$\begin{aligned}
&\min_{\{r_k\}} \quad \sum_{k=1}^K \frac{2^{2r_k} - 1}{G_k} + \beta \sum_{k=1}^K r_k + \alpha \\
&s.t. \quad \sum_{k=1}^K r_k = R \\
&\quad \quad r_k \geq 0, \quad k = 1, 2, \dots, K,
\end{aligned} \tag{9}$$

We can see that (P2) is a convex optimization problem as the objective function P_{total} is a convex function, and the solution which subjects to the KKT conditions will be the global optimal solution^[14]. Using KKT conditions to solve the above problem, the optimal rate of each subcarrier is obtained:

$$r_k^* = \left[\frac{1}{2} \log_2 \left(\frac{(\lambda^* - \beta)G_k}{2 \ln 2} \right) \right]^+, \quad (10)$$

where λ^* is the optimal Lagrange multiplier meeting all the constraints, and derived from $\sum_{k=1}^K \left[\frac{1}{2} \log_2 \left(\frac{(\lambda^* - \beta)G_k}{2 \ln 2} \right) \right]^+ = R$ by bisection method. Then, the corresponding optimal power allocation is:

$$P_k^* = \frac{2^{2r_k^*} - 1}{G_k}, \quad (11)$$

Return to original two-hop relay link, the power allocation for every subcarrier in each slot can be expressed as:

$$P_{s,k} = \frac{g_{2,k}}{g_{1,k} + g_{2,k}} P_k^*, P_{r,k} = \frac{g_{1,k}}{g_{1,k} + g_{2,k}} P_k^*. \quad (12)$$

3.2 Theoretical Analysis

Lemma 1: Total power $P_{total}(R)$ is a convex function of the total rate R .

Proof: Let $P_{total} = f(r)$, $\sum_{k=1}^K r_k = g(r)$, $R = t$, then the original problem (P2) can be expressed as:

$$\begin{aligned} \min_r \quad & f(r) \\ \text{s.t.} \quad & g(r) = t, \\ & r \geq 0 \end{aligned} \quad (13)$$

Assume r_{t_1} is the independent variable value of $\min f(r)$ when $g(r) = t_1$, while r_{t_2} is the independent variable value of $\min f(r)$ when $g(r) = t_2$.

To this end, the following just needed to be proved:

$$\theta P_{total}(t_1) + (1-\theta)P_{total}(t_2) \geq P_{total}(\theta t_1 + (1-\theta)t_2), \theta \in (0,1),$$

that is to prove: $\theta f(r_{t_1}) + (1-\theta)f(r_{t_2}) \geq f(r_{\theta t_1 + (1-\theta)t_2}), \theta \in (0,1)$.

Due to the fact that P_{total} is convex function, $f(r)$ is a convex function with r . Therefore, $\theta f(r_{t_1}) + (1-\theta)f(r_{t_2}) \geq f(\theta r_{t_1} + (1-\theta)r_{t_2})$ holds.

Because the constraint condition of the original problem is linear, then $g(\theta r_{t_1} + (1-\theta)r_{t_2}) = \theta g(r_{t_1}) + (1-\theta)g(r_{t_2})$. Moreover, $g(r_{t_1}) = t_1, g(r_{t_2}) = t_2$, so $g(\theta r_{t_1} + (1-\theta)r_{t_2}) = \theta t_1 + (1-\theta)t_2$ can be obtained. We can see that $\theta r_{t_1} + (1-\theta)r_{t_2}$ is the

feasible solution of $f(r)$ when $t = \theta t_1 + (1-\theta)t_2$ while $f(r_{\theta t_1 + (1-\theta)t_2})$ is the minimum of $f(r)$. Thus, $f(\theta r_{t_1} + (1-\theta)r_{t_2}) \geq f(r_{\theta t_1 + (1-\theta)t_2})$ holds. Therefore, $\theta f(r_{t_1}) + (1-\theta)f(r_{t_2}) \geq f(r_{\theta t_1 + (1-\theta)t_2})$, $\theta \in (0,1)$, meaning that the total power $P_{total}(R)$ is a convex function of the total rate R .

Lemma 2: EE η is a quasi-convex function of the total rate R .

According to Lemma 1, we can express the EE as follows:

$$\eta(R) = \frac{P_{total}}{R_{total}} = \frac{P_{total}(R)}{R}. \quad (14)$$

Proof: $\eta(R)$ is strictly quasi-convex of R if $S_\varepsilon = \{R \in \text{dom} \eta(R) \mid \eta(R) \leq \varepsilon\}$ is a strictly convex set for any real value ε .

Note that $\eta(\mathbf{r}) \geq 0$, which means that S_ε is empty if $\varepsilon \leq 0$, hence S_ε is strictly convex since no point lies on the contour of S_ε .

When $\varepsilon > 0$, $S_\varepsilon = \{R > 0 \mid f(R, \varepsilon) = P_{total}(R) - \varepsilon R \leq 0\}$, where $f(R, \varepsilon)$ is a strictly convex function of R . Suppose R_1 and R_2 are any two points on the contour of S_ε , and also $R_1 < R_2$. We can see from the strict convexity of $f(R, \varepsilon)$ with respect to R that $f(R, \varepsilon) \leq \max\{f(R_1, \varepsilon), f(R_2, \varepsilon)\} \leq 0$ holds for $\forall R \in (R_1, R_2)$, which means that any R between any two points on the contour of S_ε must lie in the interior of S_ε . Thus, S_ε is a strictly convex set when $\varepsilon > 0$. Therefore, η is strictly quasi-convex of R .

From the previous proof, we denote the minimum TEPB as η^* , i.e., $\eta^* = \min_{R \geq 0} \eta(R)$, and the corresponding optimum rate as R^* , i.e., $R^* = \arg \min_{R \geq 0} \eta(R)$. According to the strict quasi-convexity of $\eta(R)$, the following properties are satisfied:

Lemma 3: 1) There exists a unique R^* and it satisfies

$$\frac{\partial \eta(R^*)}{\partial R} = 0;$$

2) $\eta(R)$ is strictly decreasing with $R \in (0, R^*]$ and

$$\forall R \in (0, R^*], \frac{\partial \eta(R)}{\partial R} < 0;$$

3) $\eta(R)$ is strictly increasing with $R \in [R^*, +\infty)$ and

$$\forall R \in [R^*, +\infty), \frac{\partial \eta(R)}{\partial R} > 0.$$

Proof: Suppose there exists R_1 and R_2 satisfying $R_1 < R_2$, and $\eta(R_1) = \eta(R_2) = \eta^*$. Because of the strict quasi-convexity of $\eta(R)$, $\eta(R) \leq \max\{\eta(R_1), \eta(R_2)\} = \eta^*$ holds for $\forall R \in (R_1, R_2]$, leading to a contradiction with $\eta^* = \min_{R \geq 0} \eta(R)$. Therefore, there must

exit a unique R^* satisfying $\eta(R^*) = \eta^*$. Moreover, R^* must satisfy $\forall R \geq 0, \frac{\partial \eta(R^*)}{\partial R} (R - R^*) \geq 0$ ^[15]. As said earlier, $R^* > 0$ must hold, thus $\frac{\partial \eta(R^*)}{\partial R} = 0$ must hold to satisfy the condition. This proves the first claim.

For any R_1 and R_2 satisfying $0 < R_1 < R_2 < R^*$, $\eta(R_2) < \max\{\eta(R_1), \eta(R^*)\} = \eta(R_1)$ follows the strict quasi-convexity. This means that $\eta(R)$ is a strictly decreasing with $R \in (0, R^*]$. Therefore, $\frac{\partial \eta(R)}{\partial R} < 0$ must hold for $\forall R \in (0, R^*]$. This proves the second claim.

Likewise, we can prove the third claim easily.

4 Simulation Results

In this section, we will present simulation results to verify the correctness of the properties proposed in last section via Matlab. In this paper, we adopt the spatial channel model (SCM) conforming to the 3GPP standard model^[16] in order to simulate the practical communication scenarios. The distance of the source-relay and the relay-destination are fixed to 500m, respectively, and the parameters of the circuit power are set as $\alpha = 0, \beta = 1$. The other system parameters are listed in Table 1.

Table 1. Main simulation parameters

System parameters	Values
Number of subcarriers	100
Noise power σ^2	10^{-4}
Number of paths	6
Number of subpaths per path	20
Carrier frequency	2e9 Hz
Number of time samples	100
Height of base station	32m
Height of relay station	32m
Height of user station	1.5m
SCM scenario	Urban_macro

4.1 Relationship between Total Power and Total Rate Limiting

We randomly generate 100 sets of channels to verify the correctness of Lemma 1, and record the variation of the total power when total rate increases from zero. Then, the curve of the relationship between system power and total rate limiting is plotted as shown in Figure 4 by averaging the data recorded above. We can see from Figure 4 that the total power increases with rate increasing, meeting the characteristics of convex function, which verifies Lemma 1. It is not difficult to understand that the rate allocated to each subcarrier becomes larger when the total rate increases. Moreover, $P_k = \frac{2^{2r_k} - 1}{G_k}$ and then the overall system power consumption increases.

4.2 Relationship between EE and Total Rate Limiting

The relationship between system energy efficiency and total rate under different channel information (CSI) is analyzed in Figure 5. We verify the correctness of Lemma 2 and Lemma 3 by randomly selecting three channel conditions to simulate. The results illustrate that EE decreases first and then increases with the increase of the rate under given CSI. Moreover, there is only one specific rate corresponding to minimum EE. In addition, the similar trend of EE exists under different channel conditions, which shows that EE is a quasi-convex function with total rate. Therefore, the rate must be chosen reasonably in practical communication system in order to reach the best EE.

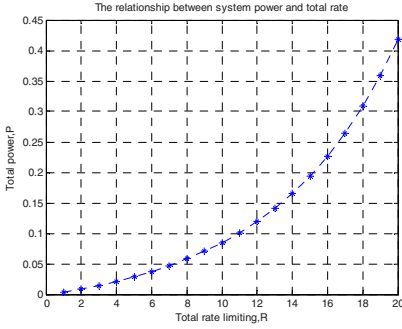


Fig. 4. The relationship between system power and total rate

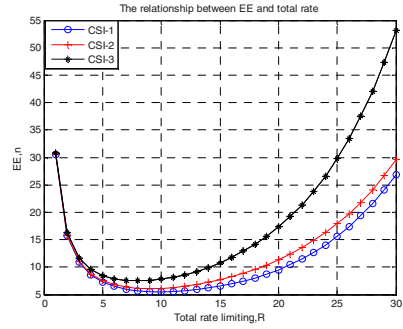


Fig. 5. The relationship between EE and total rate under different CSI

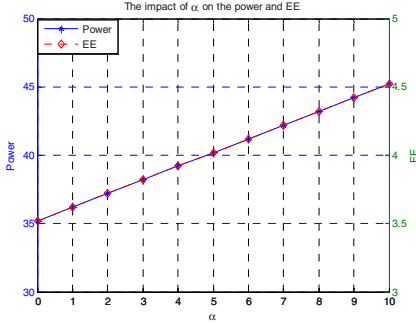


Fig. 6 The impact of α on the system when $\beta=1, R=10$

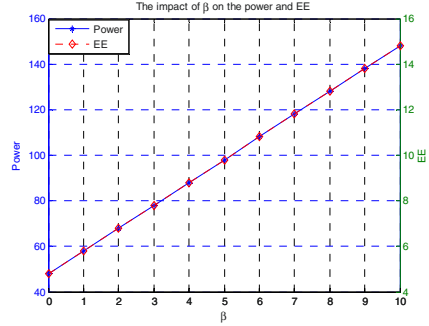


Fig. 7 The impact of β on the system when $\alpha=0, R=10$

4.3 Impact of Circuit Parameters on the System

We have done simulation experiment above setting the circuit parameters as fixed value. However, as we can see from (7) and (8) that the circuit parameter is also one of the factors affecting the system performance. The following will study the influence of circuit parameters on communication system:

In order to analyze the influence of circuit parameters on the system, the total rate is fixed to $R=10$, the results are shown in Figure 6 and Figure 7. It can be seen that the total power and EE of the system increase linearly with one of parameters increasing from zero when the other parameter is fixed. Moreover, the growth rate of the power is ten times as much as that of EE. There are reasons for this phenomenon: as can be seen from (7), the system power is linear with circuit parameters α, β under the given rate, respectively. What's more, EE is only the ratio of power with a fixed rate, meaning that EE is also a linear increasing function. In addition, the fixed rate is exactly the ratio of them.

5 Conclusion

In this paper, we have studied the power allocation in three-node OFDM two-hop relay link based on DF protocol in order to minimize EE. We use an equivalent single hop link to replace the two hop link, and model the circuit power as a linear increasing function of the total rate. Subsequently, optimization problem is solved by convex optimization, and the optimal power allocation is obtained under rate constraint. Finally, the theoretical analysis is verified by simulation results.

In the actual system, the real efficiency of the power amplifier is not a constant. Therefore, in the future work, we will consider the situation and continue to study it in depth.

Acknowledgments. This work was supported by NSFC(61401266,61571282),ChenGuang project and Innovation Program(14ZZ096) by Shanghai Municipal Education Commission and Education Development Foundation, Specialized Research Fund for the Doctoral Program of Higher Education of China(20133108120015),and NSF of Shanghai(14ZR1415100).

References

- [1]Li G Y, Xu Z, Xiong C, et al. Energy-efficient wireless communications: tutorial, survey, and open issues.[J]. IEEE Wireless Communications, 2011, 18(6):28-35.
- [2]Wang T, Fang Y, Vandendorpe L. Power minimization for OFDM Transmission with Subcarrier-pair based Opportunistic DF Relaying[J]. Communications Letters IEEE, 2013, 17(3):471 - 474.
- [3]Wang T. Weighted sum power minimisation for multichannel decode-and-forward relaying[J]. Electronics Letters, 2012, 48(7):410-411.
- [4]Isheden C, Fettweis G P. Energy-Efficient Multi-Carrier Link Adaptation with Sum Rate-Dependent Circuit Power[C]// Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE. IEEE, 2010:1-6.
- [5]Cui S, Goldsmith A J, Bahai A. Energy-constrained modulation optimization[J]. Wireless Communications IEEE Transactions on, 2005, 4(5):2349-2360.
- [6]Miao G, Himayat N, Li G Y. Energy-efficient link adaptation in frequency-selective channels[J]. Communications IEEE Transactions on, 2010, 58(2):545-554.
- [7]Xiong C, Li G Y, Zhang S, et al. Energy-Efficient Resource Allocation in OFDMA Networks[J]. IEEE Transactions on Communications, 2011, 60(12):1-5.
- [8]Sun C, Cen Y, Yang C. Energy efficient OFDM relay systems[J]. IEEE Transactions on Communications, 2013, 61(5):1797-1809.
- [9]Miao G, Himayat N, Li G Y, et al. Interference-Aware Energy-Efficient Power Optimization[J]. IEEE Transactions on Wireless Communications, 2011, 10(4):1-5.
- [10]Chinaei M H, Omid M J, Kazemi J. Circuit power considered energy efficiency in Decode-and-Forward relaying[C]// Electrical Engineering (ICEE), 2013 21st Iranian Conference on. IEEE, 2013:1-5.
- [11]Wu Y, Wang T. Energy-efficient resource allocation for OFDM transmission with opportunistic DF relaying[C]// Communications in China (ICCC), 2014 IEEE/CIC International Conference on. IEEE, 2014:570-575.
- [12]Huang G, Fang X, Yu C, et al. Optimal Energy-Efficient Path Selection Scheme in OFDM-based DF Relay Networks[J]. Xinan Jiaotong Daxue Xuebao/journal of Southwest Jiaotong University, 2015, 50(1):58-65.
- [13]Li Y, Wang W, Kong J, et al. Subcarrier pairing for amplify-and-forward and decode-and-forward OFDM relay links[J]. Communications Letters IEEE, 2009, 13(4):209-211
- [14]Boyd S, Vandenberghe L. Convex Optimization[M]. Cambridge University Press, 2004.
- [15]Bertsekas D P. Nonlinear Programming[J]. Journal of the Operational Research Society, 1995, 4(1):67-110.
- [16]3GPP, TR 25.996, V9.0.0, <http://www.3gpp.org>

Mobile and Wireless Technologies 2016

Kim, K.; Wattanapongsakorn, N.; Joukov, N. (Eds.)

2016, XIII, 252 p. 133 illus., Hardcover

ISBN: 978-981-10-1408-6