Optimal energy-efficient power allocation with physical network coding in 60 GHz OFDM system

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Abstract: In this letter, we investigate energy-efficiency power allocation (PA) based on physical layer network coding (PNC) in 60 GHz orthogonal frequency division multiple (OFDM) system. To optimization the energy-efficiency with required system throughput requirement, we formulate the objective task as a constrained minimization problem. The closed form minimum power allocation solutions are obtained by analyzing Karush-Kuhn-Tucker (KKT) conditions. Based on the derived solution, we propose a novel optimal energy-efficient power allocation (OE-PA) scheme. Numerical results have demonstrated the energy-efficient optimality of the derived scheme as compared to other conventional power allocation schemes.

Keywords: 60 GHz millimeter-wave, OFDM system, energy efficiency, Power allocation

Classification: Energy in Electronics Communications

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1 Introduction

As up to 7-9 GHz of bandwidth at 60 GHz carrier frequency is allocated by most regulatory bodies worldwide [1], which enables multi-Gbps wireless data communications. The 60 GHz band becomes the most attractive candidate for the next generation of very high rate wireless access and backhaul links. In high user density scenarios, line of sight (LOS) paths may be blocked by obstacles or the users themselves where high-speed transmission may not be achieved at all as promised in 60 GHz system. In [2], a routing algorithm was proposed which tried to maximize the system throughput. A multi-hop transmission scheme by allowing nodes to transmit concurrently in communication links was studied in [3].

Since severe propagation loss and implementation complexity limitations make it difficult to apply high spectral efficiency technologies in 60 GHz, high energy consumption has become one of the vital problems to restricting the performance of the system. However, there are limited works available in energy-efficient. In this paper, we study energy-efficient PA in 60 GHz OFDM based system, and obtain closed form minimum power allocation solutions. Based on the derived solutions, a novel power allocation scheme with UEs joint optimal energy-efficient power consumption (OE-PA) is proposed.

2 System model

We consider a typical centralized network, in which an access point (AP) is located on the ceiling. There distribute M random UEs which obey Poisson distribution. We assume the overall bandwidth is W , which can be divided into N orthogonal narrow-band subcarriers which are narrow enough to undergo flat fading. Suppose that two UEs (UE_1 , UE_2) intend to exchange information with each other and severe propagation and penetration loss resulting received signal-to-noise ratio (SNR) lower than the receiver threshold requirements. In order to improve the SNR of receiver, idle UEs or AP should be selected as relay nodes (RNs) for dual-hop transmission.

RNs apply the principle of PNC, and the PNC protocol consists of two time slots, include the medium access control (MAC) slot and the broadcast (BC) slot. In MAC slot, both UEs transmit symbols to RN respectively. During the BC slot, the RN converts the received signal from both UEs to a PNC-modulated signal [4] and broadcast to all UEs. At each destination extracts the desired information by using the local information. As a result, to complete information exchange in RN assist transmission with PNC requires only two time slots. It can achieve higher spectral efficiency than straightforward network coding and traditional scheduling.

Assume the allocated transmission power at UE or RN on the n th sub-carrier is P_i^n , while the additive white Gaussian noises at UE_1 , UE_2 and RN are denoted by $CN(0, \sigma^2)$. To facilitate the derivation, the noise variance σ^2 is chosen as 1, thus, the achievable throughput is expressed as

$$R_{i,j}^n = \log_2(1 + |h_{i,j}^n|^2 P_i^n) \quad (1)$$

Where $h_{i,j}^n$ denotes the complex channel coefficient on the n th subcarrier between the transmitter i and the receiver j .

Since it is a dual-hop relay node assisted transmission system, transmit powers and link gains are different in both UE₁ to UE₂ and UE₂ to UE₁ transmissions. Therefore, the rate in each transmission direction is defined by the minimum rate of the link. The achievable throughput can be expressed as,

$$R_{sum} = R_{1,2} + R_{2,1} = \frac{1}{2} \min(R_{1,r}, \bar{R}_{r,2}) + \frac{1}{2} \min(R_{2,r}, \bar{R}_{r,1}) \quad (2)$$

where $\bar{R}_{ij}$ denotes the rate from i th node to j th node when PNC-modulated symbol is transmitted. The pre-log factor 1/2 comes from the two stages.

3 Proposed scheme

As two UEs and RNs subject to satisfying the required system total throughput R_S and also each UE power constraint, in mathematical terms the optimization problem can be represented as

$$\begin{aligned} \text{minimize} \quad & P_{overall} = \sum_{n=1}^N (p_1^n + p_2^n + \sum_{i=1}^K p_{r,i}^n) \\ \text{subject to} \quad & \sum_{n=1}^N R_{12}^n + \sum_{n=1}^N R_{21}^n \geq R_S \\ & \sum_{n=1}^N p_1^n \leq P_0, \sum_{n=1}^N p_2^n \leq P_0 \end{aligned} \quad (3)$$

The objective function (3) is continuously differentiable function, by Karush-Kuhn-Tucker (KKT) conditions [5], Lagrangian can be given as

$$\begin{aligned} L = & \sum_{n=1}^N (p_1^n + p_2^n + \sum_{i=1}^K p_{r,i}^n) \\ & - \lambda \left\{ \prod_{n=1}^N \left[\prod_{i=1}^K (1 + p_1^n |h_{1,i}^n|^2) \prod_{i=1}^K (1 + p_2^n |h_{2,i}^n|^2) \right] - 2^{2R_S^*} \right\} \end{aligned} \quad (4)$$

where λ is Lagrange multipliers, $R_S^* = R_S N/W$.

In order to simplify the complexity of problem, in this paper, we focus on an opportunistic RN assignment where the best relay node R_k is selected to participate in the transmission. To obtain closed form solutions of (4), we can decompose the problem into two cases:

Case 1: Power unconstrained case. Assuming the rate requirement is low enough, the power constraints can be satisfied at each UE.

Case 2: Power constrained case. Assuming the rate requirement is not low enough, one of UEs exceed the power budgets which means the solutions in case 1 will result in $\sum_{n=1}^N p_i^n \geq P_0$.

3.1 Optimal solution for unconstrained case

Relay transmit power should satisfy all UEs required rates requirement in the first timeslot, it can be expressed as,

$$p_{r,k}^n = \max \left(p_1^n |h_{1,k}^n|^2 / |h_{2,k}^n|^2, p_2^n |h_{2,k}^n|^2 / |h_{1,k}^n|^2 \right) \quad (5)$$

Without loss of generality, assuming

$$p_{r,k}^n = p_1^n |h_{1,k}^n|^2 / |h_{2,k}^n|^2 \quad (6)$$

Since the best RN is selected to minimize total transmit power, by substituting (6) into (4), the Lagrangian transforms to [5]

$$\begin{aligned} \Lambda = & \sum_{n=1}^N (p_1^n + p_1^n |h_{1,k}^n|^2 / |h_{2,k}^n|^2) \\ & + \sum_{n=1}^N p_2^n - \lambda \prod_{n=1}^N \left[(1 + p_1^n |h_{1,k}^n|^2) (1 + p_2^n |h_{2,k}^n|^2) - 2^{2R_s^*} \right] \end{aligned} \quad (7)$$

Firstly, λ can be derived as

$$\lambda = \frac{1}{2^{2R_s^*}} \left(\frac{2^{2R_s^*} \prod_{n=1}^N (1 + |h_{1,k}^n|^2 / |h_{2,k}^n|^2)}{\prod_{n=1}^N |h_{1,k}^n|^2 |h_{2,k}^n|^2} \right)^{\frac{1}{N}} \quad (8)$$

Accordingly, we can obtain the closed form power allocation solutions as follows

$$p_1^n = \frac{\lambda 2^{2R_s^*} |h_{2,k}^n|^2}{|h_{1,k}^n|^2 + |h_{2,k}^n|^2} - \frac{1}{|h_{1,k}^n|^2}, \quad p_2^n = \lambda 2^{2R_s^*} - \frac{1}{|h_{2,k}^n|^2} \quad (9)$$

Total power consumption is

$$\begin{aligned} & 2N \left(\frac{2^{2R_s^*} \prod_{n=1}^N (1 + |h_{1,k}^n|^2 / |h_{2,k}^n|^2) \prod_{k=1}^N (1 + |h_{2,k}^n|^2 / |h_{1,k}^n|^2)}{\prod_{n=1}^N |h_{1,k}^n|^2 |h_{2,k}^n|^2} \right)^{\frac{1}{N}} \\ & - \sum_{n=1}^N \left(\frac{1}{|h_{1,k}^n|^2} + \frac{2}{|h_{2,k}^n|^2} \right) \end{aligned} \quad (10)$$

3.2 Optimal solution for unconstrained case

However, if the rate requirement is not low enough, and assuming one of UEs exceed the power budgets, to satisfying the system throughput requirement, we have to reallocate transmission power for UEs. We assuming $\sum_{n=1}^N p_1^n \geq P_0$ and $\sum_{n=1}^N p_2^n \leq P_0$. It is obvious that UE₁ should provide its full power, and the Lagrangian (7) becomes

$$\begin{aligned} \Lambda = & p_0 + \sum_{n=1}^N (p_1^n |h_{1,k}^n|^2 / |h_{2,k}^n|^2) + \sum_{n=1}^N p_2^n \\ & - \lambda \prod_{n=1}^N \left[(1 + p_1^n |h_{1,k}^n|^2) (1 + p_2^n |h_{2,k}^n|^2) - 2^{2R_s^*} \right] \end{aligned} \quad (11)$$

Thus we have

$$\lambda = \frac{1}{2^{2R_S^*}} \left(\frac{2^{2R_S^*}}{\prod_{n=1}^N |h_{2,k}^n|^4} \right)^{\frac{1}{N}} \quad (12)$$

Then, we can obtain the power allocation solutions as follows

$$p_1^n = \frac{\lambda 2^{2R_S^*} |h_{2,k}^n|^2}{|h_{1,k}^n|^2} - \frac{1}{|h_{1,k}^n|^2}, \quad p_2^n = \lambda 2^{2R_S^*} - \frac{1}{|h_{2,k}^n|^2} \quad (13)$$

Finally, the minimum total power consumption ratio is

$$\sum_{n=1}^N (p_1^n + p_2^n + p_{r,k}^n) = P_0 + 2N \left(\lambda 2^{2R_S^*} - \frac{1}{|h_{2,k}^n|^2} \right) \quad (14)$$

As can be seen from the solutions (7) and (11), to optimize energy efficiency of system, the two UEs should allocate power cooperatively.

Fig. 1. Iterative OEE-PA power allocation algorithm.

According to the derivation, we propose an iterative joint optimal energy efficient power consumption (OE-PA) algorithm. As depicted in Fig. 1, the optimal power allocation p_1^n and p_2^n can be obtained.

4 Results

Energy efficiency analysis is depicted in Fig. 2, in which energy consumption index (ECI) of OE-PA scheme, three-stage time division broadcast (TDBC), one way relay channel scheme, as well as PNC with equal rate power consumption (ER-PA) are compared. Fig. 2 indicates ECI of all schemes increase rapidly with the system throughput and the proposed OE-PA scheme achieves stable significant gain with less ECI compared with the other schemes under different throughput requirements. Furthermore, due to the power constraint at each UE, the ability of achieving throughput in one way relay channel scheme, ER-PA and TDBC are 5.1 bit/s/Hz, 5.4 bit/s/Hz and 7.3 bit/s/Hz, respectively. However, in our proposed OE-SRS-PA scheme, the achieving throughput is 11.1 bit/s/Hz when both the transmitted power reached the constraint.

Fig. 2. Energy efficiency analysis for increasing system throughput, where $r_1 + r_2 = 3$ bit/s/Hz $D = 20$ m.

5 Conclusion

In this letter, we investigate energy efficiency based on PNC in 60 GHz OFDM system. We derived closed form OE-PA minimum power allocation solutions. To analysis the performance of energy efficiency in a practical 60 GHz system, e.g., interference from other UEs and adaptive power allocation on subcarriers will be conducted in the future.

Acknowledgments

This work was supported by the Science Instrument Special Funds of the National Natural Science Foundation of China under Grant No.61027003 and the National High Technology Research and Development Program of China under Grant No.2012AA01A50604.