Energy-Efficient Resource Management for Massive MIMO Systems

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Abstract

In massive MIMO systems, both energy efficiency (EE) and spectral efficiency (SE) have been recognized as important metrics for future communication system design. This paper investigates joint optimization of spatial and power resources to maximize the EE with guaranteed data rate requirement in downlink multiuser systems. Benefiting from the orthogonality of multiple propagation channels, the optimal number of antennas and radiated power are derived with closed forms. Analysis and simulation results demonstrate that when the circuit power consumed by each antenna decreases, configuring more antennas and radiating less power is more helpful to save energy. The SE points corresponding to the maximum EE decreases with the circuit power.

1. Introduction

Multiple-Input-Multiple-Output (MIMO) techniques have achieved a huge success in Long-Term Evolution (LTE) and exploiting spatial resources, i.e. multiple antennas, has been demonstrated to improve system spectral efficiency (SE) and support high data rate. In the LTE standard, up to 8 antenna ports are allowed at the base station. To continue playing a critical role in the fifth generation wireless networks, hundreds of antenna ports are suggested to be configured to support several Giga bps data rate [1-3]. In massive MIMO systems, amounts of antennas are shared by much smaller number of terminals in the same time-frequency resource and thus higher quality of service can be provided to each terminal.

Massive MIMO builds a favorable signal propagation environment [2]. With the increase of the number of antennas at the base station, the channels from the base station to multiple terminals become more and more orthogonal, and the inter-cell and intra-cell interference is automatically mitigated. On the other hand, hundreds of antennas bring large beamforming gain and the effect of noise can be well averaged out. The performance difference of various precoding schemes becomes smaller with the increase of the number of antennas and the simple maximum-ratio combining is recommended for massive MIMO downlink and uplink transmission. Due to the large beamforming gain, the radiated power on each antenna can be dramatically reduced and thus inexpensive low-power components can be used for RF chains. This yields a new field on hardware implementation. In summary, massive MIMO brings new research focus in the fields of communication theory, channel propagation, and electronics, etc.

High energy efficiency (EE) is believed to be an advantage of massive MIMO transmission. The EE and SE relationship is studied in [4]. When the number of antennas at the base station, M, grows without bound, the transmit power of each user reduces proportionally to $1/M$ if the base station has perfect channel state information (CSI), and proportionally to $1/\sqrt{M}$ if the CSI is estimated via uplink pilots. From the perspective of transmit power, the EE increases with the number of antennas. However, additional price has to be paid. Hundreds of RF chains have to be configured with the antennas and large-scale signal processing should be carried out in massive MIMO. Therefore, circuit power generated by RF and baseband hardware increases with the number of antennas [5]. When considering the power consumption overhead from the hardware, the EE of massive MIMO may not always increase with the number of antennas. It is possible to jointly adjust the number of antennas and the transmit power to achieve the maximum EE while satisfying the data rate requirement in massive MIMO systems.

The EE of massive MIMO has been studied in the literatures [4, 6, 7]. The EE-SE relationship is studied in [4] with different linear receivers in the uplink transmission. It is shown that the use of large antenna arrays can improve both the SE and EE. However, only the transmit power is evaluated and the circuit power induced by large arrays is not taken into account. In [6], the circuit power for baseband computations and RF chains is well modeled. The number of terminals simultaneously served and the total radiated power are optimized through simulation to maximize the EE. It has found that there exist the optimal values for the number of terminals and total radiated power. In [7], the optimal

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number of antennas in MIMO systems is optimized with frequency resources.

This paper will study the optimal antenna configuration and the optimal radiated power allocation in the massive MIMO systems. The closed-form expressions of the optimal number of antennas and the optimal radiated power will be derived. Simulation results will show how these two optimal values change with the SE and affect the EE. The remainder of this paper is organized as follows. System model and the expressions of EE and SE expressions are presented in Section 2. The optimal transmit power and number of antennas to maximize the EE while guaranteeing each user's data rate requirements are derived in Section 3. Simulation results are illustrated in Section 4 and the paper is finally concluded in Section 5.

2. SYSTEM MODEL AND EE-SE Expressions

We consider the downlink of an MU-MIMO system. The system includes one base station equipped with hundreds of antennas with the number of *M*. *K* single-antenna users are assumed to receive the signals from the base station in the same time-frequency resource. The channel from the base station to the *k*th user is denoted as a column vector $\mathbf{h}_k$ with the size of *M*. Each element of $\mathbf{h}_k$ is assumed to have zero mean and variance ψ_k. Then the received signal at the *k*th user can be expressed as

$$y_k = \mathbf{h}_k^T \mathbf{w}_k s_k + \sum_{i \neq k} \mathbf{h}_k^T \mathbf{w}_i s_i + n_k \tag{1}$$

where s_k is the *k*th user's signal, $\mathbf{w}_k$ represents the precoding vector for the *k*th user, and n_k denotes the noise.

According to the theory of massive MIMO [2], regardless of the precoding schemes, the channels from the base station to each user are almost orthogonal, and then the channel capacity for the *k*th user can be approximately expressed as

$$C_k = B \log_2 \left(1 + \frac{M \psi_k p_k}{\sigma^2} \right) \tag{2}$$

where *B* denotes the system bandwidth, p_k is the power used for the data transmission of the *k*th user, and σ^2 denotes the noise power.

The EE for downlink transmission is defined as the number of bits transmitted per unit energy [1], and is equivalent to the channel capacity per unit power, which is

$$\eta_{EE} = \frac{\sum_{k=1}^{K} C_k}{\sum_{k=1}^{K} p_k / \rho + P_c} \tag{3}$$

where ρ denotes the efficiency of power amplifier and P_c is the circuit power.

In massive MIMO, the circuit power is mainly consumed at the base station and is affected by the number of antennas. In this paper, P_c is modeled to be a linear function of the number of transmit antennas as [6]

$$P_c = Ma + b \tag{4}$$

where *a* is the circuit power related to each antenna and *b* is constant circuit power.

Replacing C_k in (3) by (2) and P_c in (3) by (4), we can find the EE for downlink transmission as

$$\eta_{EE} = \frac{B \sum_{k=1}^{K} \log_2 (1 + \frac{M \psi_k p_k}{\sigma^2})}{\sum_{k=1}^{K} p_k / \rho + Ma + b} \tag{5}$$

3. Optimal Antenna Configuration and Power Allocation

When the data rate of the *k*th user is R_k, using (2) and (5), we can obtain the EE expression with respect to the number of antennas as

$$\eta_{EE} = \frac{\sum_{k=1}^{K} R_k}{\frac{\sigma^2}{M\rho} \cdot \sum_{k=1}^{K} \left(2^{R_k/B} - 1\right) \Big/ \psi_k + Ma + b} \tag{6}$$

It is very easy to derive the optimal number of antennas and the optimal power allocation that maximizes the EE as follows

$$M^* = \sqrt{\frac{\sigma^2}{\rho a} \cdot \sum_{k=1}^{K} \frac{\left(2^{R_k/B} - 1\right)}{\psi_k}} \quad \text{and} \quad p_k^* = \frac{\left(2^{R_k/B} - 1\right)\sqrt{\rho a \sigma^2}}{\psi_k \sqrt{\sum_{k=1}^{K} \left(2^{R_k/B} - 1\right) \Big/ \psi_k}} \tag{7}$$

From these two equations, we can see that when the circuit power for each antenna, *a*, decreases, the optimal number of antennas will increase and the optimal power will decrease. This means that when the circuit power overhead from configuring more antennas is smaller, increasing antennas rather than increasing the radiated power is more energy efficient. Massive MIMO can play much its role in the low circuit power case. On the other hand, when the efficiency of the power amplifier, ρ, increases, the radiated power will increases and the number of antennas will decrease to save circuit power. All these observations imply that there exists a balance between the radiated power and the number of antennas depending on the capability of power amplifier and the circuit power level.

4. Simulation Results

In this section, we will study the EE-SE relationship and the optimal resource management under different data rate requirements. The main parameters in the simulation are listed in Table I. Users are uniformly distributed in the cell region and the required sum capacity is randomly allocated to multiple users.

TABLE1. LIST OF SIMULATION PARAMETERS

Parameters	Values
Bandwidth, *B*	20 MHz
Cell radius	250 m
Minimum distance from the base station to users	35 m
Efficiency of the power amplifier, ρ	38%
Circuit power parameters, *a*	0.01 W, 0.1 W, 1 W
Circuit power constant, *b*	20W
Number of single-antenna users, *K*	10
Power spectral density of noise	-174 dBm/Hz
Path loss model(dB)	$128.1 + 37.6\log_{10} d(\text{km})$
Small-scale fading	Flat Rayleigh fading with zero means and unit variance

Figure 1 shows the EE-SE relationships with different values of *a*. The SE, η_{SE}, is defined as the sum channel capacity per unit bandwidth, and its values can be obtained through dividing (2) by the system bandwidth, *B*. We can see that there exists an optimal SE point to achieve the maximum EE. With the increase of the value of *a*, the EE value corresponding to each SE decreases, and the optimal SE point decreases. Figure 2 shows the optimal number of antennas, M^*, and the optimal total transmit power, $P_t^* = \sum_{k=1}^{K} p_k^*$, with respect to the SE. We can see that with the increase of the SE, both M^* and P_t^* increase, which means that to achieve the maximum EE, the spatial and power resources should be adjusted upon the data rate requirements. When the SE is given, we can see that M^* decreases while P_t^* increases with the increase of the value of a, which validates the analysis in Section 3.

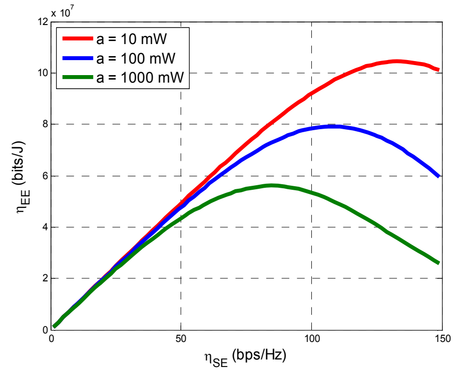

Figure 1. EE-SE relationship with different circuit power parameters

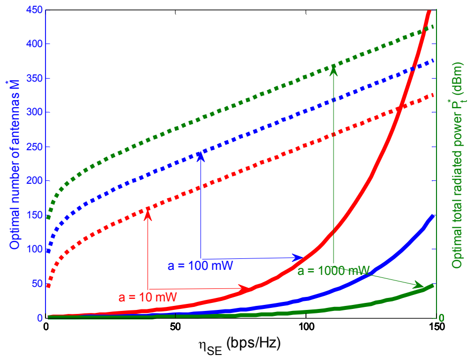

Figure 2. Optimal spatial and power resources vs. SE

5. Conclusion

In this paper, we have studied energy-efficient joint spatial and power management in downlink massive MIMO systems. The optimization problem to maximize the system EE while guaranteeing the data rate requirements from multiple users is formulated and solved. We have derived the closed-form solutions for the optimal number of antennas and transmit power. From the analysis and simulation results, it can be revealed that there exists a balance between the radiated power and the number of antennas depending on the capability of power amplifier and the circuit power. When the circuit power consumed by each antenna decreases, configuring more antennas and radiating less power is more energy efficient and the SE points corresponding to the maximum EE increase.

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