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# Energy-Efficient Configuration of Spatial and Frequency Resources in MIMO-OFDMA Systems

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## ABSTRACT:

In this paper, we proposed adaptive configuration of spatial and frequency resources to maximize energy efficiency (EE) and reveal the relationship between the spectral efficiency (SE) and the EE in downlink multiple-input-multiple-output (MIMO) orthogonal frequency division multiple access (OFDMA) systems. The problem is formulated as minimizing the total power consumed at the base station under constraints on the average data rates from multiple users, the total number of subcarriers, and the number of radio frequency (RF) chains. A two-step searching algorithm is developed to solve this problem, which first finds the near-optimal numbers of subcarriers for multiple users based on Karush-Kuhn-Tucker (KKT) conditions and then optimize the number of active RF chains. Simulation results demonstrate that increasing frequency resource improves both the SE and the EE, and it is more efficient than increasing spatial resource. Consequently, there is tradeoff between the SE and the EE only when the frequency resource is limited. In general, the adaptive configuration of spatial and frequency resources outperforms the adaptive configuration of only spatial resource and that of only frequency resource.

## INTRODUCTION:

Multiple-input-multiple-output (MIMO) orthogonal frequency division multiple access (OFDMA) systems are very popular these days owing to high spectral efficiency (SE).However, whether they are with high energy efficiency (EE) is not clear. Although MIMO requires minimum transmit power than single-input-single-output (SISO) for the same data rate, it takes more circuit power because more active transmit or receive radio frequency (RF) chains are used [1].

On the other hand, in MIMO-OFDMA systems, spatial precoding and other baseband processing are carried out at each subcarrier and thus the circuit power consumption on processing increases with the number of subcarriers. Since signal processing becomes more complicated due to high need on the data rate and transmission reliability, we cannot neglect the circuit power taken by both spatial and frequency resources besides the transmit power consumption when designing an energy efficient MIMO-OFDMA system.There are some preliminary results on energy saving by adaptively using the spatial and frequency resources. The EE of Alamouti diversity scheme is discussed in [1]. It has been shown that if modulation order is adaptively adjusted to balance the transmit and circuit power consumption, multiple-input-single-output always do better than SISO.

Adaptive switching between MIMO and single-input multiple output modes are addressed in [2] to save the energy in uplink cellular networks. The relationship between the EE and bandwidth is investigated in [3] and [4]. The EE has been shown to increase with bandwidth if the circuit power consumption either does not depend on or linearly increases with the bandwidth. Energy-efficient link adaptation for MIMO-OFDM systems is studied in [5], where the active RF chains, the overall bandwidth, MIMO transmission modes can be adjusted according to the data rate need and channel fading.Priori work mainly does focus on point-to-point MIMO transmission. In downlink MIMO-OFDMA networks, RF chains are shared by different users. In this scenario switching on or switching off RF chains and allocating bandwidth are intertwined, that makes it complicated to research the EE. In this paper, we study adaptive configuration of spatial and frequency resources to reduce the EE in downlink MIMO-OFDMA systems.

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Different from optimizing the system bandwidth in [5], we fix the bandwidth of system and adjust the total number of active subcarriers, which can avoid the variation of the sampling rate and is more practical. We will reveal relationships among the EE, the SE, the number of active RF chains, and the overall number of active subcarriers.

## SYSTEM MODEL:

Consider a downlink MIMO-OFDMA system with one base station (BS) and M users. Nt and Nr RF chains are configured at the BS and each user side, respectively. Overall K subcarriers are shared by multiple users without overlap. Since a large portion of power is consumed by the BS during downlink transmission [3], we concern about how to save energy at the BS side. Consider that the number of active RF chains at the BS and the number of subcarriers allocated to each user can be adjusted based on the data rates required by the users.

A normal development structure of MIMO-OFDMA systems is represented in Fig. 1. The data first pass the channel coding and modulation mapping unit and then mapped into complex symbols. After spatial processing in the MIMO encoder unit, the signals are outputted to nt active RF chains. Different OFDM operations are done on every RF branch, including series to parallel converting (S/P), inverse fast fourier transform (IFFT), and parallel to series converting (P/S). After digital processing, the analog signals generated by the digital to analog converter (D/A) and are filtered and up-converted to a high frequency band. Finally, the signals are amplified by the power amplifiers (PAs) and radiated to the air.

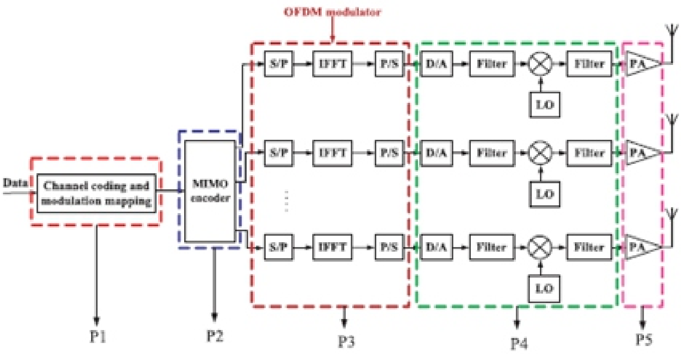


Fig. 1. Implementation structure of MIMO-OFDMA systems

## POWER CONSUMPTION AT BASE STATION:

The total power taken by the BS consists of transmit power and circuit power. The transmit power consumption is contributed by the PAs at RF chains. Represent ρ, Pi as the efficiency of the PAs and the transmit power for user i per subcarrier and per RF chain, respectively. Then the transmit power consumption can be expressed as

$$P_{tr} = \frac{n_t}{\rho}\sum_{i=1}^{M} k_i P_i. \qquad (1)$$

Besides a fixed circuit power consumption to keep operations of the BS, circuit power consumptions from different components depend on different system parameters. For example, circuit power consumption from the channel coding and modulation mapping unit is in proportion to the data rate [6]. The circuit power consumptions for different components are described in Table I. Based on (1) and the circuit power consumption models, the total power consumption of the BS can be represented as follow

$$\begin{aligned} P_{tot} =& \frac{n_t}{\rho}\sum_{i=1}^{M} k_i P_i + P_{c1}\sum_{i=1}^{M} C_i + (\alpha n_t^2 + \beta n_t) P_{c2}\sum_{i=1}^{M} k_i \\ &+ n_t P_{c3}\sum_{i=1}^{M} k_i + n_t P_{c4} + P_{c5} \qquad (2) \\ =& \sum_{i=1}^{M} k_i\left[\frac{n_t P_i}{\rho} + g(n_t)\right] + P_{c1}\sum_{i=1}^{M} C_i + n_t P_{c4} + P_{c5}, \end{aligned}$$

where

$$g(n_t) \triangleq \alpha P_{c2} n_t^2 + (\beta P_{c2} + P_{c3})$$

and Pc5 is the fixed circuit power.

## TABLE 1 : CIRCUIT POWER CONSUMPTIONS OF DIFFERENT COMPONENTS OF BS:

| | Expression | Description |
|---|---|---|
| P1 | $P_{c1}\sum_{i=1}^{M} C_i$ | linearly increases with overall data rate [6], $C_i$ is the data rate of user $i$ and $P_{c1}$ is a constant. |
| P2 | $(\alpha n_t^2 + \beta n_t)P_{c2}\sum_{i=1}^{M} k_i$ | linearly increases with overall number of used subcarriers. $(\alpha n_t^2 + \beta n_t)P_{c2}$ is the power consumed by matrix operations on each subcarrier [5]. $\alpha$, $\beta$, and $P_{c2}$ are constant. |
| P3 | $n_t P_{c3}\sum_{i=1}^{M} k_i$ | linearly increases with the number of used subcarriers and number of RF chains [5]. $P_{c3}$ is a constant. |
| P4 | $n_t P_{c4}$ | linearly increases with the number of RF chains [1]. $P_{c4}$ is a constant. |

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## ERGODIC CAPACITY:

The ergodic capacity of user i can be expressed as [8]

$$\begin{aligned} C_i =& \Delta f \sum_{j=1}^{k_i} \mathbb{E}\left[\log_2 \det\left(\mathbf{I}_{N_r} + \frac{P_i}{\sigma^2}\mathbf{H}_{ij}\mathbf{H}_{ij}^H\right)\right] \\ =& \Delta f \sum_{j=1}^{k_i} \mathbb{E}\left[\log_2 \det\left(\mathbf{I}_{N_r} + \frac{\mu_i P_i}{\sigma^2}\frac{1}{\sqrt{\mu_i}}\mathbf{H}_{ij}\frac{1}{\sqrt{\mu_i}}\mathbf{H}_{ij}^H\right)\right] \\ =& \Delta f \sum_{j=1}^{k_i} \mathbb{E}\left[\log_2 \det\left(\mathbf{I}_{N_r} + \omega_i P_i \tilde{\mathbf{H}}_{ij}\tilde{\mathbf{H}}_{ij}^H\right)\right], \end{aligned} \quad (3)$$

where Δf denotes the subcarrier spacing, INr denotes an Nr × Nr identity matrix, E[•] denotes expectation operation over small scale fading, ωi _ μ2σ2 represents the large scale channel gain to noise power ratio from the BS to user i, and Hij= is the normalized channel matrix. According to derivations in [8], (3) can be calculated as follows,

$$\begin{aligned} C_i =& \Delta f \sum_{j=1}^{k_i} m \int_0^{\infty} \log_2(1+\omega_i P_i x) p_{\mathbf{x}}(x) \mathrm{d}x \\ =& \Delta f k_i m \int_0^{\infty} \log_2(1+\omega_i P_i x) p_{\mathbf{x}}(x) \mathrm{d}x, \end{aligned} \quad (4)$$

where m _ min{nt,Nr} and px(x) is the probability density function of eigen value of ˜Hij ˜HHij , which can be found in [8]. To simplify the notation in the following analysis, we rewrite the ergodic capacity as

$$C_i = k_i f(n_t, \omega_i P_i), \quad (5)$$
$$\text{where } f(n_t, \omega_i P_i) = \Delta f m \int_0^{\infty} \log_2(1+\omega_i P_i x) p_{\mathbf{x}}(x) \mathrm{d}x.$$

## ENERGY EFFICIENCY OPTIMIZATION:

The EE in downlink transmission is defined as the overall average number of bits transmitted from the BS per unit energy [9], and is equal to the sum of the average capacities of multiple users per unit power. From the total power consumption in (2), we can get the EE of the downlink MIMO-OFDMA network as

$$\eta = \frac{\sum_{i=1}^{M} C_i}{\sum_{i=1}^{M} k_i\left[\frac{n_t P_i}{\rho} + g(n_t)\right] + P_{c1}\sum_{i=1}^{M} C_i + n_t P_{c4} + P_{c5}}. \quad (6)$$

The SE in downlink transmission, which is defined as the overall average data rate per unit bandwidth, does depend on the data rates of multiple users. To study the SE-EE relationship, we formulate a problem to maximize the EE under the constraints of average data rate deed of multiple users.

When the data rates of multiple users are given, maximizing the EE is equivalent to minimizing the total power consumption at the BS. Considering the constraints on the total number of subcarriers and the number of active RF chains, the optimization problem can be formulated as follows,

$$\min_{n_t, \mathbf{K}, \mathbf{P}} \sum_{i=1}^{M} k_i \left[\frac{n_t P_i}{\rho} + g(n_t)\right] + P_{c1}\sum_{i=1}^{M} C_i + n_t P_{c4} + P_{c5} \quad (7)$$
$$\text{s. t. } k_i f(n_t, \omega_i P_i) = C_i, \quad i = 1, 2, \cdots, M \quad (7a)$$
$$\sum_{i=1}^{M} k_i \le K, \quad (7b)$$
$$1 \le n_t \le N_t \quad (7c)$$
$$k_i > 0, \quad P_i > 0, \quad i = 1, 2, \cdots, M, \quad (7d)$$

We will optimize the number of active RF chains, the number of subcarriers used by each user, and the transmit power for each user to find the maximum EE.

## TWO-STEP SEARCHING ALGORITHM:

### A. Solution of Problem (9) Given the Number of Active RF Chains

A.1 Solution of Continuous Numbers of SubcarriersWhen the numbers of subcarriers used by different users, {ki}Mi=1, are relaxed to continuous variables, they can be expressed as a function of {Pi}Mi=1 from constraint (7a) as ki = Ci/f (nt, ωiPi) i = 1, 2, • • • ,M. (8) Substituting (8) into problem (7) and considering that constraint (7c) can be discarded automatically for a given nt, we can obtain a new optimization problem as follows

$$\min_{\mathbf{P}} \sum_{i=1}^{M} \frac{C_i\left[\frac{n_t P_i}{\rho} + g(n_t)\right]}{f(n_t, \omega_i P_i)} + P_{c1}\sum_{i=1}^{M} C_i + n_t P_{c4} + P_{c5} \quad (9)$$
$$\text{s. t. } \sum_{i=1}^{M} \frac{C_i}{f(n_t, \omega_i P_i)} \le K, \quad (9a)$$
$$P_i > 0, \quad i = 1, 2, \cdots, M. \quad (9b)$$

The Lagrange function of problem (9) is shown in (10) on the top of next page, where Φ(P) denotes the objective function in problem (9), and λ and {ξi}Mi=1 represent Lagrange multipliers for constraints (9a) and (9b), respectively. The Karush-Kuhn-Tucker (KKT) conditions of problem (9) can be expressed as follows,

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$$\frac{\partial L\left(\{P_i\}_{i=1}^{M}, \lambda, \{\xi_i\}_{i=1}^{M}\right)}{\partial P_i} = 0, \qquad (11a)$$

$$\lambda \geq 0, \quad \sum_{i=1}^{M} \frac{C_i}{f\left(n_t, \omega_i P_i\right)} \leq K, \qquad (11b)$$

$$\lambda\left(\sum_{i=1}^{M} \frac{C_i}{f\left(n_t, \omega_i P_i\right)} - K\right) = 0, \qquad (11c)$$

$$\xi_i \geq 0, \; P_i > 0, \; \text{and} \; \xi_i P_i = 0 \quad i = 1, 2, \cdots, M. \qquad (11d)$$

ξi ≥ 0, Pi > 0, and ξiPi = 0 i = 1, 2, • • • ,M. (11d)
Substituting (10) into (11) and after some manipulations, (11a) can be rewritten as

$$L\left(\{P_i\}_{i=1}^{M}, \lambda, \{\xi_i\}_{i=1}^{M}\right) = \Phi(\mathrm{P}) + \lambda\left(\sum_{i=1}^{M} \frac{C_i}{f\left(n_t, \omega_i P_i\right)} - K\right) - \sum_{i=1}^{M} \xi_i P_i$$

$$n_t f\left(n_t, \omega_i P_i\right) - \omega_i\left[n_t P_i + \rho\left(g(n_t) + \lambda\right)\right] f_i' = 0, \qquad (12)$$

where $f_i' \triangleq \frac{\partial f(n_t,\gamma)}{\partial \gamma}\Big|_{\gamma=\omega_i P_i}$.

In the following, we will first find the solution for equations (11c) and (12) and then judge whether the solutions satisfy the inequality conditions in (11). It can be readily proved from (12) that Pi monotonically increases with λ, and Pi that satisfies equation (12) can be expressed as a function of λ. Denoting Pi = θi(λ) and substituting it into (11c), we have

$$\lambda\left(\sum_{i=1}^{M} \frac{C_i}{f\left(n_t, \omega_i \theta_i(\lambda)\right)} - K\right) = 0. \qquad (13)$$

$$\sum_{i=1}^{M} \frac{C_i}{f\left(n_t, \omega_i \theta_i(\lambda)\right)} = K. \qquad (14)$$

*A.2 Discretization of the Continuous Solution*
After discretizing the number of subcarriers for each user, the transmit power $\{P_i^c\}_{i=1}^{M}$ 'may not satisfy the data rate requirement any more. According to (8), the final optimal transmit power values,

$$k_i^o f\left(n_t, \omega_i P_i^o\right) = C_i \qquad i = 1, 2, \cdots, M. \qquad (16)$$

## B. Optimal Number of Active RF Chains:

When the maximum number of RF chains at the BS, Nt, is small, we can compute the EE for each possible value of nt in the interval [1,Nt] and find the one with the maximum EE. This conclusion implies that once we find the value of n0, the optimal number of active RF chains to achieve the minimum power consumption over all possible values of nt lies in the interval [1, n0].

## SIMULATION RESULTS:

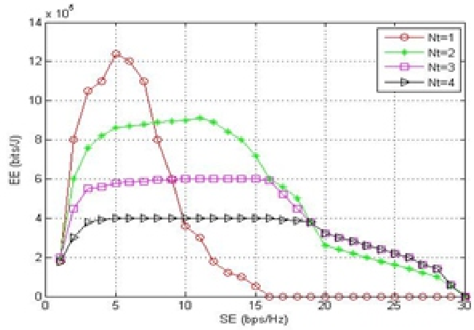


Fig.2. EE Vs SE

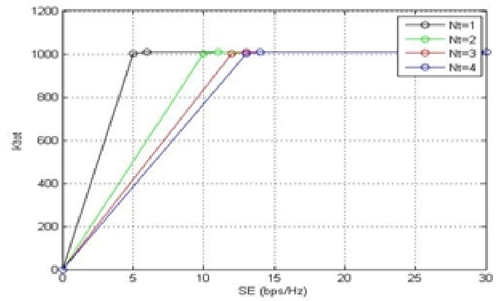


Fig.3. Ktot Vs SE

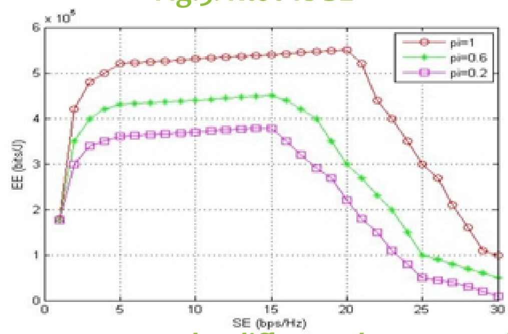


Fig.4. EE Vs SE under different data rate ratios

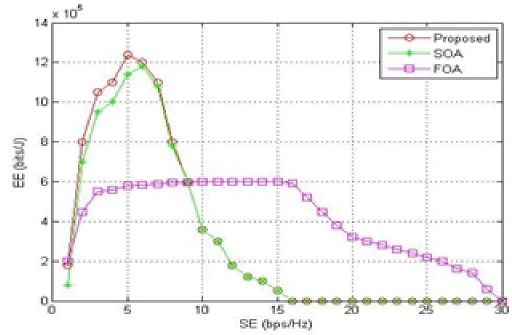


Fig.5. EE Vs SE for different configurations

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Figure 2 shows the EEs achieved by the algorithm versus the SE with different numbers of active RF chains at the BS. By comparing the EEs under different number of active RF chains, we can obtain the optimal number of active RF chains to maximize the EE. In Fig. 3, we plot the total number of used subcarriers when the optimal EE is achieved for each nt. We can see the total number of used subcarriers increases linearly with the SE when constraint (7b) is not active. In Fig. 4, we demonstrate the impact of allocating overall average data rate requirement among multiple users on the EE. From the figure, the EE increases with the data rate ratio for the user that is closer to the BS. This means that allocating more data rate to the user with high channel gain improves the relationship between the SE and the EE as a whole. Figure 5 shows the benefit of adaptive configuration of both spatial and frequency resources. We compare the EE of the proposed algorithm with spatial-only-adaptation (SOA) and frequency-only adaptation (FOA). For the SOA, the total number of used subcarriers is set to be the maximum number, K. For the FOA, the number of active RF chains at the BS is set to be the maximum value, Nt.

## CONCLUSION:

We first formulated the optimization problem to minimize the total power consumed at the BS with average data rate requirements from multiple users. Then we developed a two-step searching algorithm. Simulation results indicate that increasing frequency resource helps to improve both the SE and the EE. The tradeoff between the SE and the EE only exists when the total number of active subcarriers is restricted by a maximum value. On the other hand, the optimal number of active RF chains increases only when the total number of used subcarriers cannot be increased, which means that frequency resource is more efficient than spatial resource on improving the EE. The proposed spatial-frequency resource adaptive configuration outperforms both the spatial-only-adaptation and the frequency-only-adaptation.

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