

Utility Maximization for Uplink MU-MIMO: Combining Spectral-Energy Efficiency and Fairness

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Abstract—Driven by green communications, energy efficiency (EE) has become a new important criterion for designing wireless communication systems. However, high EE often leads to low spectral efficiency (SE), which spurs the research on EE-SE tradeoff. In this paper, we focus on how to maximize the utility in physical layer for an uplink multi-user multiple-input multiple-output (MU-MIMO) system, where we will not only consider EE-SE tradeoff in a unified way, but also ensure user fairness. We first formulate the utility maximization problem, but it turns out to be non-convex. By exploiting the structure of this problem, we find a convexization procedure to convert the original non-convex problem into an equivalent convex problem, which has the same global optimum with the original problem. Then, we present a centralized algorithm to solve the utility maximization problem, but it requires the global information of all users. Thus we propose a primal-dual distributed algorithm which consumes a small amount of overhead. Furthermore, we have proved that the distributed algorithm can converge to the global optimum. Finally, the numerical results show that our approach can both capture user diversity for EE-SE tradeoff and ensure user fairness, and they also validate the effectiveness of our primal-dual distributed algorithm.

Index Terms—MU-MIMO, Spectral Efficiency, Energy Efficiency, Fairness, Power Control, Primal-Dual

I. INTRODUCTION

Among the total worldwide energy consumption, communication networks have contributed increasingly from 1.3% in 2007 to 1.8% in 2012, and this proportion is anticipated to grow continuously in the coming years [1]. This stimulates the fast development of *green communications* recently [2]. Compared to spectral efficiency (SE), *energy efficiency* (EE), defined as the number of bits that can be transmitted with per energy consumption, becomes a new important criterion for designing green wireless systems. How to obtain optimal EE has become a hot research topic in different wireless communication systems [3].

On the other hand, multiple-input multiple-output (MIMO) has been a key technique in modern wireless communication systems, because it can significantly increase SE by exploiting transmit diversity and spatial multiplexing gains [5]. MIMO system is used for one single transmitter and one single receiver in a point-to-point way, so it is often referred to single-user MIMO (SU-MIMO). However, in some applications, especially in cellular networks, it is often difficult to install

many antennas due to the size limitations of many devices such as smartphones and tablets. To increase the network-wide SE, multi-user MIMO (MU-MIMO) technique has been proposed. Although distributed users only have a small number of antennas or even just one, they can share the same time-frequency resource block to form a MU-MIMO system [6]. In this paper, we are interested in the uplink MU-MIMO because users, such as smartphones and tablets, are often more energy-sensitive.

Recently there are some papers studying how to maximize EE for uplink MU-MIMO system. In [7], Miao investigates the uplink MU-MIMO system where each user deploys multi-antennas and he demonstrates that EE is maximized when some antennas are turned off. In [8], Rui et al. study the uplink MU-MIMO system where each user deploys only one antenna and they maximize EE by jointly doing mode selection and optimal power allocation. However, it is well-known that SE and EE are two conflicting objectives [4]. Often high EE leads to low SE and vice versa, which means it is more practical to consider SE and EE simultaneously. Thus how to study the EE-SE tradeoff has attracted a lot of attention [9], [10] whereas, only a few articles study uplink MU-MIMO system. The authors in [9] consider how to get the EE-SE tradeoff for a large-scale uplink MU-MIMO system in a system level. They study EE-SE tradeoff in low and high SE regime asymptotically and do not involve user fairness explicitly which is important in multi-user system. Different from [9], our paper investigates uplink MU-MIMO system in the link level rather than the system level. More importantly, we study EE-SE tradeoff in a unified way and we also guarantee fairness among users. Specifically, our contributions are three-fold,

- We construct a utility function of all users which not only captures the user diversity for EE-SE tradeoff in a unified way, similar to [10], but also guarantees fairness among all users. To the best of our knowledge, we are the first to study EE-SE tradeoff and user fairness together in uplink MU-MIMO system.
- We proposed an approach to convert the problem into an equivalent convex programming problem which has the same optimal solution with the original problem.
- Apart from the centralized algorithm, we further devise a

primal-dual distributed algorithm which only consumes a small amount of overhead. Moreover, we have proved that the distributed algorithm converges to the global optimal solution.

The rest of this paper is outlined as follows. We describe the system model and formulate the problem in Section II. In Section III, we analyze the optimal power allocation by converting the optimization problem into a convex programming problem. Next in Section IV, we propose a primal-dual distributed algorithm, which can achieve the global optimum. The numerical results are shown in Section V, followed by conclusion in Section VI. Throughout this paper, we will use $[\cdot]_{ij}$ to denote the matrix's entry in i -th row and j -th column, $\mathbf{E}[\cdot]$ to denote expectation, \mathbf{I}_n to denote the $n \times n$ identity matrix, and the superscript \dagger to denote Hermitian transpose.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

Consider a MU-MIMO system with N users indexed from 1 to N , and one Node-B in a single cell. In this paper, we assume that each user is only equipped with one transmitting antenna, and the Node-B is equipped with M ($M \geq N$) receiving antennas, as shown in Fig. 1. In uplink, all N users share the same time-frequency resource to transmit data to the Node-B. Denote P_i as the transmit power for user i . Then the received signal vector $\mathbf{y} \in \mathbb{C}^{M \times 1}$ is,

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \quad (1)$$

where $\mathbf{s} \in \mathbb{C}^{N \times 1}$ denotes the transmit signal vector with $\mathbf{E}[\mathbf{s}\mathbf{s}^\dagger] = \text{diag}\{P_1, P_2, \dots, P_N\}$, $\mathbf{H} \in \mathbb{C}^{M \times N}$ denotes the channel matrix, and $\mathbf{n} \in \mathbb{C}^{M \times 1}$ denotes the additive white Gaussian noise (AWGN) with zero mean and covariance matrix $\mathbf{E}[\mathbf{n}\mathbf{n}^\dagger] = \sigma_n^2 \mathbf{I}_M$.

In this paper, we assume that Node-B has perfect channel state information (CSI) for all users and the receiver at Node-B uses zero forcing (ZF) detection method. Thus, the decoded signal vector is

$$\mathbf{H}^\# \mathbf{y} = \mathbf{s} + \mathbf{H}^\# \mathbf{n}, \quad (2)$$

where $\mathbf{H}^\# = (\mathbf{H}^\dagger \mathbf{H})^{-1} \mathbf{H}^\dagger$ denotes the pseudo-inverse of channel matrix \mathbf{H} . Then the signal-to-interference-plus-noise ratio (SINR) at the Node-B's receiver for user i is,

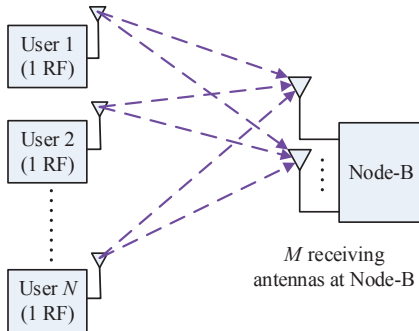


Fig. 1. System Model

$$\gamma_i = \frac{P_i}{\sigma_n^2 [(\mathbf{H}^\dagger \mathbf{H})^{-1}]_{ii}} = P_i \underbrace{\frac{1}{\sigma_n^2 [(\mathbf{H}^\dagger \mathbf{H})^{-1}]_{ii}}}_{\delta_i}. \quad (3)$$

Then we can obtain SE and EE for user i as

$$SE_i = \log(1 + \gamma_i) = \log(1 + \delta_i P_i), \quad (4)$$

$$EE_i = \frac{SE_i}{P_i + P_i^c} = \frac{\log(1 + \delta_i P_i)}{P_i + P_i^c}, \quad (5)$$

where P_i^c is a positive constant circuit power consumed by the relevant electronic devices for user i .

B. Problem Formulation

Next, we will construct the utility function in two steps. First, we consider the EE-SE tradeoff. Inspired by the widely-used Cobb-Douglas production function in economics [11], we adopt this model *empirically* to get the “production” of SE and EE for user i ,

$$u_i = (SE_i)^{w_i} (EE_i)^{1-w_i}, \quad (6)$$

where $w_i \in [0, 1]$. More specifically, we can regard $(w_i, 1-w_i)$ as a priori articulation of preferences for SE and EE, which captures EE-SE tradeoff in a unified way [10].

Second, we consider the fairness among all N users. If we apply the *proportional fairness* metric, we can define the final utility function for user i as

$$\begin{aligned} U_i(\mathbf{P}) &= \log(u_i) = \log[(SE_i)^{w_i} (EE_i)^{1-w_i}] \\ &= \log[\log(1 + \delta_i P_i)] - (1 - w_i) \log(P_i + P_i^c) \\ &= U_i(P_i), \end{aligned} \quad (7)$$

where $\mathbf{P} = (P_1, P_2, \dots, P_N)$ and the last step shows that the utility for user i is not related to the transmit power of other users.

Based on the utility function in (7), we then formulate our utility maximization problem subject to a power constraint for each user and a power sum constraint for all users,

$$\text{maximize} \quad \sum_{i=1}^N U_i(P_i) \quad (8)$$

$$(\mathbf{P1}) \quad \text{subject to} \quad 0 \leq P_i \leq P_i^{\max}, \quad \forall i \quad (9)$$

$$\sum_{i=1}^N P_i \leq P_{\max}. \quad (10)$$

In (8), we aim at maximizing the sum of the utility for all users, i.e., the network-wide utility. Inequality (9) is the individual power constraints where P_i^{\max} is the maximal transmit power for user i . Inequality (10) is the power sum constraint for the total MU-MIMO system where P_{\max} is the maximal transmit power for all users, which is the *power budget* of the whole system.

III. OPTIMAL POWER ALLOCATION

In the previous section, we have formulated the problem to maximize the network-wide utility in (8), which however is not a concave function since EE in (5) is neither convex nor concave [10]. Therefore, in this section, we will exploit the inner structure of (P1) and find that we can narrow down the feasible region without changing the global optimum.

A. Convexization Procedure

To narrow down the feasible region in (P1), we first consider the individual power constraints in (9). Since the optimization problem can be changed as,

$$\max_{0 \leq P_i \leq P_i^{\max}, \forall i} \sum_{i=1}^N U_i(P_i) = \sum_{i=1}^N \max_{0 \leq P_i \leq P_i^{\max}} U_i(P_i), \quad (11)$$

we just need to find the maximal individual utility, i.e., $U_i(P_i)$ for any user $i \in \{1, 2, \dots, N\}$. For the individual utility function $U_i(P_i)$ in (7), we have the following proposition.

Proposition 1: For any user i under individual power constraint in (9), there exists one and only one point $P_i^u \in (0, P_i^{\max}]$ that maximizes $U_i(P_i)$. The function $U_i(P_i)$ is strictly increasing and strictly concave over the interval $[0, P_i^u]$ while strictly decreasing over the interval $(P_i^u, P_i^{\max}]$. In addition, P_i^u can be derived as follows,

$$P_i^u = \begin{cases} P_i^{\max} & \text{if } w_i > 1 - \beta(P_i^{\max}) \\ P_i^0 & \text{if } w_i \leq 1 - \beta(P_i^{\max}) \end{cases} \quad (12)$$

where

$$\beta(P_i) = \frac{\delta_i(P_i + P_i^c)}{(1 + \delta_i P_i) \log(1 + \delta_i P_i)}, \quad (13)$$

and P_i^0 is the unique solution to the following equation when $w_i \leq 1 - \beta(P_i^{\max})$,

$$\beta(P_i) = 1 - w_i. \quad (14)$$

Proof: We can prove this proposition by analyzing the first and second derivative of $U_i(P_i)$ with respect to P_i . For full proof, please see Appendix A in our technical report [14]. ■

Let us denote optimal solution under individual power constraints as $\mathbf{P}^u = \{P_1^u, P_2^u, \dots, P_N^u\}$.

Now we consider the power sum constraint in (10). In (P1), since the feasible region is a compact set and the objective function is continuous, a global optimal solution can be attained. Let us denote the global optimal solution as $\mathbf{P}^* = \{P_1^*, P_2^*, \dots, P_N^*\}$. Then we have the following proposition.

Proposition 2: $\mathbf{P}^* \leq \mathbf{P}^u$, i.e., $P_i^* \leq P_i^u, \forall i \in \{1, 2, \dots, N\}$.

Proof: $\forall i \in \{1, 2, \dots, N\}$, suppose $P_i^* > P_i^u$. Then $\sum_{k \neq i} P_k^* + P_i^* < \sum_{k=1}^N P_k^* \leq P_{\max}$, which means $\mathbf{P}' = \{P_1^*, \dots, P_{i-1}^*, P_i^u, P_{i+1}^*, \dots, P_N^*\}$ is a feasible solution to (P1). According to the Proposition 1, we have $U_i(P_i^*) < U_i(P_i^u)$. So $\sum_{k=1}^N U_k(P_k^*) < \sum_{k \neq i} U_k(P_k^*) + U_i(P_i^u)$, which is a contradiction to the fact that \mathbf{P}^* is the optimal solution to (P1). This completes the proof. ■

Proposition 2 shows that for any user i , the optimal transmit power P_i^* cannot be greater than P_i^u . Therefore we have the following main result of this section.

Theorem 1: (P1) is equivalent to the following problem,

$$\begin{aligned} & \text{maximize} && \sum_{i=1}^N U_i(P_i) \\ (\mathbf{P2}) \quad & \text{subject to} && 0 \leq P_i \leq P_i^u, \quad \forall i \end{aligned} \quad (15)$$

$$\sum_{i=1}^N P_i \leq P_{\max}. \quad (16)$$

In addition, (P2) is a convex programming problem.

Proof: Following from Proposition 2, we immediately conclude that (P1) is equivalent to (P2). In addition, from Proposition 1, we know that $U_i(P_i)$ is strictly concave at $P_i \in [0, P_i^u]$. Thus, (P2) is a problem to maximize a strictly concave function in a convex region, which means it is a convex problem now. This completes the proof. ■

B. Some Analysis

Next we will give some analysis for the optimal solution \mathbf{P}^* in the following two cases.

Case 1: $\sum_{i=1}^N P_i^u \leq P_{\max}$

In this case, \mathbf{P}^u is feasible for (P2), so it is also the optimal solution for (P2), i.e., $\mathbf{P}^* = \mathbf{P}^u$.

Case 2: $\sum_{i=1}^N P_i^u > P_{\max}$

In this case, we can further narrow down the feasible region for (P2) and achieve the following proposition.

Proposition 3: If $\sum_{i=1}^N P_i^u > P_{\max}$, (P2) is equivalent to the following convex optimization problem,

$$\begin{aligned} & \text{maximize} && \sum_{i=1}^N U_i(P_i) \\ (\mathbf{P3}) \quad & \text{subject to} && 0 \leq P_i \leq P_i^u, \quad \forall i \end{aligned} \quad (17)$$

$$\sum_{i=1}^N P_i = P_{\max}. \quad (18)$$

Proof: Suppose $\sum_{i=1}^N P_i^* < P_{\max}$. Since $\sum_{i=1}^N P_i^u > P_{\max}$, there exists at least one $i \in \{1, 2, \dots, N\}$ such that $P_i^* < P_i^u$ (Otherwise, $\sum_{i=1}^N P_i^* = \sum_{i=1}^N P_i^u > P_{\max}$, which is a contradiction). Therefore, there exists a $\epsilon > 0$ such that $P_i^* + \epsilon \leq P_i^u$ and $\sum_{k \neq i} P_k^* + (P_i^* + \epsilon) \leq P_{\max}$. So $\mathbf{P}' = \{P_1^*, \dots, P_{i-1}^*, P_i^* + \epsilon, P_{i+1}^*, \dots, P_N^*\}$ is a feasible solution for (P2). According to the Proposition 1, we have $U_i(P_i^*) < U_i(P_i^* + \epsilon)$. Then $\sum_{k=1}^N U_k(P_k^*) < \sum_{k \neq i} U_k(P_k^*) + U_i(P_i^* + \epsilon)$, which is a contradiction to the fact that \mathbf{P}^* is the optimal solution to (P1). Therefore, we must have $\sum_{i=1}^N P_i^* = P_{\max}$, which completes the proof. ■

C. Centralized Algorithm

Based on the above analysis, we can readily get the optimal power allocation \mathbf{P}^* for (P1) with a centralized algorithm, as shown in Algorithm 1. In practice, we can implement such a centralized algorithm as follows. First, each user i

transmits its parameters, including P_i^{\max} , P_i^c and w_i to Node-B. After collecting all the information of all users, Node-B runs Algorithm 1 to obtain the optimal power allocation \mathbf{P}^* , and then updates the optimal transmit power P_i^* to each user i . Finally, each user transmits data at the optimal transmit power.

Algorithm 1 Centralized Algorithm for (P1)

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1: for  $1 \leq i \leq N$  do
2:   if  $w_i > 1 - \beta(P_i^{\max})$  then
3:      $P_i^u = P_i^{\max}$ ;
4:   else
5:     Get  $P_i^0$  with Newton-Raphson iteration method for
       the equation (14);
6:      $P_i^u = P_i^0$ ;
7:   end if
8: end for
9: if  $\sum_{i=1}^N P_i^u \leq P_{\max}$  then
10:   $\mathbf{P}^* = \mathbf{P}^u$ ;
11: else
12:  Get  $\mathbf{P}^*$  with gradient projection method for (P3);
13: end if

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IV. DISTRIBUTED PRIMAL-DUAL IMPLEMENTATION

In the previous section, we provide Algorithm 1 to solve the utility maximization problem in a centralized manner. However, it requires Node-B to have knowledge of all the global information of all the users. Furthermore, the centralized algorithm still incurs some computational complexity and is not robust against temporary variation of system parameters, such as instantaneous CSI. Hence, we hope to implement the algorithm in a distributed manner. Inspired by the distributed algorithm in network flow optimization problem [12], we design the following primal-dual distributed algorithm to achieve the optimal power allocation \mathbf{P}^* ,

$$\begin{cases} \dot{P}_i = k_i [U'_i(P_i) - \lambda]_{P_i^u}^{P_i^{\max}}, \forall i \in \{1, 2, \dots, N\} \\ \dot{\lambda} = g[\sum_{i=1}^N P_i - P_{\max}]_{\lambda}^+, \end{cases} \quad (19)$$

where

$$[f]_z^+ = \begin{cases} \max(f, 0), & z \leq 0 \\ f, & z > 0 \end{cases} \quad (20)$$

and

$$[f]_z^{a+} = \begin{cases} \max(f, 0), & z \leq 0 \\ \min(f, 0), & z \geq a \\ f, & 0 < z < a \end{cases} \quad (21)$$

and k_i and g are positive stepsize.

From (19), each user does not need the information of others but just the penalty λ . The only overhead is that Node-B broadcasts λ to all users and each user i updates P_i to Node-B until convergence. Therefore, such implementation only consumes a small amount of overhead between each user and Node-B. Also, our proposed distributed algorithm reduces computational complexity compared to Algorithm 1. Moreover, we further prove that this primal-dual distributed

algorithm in (19) can converge to the global optimal, as shown in the following theorem.

Theorem 2: The distributed algorithm in (19) is globally asymptotically stable and the only equilibrium is \mathbf{P}^* .

Proof: We can prove this theorem by constructing the following Lyapunov function,

$$V(\mathbf{P}, \lambda) = \frac{1}{2} \sum_{i=1}^N \frac{(P_i - P_i^*)^2}{k_i} + \frac{(\lambda - \lambda^*)^2}{2g}, \quad (22)$$

where $(P_1^*, P_2^*, \dots, P_N^*, \lambda^*)$ satisfy the KKT conditions for (P2) and λ^* is the multiplier for (16). For full proof, please see Appendix B in our technical report [14]. ■

V. NUMERICAL RESULTS

In this section, simulation results are provided to validate our theoretic analysis. Throughout this section, we will set the maximal transmit power to be 1W (30dBm) for all users, by adopting the transmitter's power level 1 for 1800/1900 MHz mobile phones [13]. The circuit power is set to be 0.1W for all users.

A. User Diversity for EE-SE Tradeoff

As shown in (6), different users can have different preferences for SE and EE according to w_i . In this part, we will show how to capture user diversity with w_i . Fig. 2 shows the impact of users' different preferences, i.e., w_1 and w_2 . From Fig. 2(a), we can see the optimal transmit power for user 1. Under the optimal transmit power for user 1, Fig. 2(b) demonstrates that SE increases as w_1 increases while Fig. 2(c) demonstrates that EE decreases as w_1 increases. Such results comply with our intuition for the effect of w_i in (6), and therefore verify that our utility function can capture user diversity for EE-SE tradeoff very well with the preference w_i .

B. User Fairness

In this part, we will show that our utility function in (7) can ensure fairness among all users. As shown in Fig. 4, the closer the channel conditions are, the better the fairness is. In addition, when $\delta_1 = \delta_2$, the index is 1 (the best fairness) which means no bias exists and two users have the same utility. Furthermore, even though when the channel condition is worst for user 1 with $\delta_1 = -20\text{dB}$ and the channel condition is best for user 2 with $\delta_2 = 20\text{dB}$, the index still does not touch 0.5 (the worst fairness) exactly and it is actually 0.5017. This means user 1 can still transmit data with a positive transmit power. Therefore, user fairness can be guaranteed under our proposed utility function in (7).

C. Primal-Dual Distributed Algorithm

In this part, we will validate the effectiveness of our primal-dual distributed algorithm in (19). From Fig. 4, we can see that the distributed algorithm can converge to the global optimum, which verifies Theorem 2.

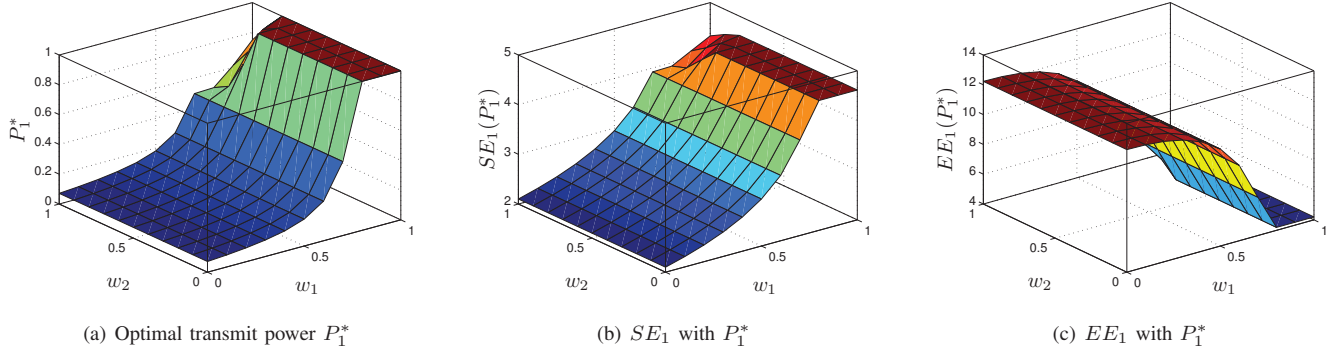


Fig. 2. User diversity for EE-SE tradeoff with $N = 2, M = 2, P_1^{\max} = P_2^{\max} = 1W, P_{\max} = 1.5W, P_1^c = P_2^c = 0.1W, \delta_1 = \delta_2 = 20\text{dB}$.

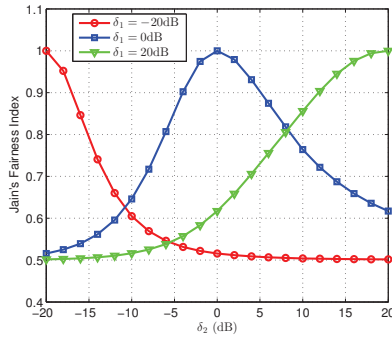


Fig. 3. User fairness with $N = 2, M = 2, P_1^{\max} = P_2^{\max} = 1W, P_{\max} = 1.5W, P_1^c = P_2^c = 0.1W, w_1 = w_2 = 0.5$.

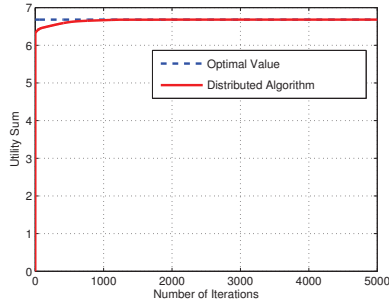


Fig. 4. Convergence of primal-dual distributed algorithm.

VI. CONCLUSION AND FUTURE WORK

In this paper, we consider utility maximization for the uplink MU-MIMO system. We define the utility function combining both EE-SE tradeoff and user fairness. After formulating the utility maximization problem with individual power constraints and sum power constraint, we analyze the optimal power allocation scheme. Although the original optimization problem is not convex, we propose a convexization procedure to convert it into an equivalent convex programming problem, which has been proven to have the same global optimal solution as the original problem. Moreover, we have proposed two algorithms

to obtain the optimal solution: one is the centralized algorithm which requires knowledge of all the global information; the other is the primal-dual distributed algorithm which only needs a small amount of overhead between each user and Node-B. Furthermore, we have proved that our proposed distributed algorithm can converge to the global optimal solution.

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REFERENCES

- [1] S. Lambert, W. Van Heddeghem, W. Vereecken, B. Lannoo, D. Colle, and M. Pickavet, "Worldwide electricity consumption of communication networks," *Optics Express*, vol. 20, no. 26, pp. B513-B524, 2012.
- [2] F. R. Yu, X. Zhang, and V. C. M. Leung, *Green Communications and Networking*. CRC Press, 2012.
- [3] D. Feng, C. Jiang, G. Lim, L. J. Cimini, Jr., G. Feng, and G. Y. Li, "A survey of energy-efficient wireless communications," *IEEE Commun. Surveys & Tutorials*, vol. 15, no. 1, pp. 167-178, 2013.
- [4] Y. Chen, S. Zhang, S. Xu, and G. Y. Li, "Fundamental trade-offs on green wireless networks," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 30-37, Jun. 2011.
- [5] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*. Cambridge University Press, 2005.
- [6] 3GPP TR 25.814 (V7.1.0), "Physical layer aspects for evolved universal terrestrial radio access (UTRA)," Sept. 2006.
- [7] G. Miao, "Energy-efficient uplink multi-user MIMO," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2302-2313, May 2013.
- [8] Y. Rui, Q. T. Zhang, L. Deng, P. Cheng, and M. Li, "Mode selection and power optimization for energy efficiency in uplink virtual MIMO systems," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 5, pp. 926-936, May. 2013.
- [9] X. Hong, Y. Jie, C. X. Wang, J. Shi, and X. Ge, "Energy-spectral efficiency trade-off in virtual MIMO cellular systems," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 10, pp. 2128-2140, Oct. 2013.
- [10] L. Deng, Y. Rui, P. Cheng, J. Zhang, Q. T. Zhang, and M. Li, "A unified energy efficiency and spectral efficiency tradeoff metric in wireless networks," *IEEE Commun. Lett.*, vol. 17, no. 1, pp. 55-58, Jan. 2013.
- [11] C. W. Cobb and P. H. Douglas, "A theory of production," *American Economic Review*, vol. 18, no. 1, pp. 139-165, Mar. 1928.
- [12] S. Shakkottai and R. Srikant, "Network optimization and control," *Foundations and Trends in Networking*, vol. 2, no. 3, pp. 271-379, 2007.
- [13] 3GPP TS 05.05 (V8.20.0), "Radio transmission and reception," Nov. 2005.
- [14] L. Deng, W. Zhang, Y. Rui, and Y. C. Kiat, "Utility Maximization for Uplink MU-MIMO: Combining Spectral-Energy Efficiency and Fairness," *Technical Report*.