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Joint Transmit Antennas for Energy Efficiency in Downlink Massive MIMO Systems

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Abstract: Massive multiple-input-multiple-output (MIMO) systems are an exciting area of fifth-generation (5G) technology and very important in maximizing energy efficiency (EE) and saving battery technology. Obtaining energy efficiency without sacrificing the quality of service (QoS) has become increasingly important for mobile devices. In this paper, we investigate the maximal EE for downlink massive MIMO systems using zero-forcing beamforming (ZFBF), dependent on the number of antenna elements and the optimal number of users inside the cell to optimize the transmit power. The linear precoding ZFBF is able to mitigate interbeam interference, in addition to noise, due to expanding the reception at low power transmission. The simulation results reveal that the maximal energy efficiency can be obtained dependent on increasing the number of antennas M and choosing the $K^{opt} \geq 1$, where the number of antennas is greater than the critical number of antennas $M_{Tx} \geq M_{Tx}^{cri}$, which minimizes the received interference due to increased transmit power.

Keywords: Massive MIMO, energy efficiency (EE), quality of service (QoS), zero-forcing beamforming (ZFBF)

1. Introduction

A massive multiple-input-multiple-output (MIMO) system is very important in 5G technology because it gives a higher EE performance than a single antenna, where a high data rate, strong interference suppression, and increased multiplicity can be achieved, when only taking into account the transmit power [1]. A massive MIMO system has a large ability to maximize EE, when the $M \to \infty$, besides reducing circuit consumption power.

The transmit power in massive MIMO can be decreased proportional to $1/M$ if the base station (BS) has perfect channel state information (CSI), and $1/\sqrt{M}$ if the BS has imperfect CSI, with only a slight loss in data rate as explained in [2- 4]. The linear ZFBF provides a high capacity and is able to create an orthogonal channel at the transmitter, as shown in Fig. 1. Getting the optimal transmit power of the base station with ZFBF requires increasing the number of antennas, where $M \gg K$, to maximize the EE. All antennas in the BS transmit same data to multiple users at the same time and on the same frequency band by choosing ZFBF to get the optimal transmit power and maximize the EE [5]. In this paper, we derive the EE based on transmit power in terms of the number of antenna elements and the limited number of users inside the cell with ZFBF. Consequently, the effect of power constraints on EE in a massive antenna system is dependent on the use of full power with different numbers of antennas.

The performance EE gradually increases with equal power allocation, while a decreased number of antennas decreases the performance gain as shown in [6] and [7]. Moreover, increasing the number of users inside the cell requires increasing the total transmit power, which does not satisfy the quality of service (QoS) because the data rate for every user is achieved in parallel and the EE will decrease due to the high transmit power.

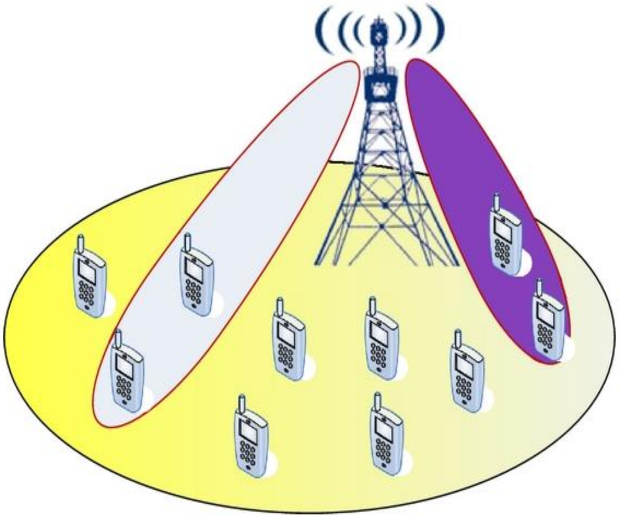

Fig. 1 Beamforming antennas in a single- cell massive MIMO system.

The transmitted power can achieve a high data rate using power allocation as described in [8-11]. The purpose of determining an antenna selection algorithm in massive

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MIMO systems is to obtain a high data rate that maximizes the EE. Greater EE is achieved by increasing the number of antennas at BS, where the maximum EE clearly depends on choosing the optimum number of antennas for using linear precoding techniques, such as ZFBF, which are used to suppress high signal-to-interference noise ratio (SINR) at high transmit power.

2. System Model

The downlink signal multiuser-MIMO system includes the BS, which contains many antenna arrays *M* and receives data from many random active users, where every user still receives limited data rate because multi-user interference in downlink MIMO. The received signal vector for active users is given by

$$z_k = \sqrt{Q_k}\ h_k \gamma_k\, x_k + n_k \tag{1}$$

where x_k represents the data symbol signal of the *Kth* user, γ_k is the beam-forming matrix, h_k is a matrix channel of $K \times M$, and $\mathrm{n_k}$ is the received noise with zero mean and variance. The signal received in terms of active users is given by

$$r_k = \sqrt{Q_k}\ h_k\, \gamma_k x_k + \sum_{i=1, i\neq k}^{K} \sqrt{Q_i}\ h_k\, \gamma_i x_i + \ n_k \tag{2}$$

where Q_k is the transmitted power for every active user, and the BS transmits a different amount of power to each active users. The received SINR used to describe the achievable data rate for active user K is

$$SINR\ _k = \frac{\frac{Q_k}{k}\sum_{k=1}^{K}|h_k\gamma_k|^{\,2}}{\frac{Q_i}{k}\sum_{i=1,i\neq k}^{K}|h_k\gamma_i|^2+\sigma^2} = \frac{\frac{Q_k}{k}\left|h_k h_k^H\right|^2}{\frac{Q_i}{k}\left|h_k h_i^H\right|^2+1} \tag{3}$$

The transmit beamforming technique is used to maximize the performance of the transmitted power. The purpose of using SINR in each user is to provide the conjugate of beamforming matrix $\sum_{k=1}^{K}\|\gamma_k\|^2$. The optimal zero-forcing beamforming has low complexity, and the performance is very close to that of a maximum-likelihood multi-user and is expressed as follows:

$$\gamma_k^{opt} = \left(I_N + \frac{1}{\tau^2} HAH^H\right)^{-1} H\sqrt{\tilde{Q}} \tag{4}$$

where the $\tilde{Q}$ parameter is defined as $\tilde{Q} = diag\ (Q_k / \|(\tau^2 I_k + HAH^H)^{-1} h_k\|)$ according to the power allocation, τ^2 is the noise power at the transmitted signal, I_N is the $M{\times}M$ identity matrix, and $A = diag\ [\vartheta_1\ , \dots, \vartheta_k]$is the diagonal matrix in the Lagrange multiplier associated with many of the active users.

The corresponding power allocation matrix, when $\tau^2 \to 0$ and $\tilde{Q}_{\tau^2 \to 0}$, the asymptotic power allocation with the zero-forcing beamforming channel, is given as

$$\gamma_k^{opt} = (0\ I_N + HAH^H)^{-1} H \tilde{Q}_{\tau^2\to 0} = H(HH^H)^{-1}A^{-1}\tilde{Q}_{\tau^2\to 0} \tag{5}$$

The average data rate for each active user is given by

$$R_{avg} = Blog_2(1 + SINR_K) = \sum_{i=1}^{K} \mathbb{E}(R_k) \tag{6}$$

where *B* represents the coherence of the bandwidth.

The total average data rate is given as

$$R_{avg} = Klog_2\ (1 + SINR_K) = \sum_{i=1}^{K} \mathbb{E}(R_k) \tag{7}$$

The superscript ( )+ denotes the pseudoinverse and the superscript *H* represents the conjugate transpose. In order for the pseudoinverse $H(HH^H)^{-1}$ to exist, the number of transmit antennas should be less or identical to the number of receive antennas. The ZFBF completely removes the interference by inverting the channel matrix at the transmitter. Otherwise, the transmit beamforming is used to maximize the performance of transmitted power and to reduce the inter-user-interference. Therefore, the purpose of using SINR for each user is to provide the optimal beamforming. The SINR of each active user can expressed as

$$SINR_k = \frac{Q_t}{tr\left(\left(HH^H\right)^{-1}\right)} \tag{8}$$

The linear precoding zero forces beamforming to use the CSI, where the ZFBF is able to make the massive MIMO system less sensitive to the SNR at an increased number of antennas for the achievable data rate, when $M \geq K$ and the data rate per user K is r_k for all users expressed as $R = [r_1\, , r_2\, , \dots \dots .,\ r_k]$, and considers the Gaussian noise as 1. The linear precoding technique with CSI for active users adopts ZFBF, which cancels the intra-cell interference; according to the random matrix theory [12], this can be written as

$$\frac{1}{\mathbb{E}\left\{tr\left(\left(HH^H\right)^{-1}\right)\right\}} = \frac{M-K}{K}\ , \qquad M \to \infty \tag{9}$$

The data rate for a large value of the number of antennas *M* and taking into account a fixed number of active users *K* is given by

$$R_{avg} = Klog_2\left(1 + Q_t\,\frac{M-K}{K}\right) \tag{10}$$

2.1 Maximize Energy Efficiency

In this section, we maximize the EE dependent on using transmit power beside optimal zero-forcing beamforming.

Problem 1: To obtain the maximum EE, it requires to use the ZFBF transmit power which can achieve high throughput for the total power consumption. Therefore, the EE can be expressed as:

$$EE = \frac{\sum_{k=1}^{K} R_k}{\eta Q_t + KQ_c} = \frac{Klog_2\left(1+Q_t\frac{M-K}{K}\right)}{\eta Q_t + KQ_c + Q_{SP}} \tag{11}$$

where Q_t represents the total transmit power from the BS to every active user, and R_k represents the achievable data rate.

In order to obtain the maximum EE, the system needs to provide a high data rates for active users without sacrificing the QoS by using the beamforming transmit power. The consumption circuit power increases as the number of antennas increases, where the consumption circuit power Q_c represents the base band processing power Q_{BB} due to conversion from analog to digital or digital to analog (ADC/DAC), and Q_{RF} is the consumption power in the radio frequency chains due to the noise amplifier. The equation is given as

$$Q_c = (Q_{BB} + Q_{RF}) \tag{12}$$

For BS, every antenna element requires radio frequency chain. This RF chain consumption power will produce the noise, due to the conversion processes from digital-to-analog (DAC), and analog-to-digital (ADC), when the power is transmitted from BS to users. An increase in the number of antenna arrays at BS causes a very large increase in the cost of wireless communication due to the large number of radio frequency chains (RF).

The consumption circuit power transmitted with zero-forcing beamforming from every antenna to every active user is given by

$$Q_{SP} \triangleq \frac{R_{flops}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{Cool})} \tag{13}$$

where R_{flops} represents the floating-point operations per antenna for all UE. The power amplifier efficiency [13] and [14] is given by

$$\eta \triangleq \frac{1}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{Cool})} \tag{14}$$

where η represents the independent power for cooling, the main power supply, and the DC-DC converter loss.

We investigate the maximal EE for downlink massive MIMO systems using zero-forcing beamforming (ZFBF), dependent on the number of antenna elements and the optimal number of users inside the cell to optimize the transmit power.

Lemma 1: The maximal EE with CSI depends on the optimal number of antennas, M and a limited number of active users, where active users (UE) should be scheduled in each cell due to the transmit power:

$$EE = \frac{K log_2\left(1+Q_t\frac{M-K}{K}\right)}{\eta Q_t + KQ_c + Q_{SP}} \tag{15}$$

The EE is affected by various system parameters such as the number of users inside cells and the number of transmit antennas. A function $\mathscr{b}(K, M_{Tx})$ is given as in Equation (16)

$$\mathscr{b}(K, M_{Tx}) = \left[\frac{Q_t Q_c\,(M-K)}{(\eta Q_t + Q_{SP})\,ln\,2} + Q_t\frac{M-K}{K\,ln\,2}\right] - \left[\left(1 + Q_t\frac{M-K}{K}\right) \times log_2\left(1 + Q_t\frac{M-K}{K}\right)\right] \tag{16}$$

We assume the variable to be as follows: $\mathscr{w} = \frac{1}{K}$, where the interval for UEs is $\mathscr{w} \in (0,1]$, $\tau = Q_t(M-K)$, $\mathcal{Z} = \eta Q_t + Q_{SP}$, and $\mathscr{y} = Q_c$.

Based on the average data rate, the upper bound of EE for BS is derived by

$$\frac{\partial \widehat{EE_{ZFBF}}}{\partial \mathscr{w}} = \frac{\partial\left(\frac{log_2(1+\tau\mathscr{w})}{\mathscr{y}+\mathscr{w}\mathcal{Z}}\right)}{\partial \mathscr{w}} \tag{17}$$

To get the maximum EE and total transmit power Q_t with respect to $\mathscr{w} = \frac{1}{K}$, we derive the EE to get the closed-form expression of $\mathscr{w}$ from Equation (17):

$$\frac{\partial \widehat{EE_{ZFBF}}}{\partial \mathscr{w}} = \frac{\frac{\tau(\mathscr{y}+\mathscr{w}\mathcal{Z})}{(1+\tau\mathscr{w})ln2} - \mathcal{Z}\,log_2(1+\tau\mathscr{w})}{(\mathscr{y}+\mathscr{w}\mathcal{Z})^2} \tag{18}$$

$$= \frac{\left(\frac{\tau\mathscr{y}}{\mathcal{Z}ln2} - \frac{\tau}{ln2}\mathscr{w}\right) - (1+\tau\mathscr{w})log_2(1+\tau\mathscr{w})}{\frac{1}{\mathcal{Z}}(\mathscr{y}+\mathscr{w}\mathcal{Z})^2(1+\tau\mathscr{w})} \tag{19}$$

According to the numerator in Equation (18),

$$f(\mathscr{w},\tau) = \left(\frac{\tau\mathscr{y}}{\mathcal{Z}ln2} + \frac{\tau}{ln2}\mathscr{w}\right) - (1+\tau\mathscr{w})log_2(1+\tau\mathscr{w}) \tag{20}$$

According to the first derivative, we simplify Equation (18):

$$\frac{\partial \widehat{EE_{ZFBF}}}{\partial \mathscr{w}} = \frac{f(\mathscr{w},\tau)}{\frac{1}{\mathcal{Z}}(\mathscr{y}+\mathscr{w}\mathcal{Z})^2(1+\tau\mathscr{w})} \tag{21}$$

where the derivative in term $\mathscr{w}$ is given by

$$\frac{f(\mathscr{w},\tau)}{\partial \mathscr{w}} = \frac{\tau}{ln2} - \left(\tau log_2(1+\tau\mathscr{w}) + \frac{\tau}{ln2}\right) < 0 \tag{22}$$

From the derivative, we note that the function $f(\mathscr{w},\tau)$ decreases according to the interval between $\mathscr{w} \in (0,1]$ at an increase of $\mathscr{w}$, and is given by

$$\lim_{\mathscr{w}\to 0^+} f(\mathscr{w},\tau) = \frac{\tau\mathscr{y}}{\mathcal{Z}ln2} > 0 \tag{23}$$

Consequently, when the $\lim_{\mathscr{w}\to 0^+} f(\mathscr{w},\tau) > 0$, the EE increases depending on the interval from $\mathscr{w} \in (0,1]$. When $f(\mathscr{w},\tau_{min}) > 0$, the transmit power increases, which provides the critical number of antennas M_{Tx}^{cri}. The critical number of antennas can be calculated using the root of Equation (16) due to the increased number of antennas at the BS, which confirms $f(\mathscr{w},\tau)|_{M_{Tx}=M_{Tx}^{cri}=0}$.

In addition, the maximum energy efficiency that can be obtained according to $(\mathscr{w}^{opt},\tau) = 0$ is dependent on the optimal number of users K^{opt}. When using the root in Equation (16), the number of antennas becomes greater than the critical number of antennas $M_{Tx} \geq M_{Tx}^{cri}$ and there exists an optimal number of $K^{opt} = \frac{1}{w^{opt}}$. In this case, when the number of antennas becomes less than the critical number of antennas $M_{Tx} \leq M_{Tx}^{cri}$, the number of UEs inside the cell increases, and the EE start decreasing according to $w = \frac{1}{K}$:

$$f(w,\tau) = \begin{cases} > 0 & M_{Tx} = M_{Tx}^{cri} \\ = 0 & M_{Tx} \geq M_{Tx}^{cri} \\ \leq 0 & M_{Tx} < M_{Tx}^{cri} \end{cases} \quad (24)$$

3. Results and Discussion

Fig. 2 shows that the number of transmit antennas plays very important role to determine the optimal number of users for maximal EE. The maximal value of EE at $M = 105$ and $K = 13$ is achieved when $Q_t = 0.7684$. The maximal EE can be achieved when the number of transmit antennas more than the critical number of antennas $M_{Tx} \geq M_{Tx}^{cri}$. The optimal number of active users $K^{opt} \geq 1$ can be achieved under different amounts of transmit power to every active user, when $\mathscr{b}(K, M_{Tx}) = 0$. Based on Fig. 2, the EE is a quasi-concave function. The adoption of 50-150 antennas is able to provide high data rate for optimal number of users to get the maximal EE, and the maximal EE is equal to 13.24 (Mbit/Joule), when the *(M, K)* = (105, 13).

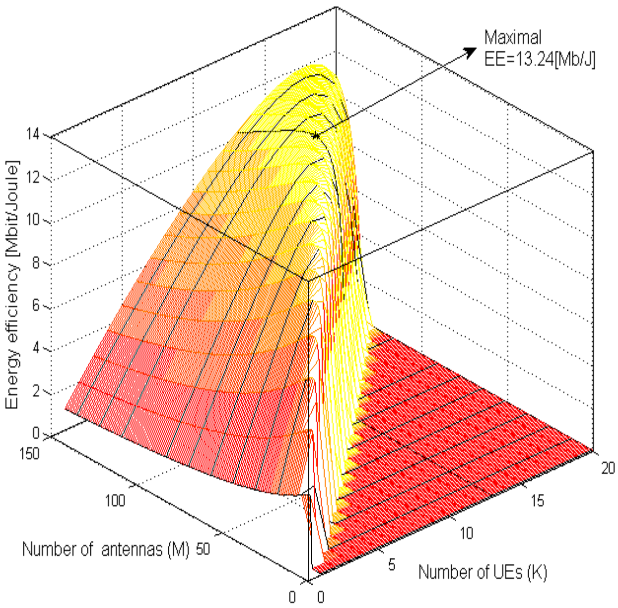

Fig. 2 Relation of EE to the number of antennas *M* and the number of UEs.

From Fig. 3, the maximal EE can be obtained dependent on increasing the number of antennas and limiting the number of users when $M_{Tx} \geq M_{Tx}^{cri}$ and $\mathscr{b}(K, M_{Tx}) = 0$. From Fig. 3, the EE first increases and then decreases corresponding to the increase number of antennas, which maximizes the transmit power Q_t, when taking into account the consumption circuit power and the transmit power. The maximum EE occur when the numbers of antennas are $(30, 35, 38)$, and the number of the active users are equals $(15, 20, 25)$ as shown in Fig.3. Otherwise, the performance of EE and optimal number of antennas can be obtained when the transmit power is larger than the consumption circuit power. The EE begins to decrease after achieving the peak value due to the increment of transmit power and number of distributed users K inside the cells. Otherwise, the maximum EE occurs when the consumption circuit power is comparable to the transmission power. In addition, the randomly distributed of active users inside the cell and the increment of number of antennas will increase both of the transmit power and the circuit operating power consumption, which makes the EE distribution becomes concave shape.

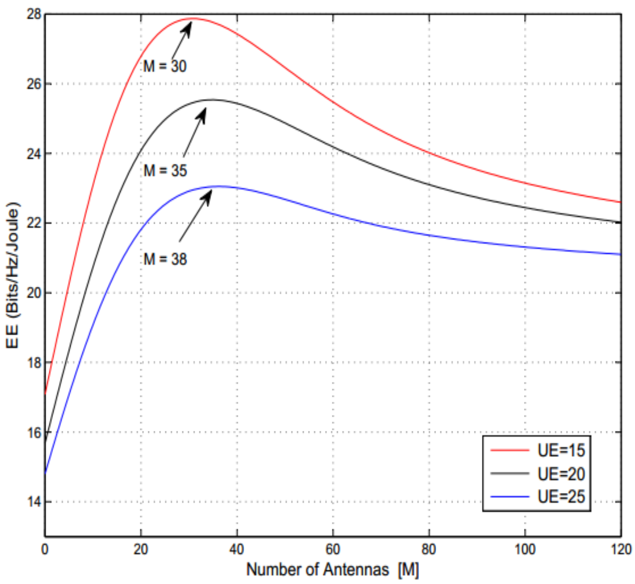

Fig. 3 Performance EE with the number of antennas *M*.

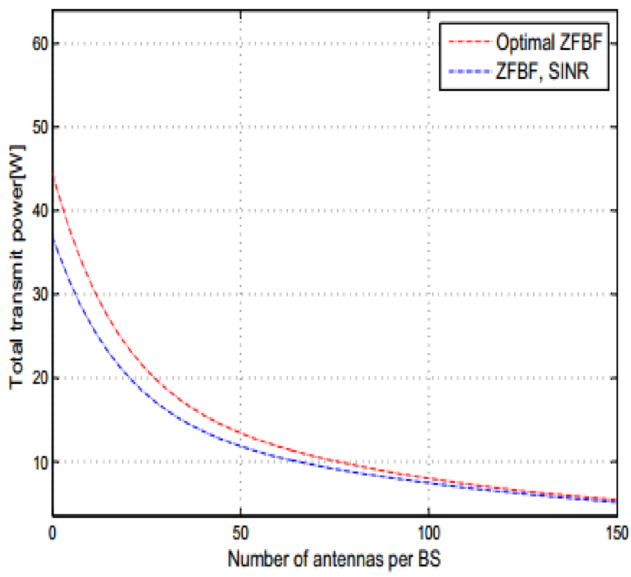

Fig. 4 Total transmit power versus number of antennas per BS.

Fig. 4, illustrates the total transmit power in single-cell massive MIMO systems. The BS transmits signal to every UE, which maximizes the EE according to the numbers of transmitting antennas. Otherwise, the total transmits power increases as the numbers of antennas becomes smaller in a single cell. This is due to the increase number of distributed users K inside cell and the effect of different numbers of antennas as shown in Fig. 4. The transmitted power will decrease with the increment of M, where the larger numbers of BS antennas consumes more power and provides the same target QoS level compared to only a few BS antennas. The ZFBF has low complexity and the performance is very close to the maximum-likelihood multi-user. We can state that the ZFBF are able to work at high SINR and cancels the intra-cell interference when the number of antenna arrays increases.

4. Conclusion

The energy efficiency in a massive MIMO system is achieved by increasing the number of antennas at the BS. Therefore, the randomly distributed number of users inside the cell will make the EE decreases due to the increase number of antennas when the total transmit power is large. In addition, the EE also decreases due to the influence of circuit power, which does not satisfy the QoS because the data rate for every user is achieved in parallel. From the simulation result, the performance of EE and optimal number of antennas can be obtained when the transmit power is larger than the consumption circuit power and the optimal number of users $K^{opt} \geq 1$, when $M_{Tx} \geq M_{Tx}^{cri}$, for optimal function $\mathscr{b}(K, M_{Tx})$.

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