Antenna Scheduling for Energy-Efficient Transmission in Massive MIMO Environments

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Abstract: The use of massive multiple-input multiple-output (m-MIMO) systems has been considered as one of key technologies in advanced wireless communication systems. However, it may need to employ an energy-efficient transmission technique. The energy efficiency can be improved by using a minimal number of transmit antennas enough to provide desired performance. However, it may require large computational complexity to optimally schedule a set of transmit antennas. In this paper, we consider minimal use of m-MIMO antennas with power control without large computational complexity. We determine the number of transmit antennas and the corresponding antenna subset by exploiting average channel information. We also adjust the transmit power and the spatial multiplexing order to provide desired performance. Finally, we verify the proposed scheme by computer simulation.[1]

Keywords—**Massive MIMO, Energy-efficiency, Antenna scheduling, Transmit power allocation**

1. Introduction

The use of massive multiple-input multiple-output (m-MIMO) has widely been considered as one of the key technologies in advanced wireless communication systems due to the advantages of large-scale antennas [1]. However, the use of a large number of antennas may increase the power consumption of antenna circuitry, which may offset the transmit power saving through m-MIMO transmission. As a matter of fact, it may be desirable to consider the total power consumption, i.e., the power consumption of signal transmission and antenna circuitry.

Recently, a few research works have considered partial use of m-MIMO antennas to maximize energy efficiency [2]-[3]. However, they may require a large number of iteration processes, making it infeasible in m-MIMO environments. It may be desirable for energy efficiency to schedule transmit antennas without large complexity in m-MIMO environments.

In this paper, we consider the antenna scheduling with power control for energy-efficient transmission in m-MIMO environments. We first determine the number of transmit antennas to minimize the total power consumption in a suboptimal manner. Showing that the total power consumption is a monotonically decreasing function of the Frobenius norm of the channel, we select a set of antennas to maximize the Frobenius norm. For a selected set of transmit antennas, we can formulate minimizing the total power consumption as a convex problem. Finally, we adjust the transmit power and the spatial multiplexing order by exploiting the KarushKuhn-Tucker (KKT) condition [4].

The rest of this paper is organized as follows. The systems model is described in Section 2. The proposed energy-efficient transmission scheme is described in Sections 3. The performance of the proposed scheme is verified by computer simulation in Section 4. Finally, conclusions are summarized in Section 5.

2. System Model

Consider the downlink transmission in a m-MIMO environment, where a base station (BS) has N_T transmit antennas and each user have N_R receive antennas. We assume that the BS has perfect channel state information (CSI) of users and transmits the signal using $N_{T,sel}\,(\leq N_T)$ antennas. Let $S^{N_{T,sel}}$ be a set of all $N_{T,sel}$-transmit antenna subsets, denoted by $S^{N_{T,sel}} \equiv \{\Omega_1^{N_{T,sel}}, \ldots, \Omega_{{}_{N_T}C_{N_{T,sel}}}^{N_{T,sel}}\}$, and $\mathbf{H}_l^{N_{T,sel}}$ be the channel matrix from the BS to a user, formed by the l-th antenna subset of $S^{N_{T,sel}}$, $\Omega_l^{N_{T,sel}}$. Assume that M beams are transmitted through antenna subset $\Omega_l^{N_{T,sel}}$. The signal received by the user can be represented as

$$\mathbf{y} = \sqrt{\alpha}\mathbf{W}^H\mathbf{H}_l\mathbf{F}\mathbf{x} + \mathbf{W}^H\mathbf{n}, \tag{1}$$

where $\mathbf{y}$ is the $(M \times 1)$ received signal vector, α is the path loss from the BS to the user, $\mathbf{W}$ is the $(N_R \times M)$ receive combining matrix and $\mathbf{F}$ is the $(N_{T,sel} \times M)$ precoding matrix, $\mathbf{H}_l$ is the $(N_R \times N_{T,sel})$ channel matrix from the BS to the user, $\mathbf{x}$ is the symbol vector, and $\mathbf{n}$ is zero-mean complex circular-symmetric additive white Gaussian noise (AWGN).

We consider the signal transmission by means of singular value decomposition (SVD)-based spatial multiplexing. It can be shown that $\mathbf{W}$ and $\mathbf{F}$ are unitary matrices, and that the achievable transmission rate through the m-th beam can be represented as

$$C_m = \log_2\left(1 + \frac{\alpha\sigma_{l,m}^2 p_{t,m}}{\sigma_n^2}\right), \tag{2}$$

where $\sigma_{l,m}^2$ is the m-th eigenvalue of $\mathbf{H}_l\mathbf{H}_l^H$, $p_{t,m}$ is the transmit power allocated to the m-th beam and σ_n^2 is the noise power.

The total power consumption by an antenna module can be represented as [5]

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$$P_{total} = \sum_{m=1}^{M} p_{t,m} + P_{RF} N_{T,sel} + P_{idle}\left(N_T - N_{T,sel}\right) + P_{syn}, \quad (3)$$

where P_{RF} is the power consumption by the antenna circuitry including digital-to-analog converters, mixers and filters, P_{idle} is the power consumption of antenna circuitry in an idle mode, and P_{syn} is the power consumption by the frequency synthesizer (i.e., local oscillator) [5]. We define the energy efficiency by the ratio of the achievable transmission rate and the total power consumption by the antenna module, represented as [5]

$$\eta = \frac{B \sum_{m=1}^{M} C_m}{P_{total}} \text{ (bits/Joule)}, \quad (4)$$

where B denotes the signal bandwidth.

3. Proposed m-MIMO Transmission

We consider the scheduling of m-MIMO antennas, and the adjustment of spatial multiplexing order and transmit power to provide the required transmission rate C_{req} in an energy-efficient manner. The optimal solution maximizing the energy efficiency can be found through the exhaustive search. Instead, we consider the derivation of a solution in a suboptimal manner. To this end, we first determine the number of transmit antennas, $\hat{N}_{T,sel}$, and the corresponding transmit antenna subset. Then, we adjust the transmit power and the spatial multiplexing order.

3.1 Antenna Scheduling

We can determine the number of transmit antennas to minimize the total power consumption as

$$\begin{array}{ll} \min & \sum_{m=1}^{M} \frac{\left(2^{C_m}-1\right)\sigma_n^2}{\alpha \sigma_{l,m}^2} + \Delta P N_{T,sel} + P_{static} \\ \text{s.t.} & \sum_{m=1}^{M} C_m \geq C_{req}, \end{array} \quad (5)$$

where $\Delta P = P_{RF} - P_{idle}$, $P_{static} = P_{idle} N_T + P_{syn}$, the first term of (5) is the power consumption for the signal transmission, and the rest two terms are the power consumption by antenna circuitry. It can be conjectured that the power consumption by the antenna circuitry is an affine function of $N_{T,sel}$. However, it may not be easy to conjecture the relation between the power consumption for the signal transmission and $N_{T,sel}$. Instead, we estimate the transmit power consumption in an average sense.

The transmission of M beams with $\{\sigma_1^2, ..., \sigma_M^2\}$ can approximately be interpreted as one with an average eigenvalue of $\overline{\sigma}_l^2 = \sum_{m=1}^{M} \sigma_{l,m}^2 / M$. The average rate is defined as $\overline{C} = \log_2\left(1 + \frac{\alpha \overline{\sigma}_{l,m}^2 \overline{p}_{t,m}}{\sigma_n^2}\right)$, where $\overline{p}_t$ is the average transmit power. The problem (5) can be reformulated as

$$\begin{array}{ll} \min & \tilde{P}_{total} = \frac{\Gamma(M)}{\overline{\sigma}_l^2} + \Delta P N_{T,sel} \\ \text{s.t.} & \overline{C} \geq C_{req}/M, \end{array} \quad (6)$$

where $\Gamma(M) \equiv \overline{\sigma}_l^2 \sum_{m=1}^{M} \overline{p}_t = \frac{M\sigma_n^2}{\alpha}\left(2^{\overline{C}} - 1\right)$, and P_{static} is omitted since it is a constant. Since $\tilde{P}_{total}$ in (6) is an increasing function of $\overline{C}$, and the inequality constraint is a convex set, it can be conjectured that the solution can be obtained when the inequality constraint satisfies the equality (i.e., $\overline{C} = C_{req}/M$) [4].

It can be shown that the average $\overline{\sigma}_l^2$ over $\mathbf{H}_l$ can be represented as [refer to Appendix]

$$\begin{aligned} \mathrm{E}\left[\overline{\sigma}_l^2\right] &\approx \left[1 + \sqrt{\frac{(N_R - M)}{M}\left(\frac{1}{\mathrm{E}\left[\cos^2(\theta_l)\right]} - 1\right)}\right] N_{T,sel} \\ &= \Psi(M) N_{T,sel}. \end{aligned} \quad (7)$$

The total power $\tilde{P}_{total}(N_{T,sel}, M)$ in (6) can be further simplified to

$$\overline{P}_{total}(N_{T,sel}, M) = \frac{\Gamma(M)}{\Psi(M)} \frac{1}{N_{T,sel}} + \Delta P N_{T,sel}. \quad (8)$$

Since $\overline{P}_{total}(N_{T,sel}, M)$ is a convex function of $N_{T,sel}$, it can be shown from $\nabla_{N_{T,sel}} \overline{P}_{total}(N_{T,sel}, M) = 0$ that

$$N_{T,sel}^*(M) = \left\lfloor \sqrt{\frac{\Gamma(M)}{\Psi(M)} \frac{1}{\Delta P}} \right\rfloor. \quad (9)$$

It can be seen that $\overline{P}_{total}(N_{T,sel}, M)$ in (8) is a function of M. Thus, $N_{T,sel}^*$ can be determined by finding M^* minimizing $\overline{P}_{total}(M)$ can be found as

$$M^* = \underset{1 \leq M \leq N_R}{\arg\min} \frac{\Gamma(M)}{\Psi(M) N_{T,sel}^*} + \Delta P N_{T,sel}^*(M). \quad (10)$$

We can sub-optimally determine the transmit antenna size as $\hat{N}_{T,sel} = N_{T,sel}^*(M^*)$. It can be seen from (6), (22), and the approximated eigenvalue in [6, Theorem 2.2] that $\tilde{P}_{total}$ is a monotonically decreasing function of $||\mathbf{H}_l||_F^2$. The corresponding antenna subset can be determined by choosing transmit antennas that maximize $||\mathbf{H}_l||_F^2$ as

$$\hat{\mathbf{H}}_l = \underset{\mathbf{H}_l \in S^{\hat{N}_{T,sel}}}{\arg\max} ||\mathbf{H}_l||_F^2. \quad (11)$$

3.2 Power Control and Beam Selection

For a selected set of transmit antennas, we consider the optimization of $p_{t,m}$ and M. It can be shown from (5) that optimizing $\mathbf{P}_t \left(= [p_{t,1}, \ldots, p_{t,M}]^T\right)$ is equivalent to optimizing $\mathbf{C}\left(= [C_1, \ldots, C_M]^T\right)$. Thus, $\mathbf{C}$ can be optimized as

$$\begin{aligned} \min \quad & \hat{P}_t\left(\mathbf{C}\right) = \sum_{m=1}^{M} \frac{\left(2^{C_m}-1\right)\sigma_n^2}{\alpha\hat{\sigma}_{l,m}^2} \\ \text{s.t.} \quad & \sum_{m=1}^{M} C_m \geq C_{req}, \end{aligned} \tag{12}$$

where $\hat{\sigma}_{l,m}^2$ denotes the m-th eigenvalue of $\hat{\mathbf{H}}_l\hat{\mathbf{H}}_l^H$. $\hat{P}_t\left(\mathbf{C}\right)$ is a strictly convex function of $\mathbf{C}$ and the inequality constraint in (12) is a convex set [4], implying that (12) is a convex problem. Thus, in the similar way in [4], $\mathbf{C}$ can be optimized as

$$\hat{C}_m = \left[\log_2\left(\frac{\hat{\mu}\alpha\hat{\sigma}_{l,m}^2}{\left(\log 2\right)\sigma_n^2}\right)\right]^+, \tag{13}$$

where $x^+ = \max\left(x, 0\right)$, and $\hat{\mu}$ is the Lagrange multiplier which can be determined to provide the required rate as $C_{req} = \sum_{m=1}^{\hat{M}} \left[\log_2\left(\frac{\hat{\mu}\alpha\hat{\sigma}_{l,m}^2}{(\log 2)\sigma_n^2}\right)\right]^+$. From (13), $\hat{M}$ can be determined and $\hat{p}_{t,m}$ can be obtained as $\frac{\left(2^{\hat{C}_m}-1\right)\sigma_n^2}{\alpha\hat{\sigma}_{l,m}^2}$ as in [4].

3.3 Computational Complexity

We measure the computational complexity of the proposed scheme in terms of the FLOP [7]. For fair comparison, we also measure the complexity of the optimal scheduling (OS). The OS exhaustively searches all possible sets of transmit antennas and the corresponding antenna subset. Since the singular value calculation of an $(m \times n)$ matrix approximately requires $\left(2mn^2 + 2n^3\right)$ FLOPs [7], it can easily be shown that the computational complexity of each scheduling scheme can be represented as

$$\xi_{OS} \quad = \sum_{N_{OS}=1}^{N_T} \binom{N_T}{N_{OS}} \left(2N_R N_{OS}^2 + 2N_{OS}^3\right), \tag{14}$$

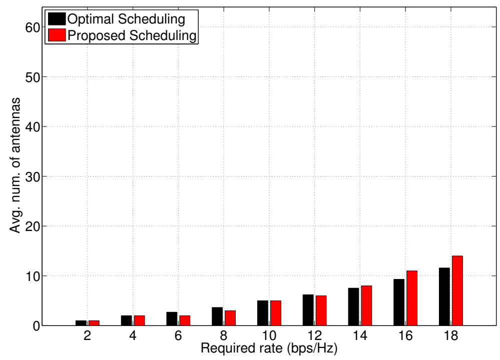
where N_{OS} is the number of antennas used by the OS.

$$\xi_{PROP} \quad = \begin{cases} N_T\left(2N_R - 1\right), & \text{if } N_{T,sel} \neq N_T \\ 0, & \text{if } N_{T,sel} = N_T. \end{cases} \tag{15}$$

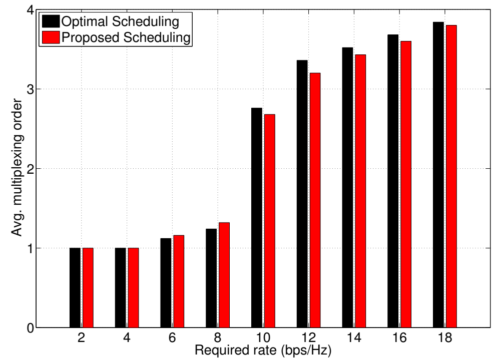
4. Performance Evaluation

We evaluate the performance of the proposed scheme by computer simulation. We assume that the signal bandwidth B is set to 180 kHz, users are equipped with 4 receive antennas, the path loss follows the 3GPP channel model [8] and the small-scale channel is subject to Rayleigh fading. The thermal noise density is set to -174 dBm/Hz. The system SNR is set to 15 dB. The parameters associated with the antenna circuitry are set as [5].

Fig. 1 depicts the average number of transmit antennas used for the signal transmission and the multiplexing order according to the required rate when $N_T = 64$. It can be seen that the proposed scheduling uses almost the same number of antennas and spatial multiplexing order as the optimal scheduling.



(a) Average number of transmit antennas



(b) Average multiplexing order

Figure 1. Average number of transmit antennas and multiplexing order for transmission.

Fig. 2 depicts the energy efficiency according to the transmit antenna size N_T when the required rate is 9 bps/Hz. For comparison, we also consider the energy efficiency of full antenna use (i.e., no scheduling), random scheduling of an antenna subset, and the optimal scheduling. The proposed power control is applied to all the schemes. It can be seen that the proposed scheduling provides energy efficiency quite similar to the optimal scheduling, while significantly outperforming the other two schemes.

Fig. 3 depicts the computational complexity of the proposed and the optimal scheduling according to the transmit antenna size N_T. It can be seen that the complexity of the proposed scheduling increases almost linearly proportional to N_T, while the optimal scheduling increases almost exponentially proportional to N_T.

5. Conclusions

In this paper, we have considered the energy-efficient transmission in m-MIMO environments. Considering the power consumption of transmit antenna circuitry in addition to the transmit power, we have considered partial use of m-MIMO antennas by exploiting the average channel information. We have also considered the management of transmit power and spatial multiplexing order to minimize the total

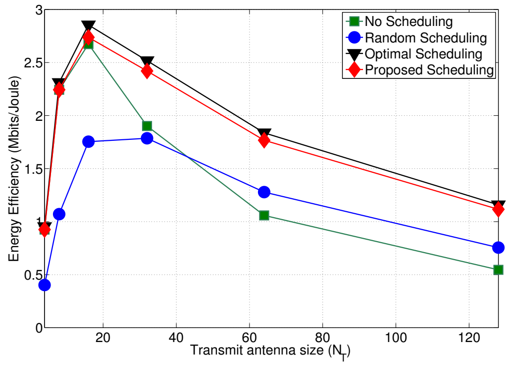


Figure 2. Energy efficiency.

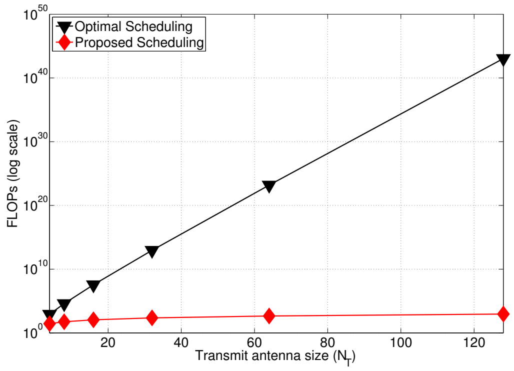


Figure 3. Computational complexity.

power consumption. The numerical results show that the proposed scheme can provide performance similar to the optimal scheme, while significantly reducing the computational complexity.

Appendix

To obtain the relation between $\mathrm{E}\left[tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)\right]\right]$ and $\mathrm{E}\left[\left(tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)\right]\right)^2\right]$, we use the inner product of Hermitian matrices, defined as $\langle \mathbf{A}, \mathbf{B}\rangle = tr\left[\mathbf{AB}\right]$ [6]. Let θ_l be the angle between the Hermitian matrix $\mathbf{H}_l\mathbf{H}_l^H$ and the identity matrix in a space of $(N_R \times N_R)$, $\mathbf{I}_{N_R}$. From the inner product of $\mathbf{H}_l\mathbf{H}_l^H$ and $\mathbf{I}_{N_R}$, it can be seen that

$$tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)^2\right] = \frac{1}{N_R\cos^2\theta_l}\left(tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)\right]\right)^2. \quad (16)$$

Using the fact that eigenvalues of $\mathbf{H}_l\mathbf{H}_l^H$ are non-negative, it can easily be shown that $tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)^2\right] \leq \left(tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)\right]\right)^2$. Thus, it can be seen that

$$\frac{1}{N_R} \leq \cos^2\theta_l. \quad (17)$$

It can also be seen from Cauchy-Schwartz inequality that

$$\begin{aligned}\left(tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)\right]\right)^2 &= \left(\sum_{m=1}^{\mathrm{rank}(\mathbf{H}_l)}\sigma_{l,m}^2\right)^2\\ &\leq \left(\sum_{m=1}^{\mathrm{rank}(\mathbf{H}_l)}\left(\sigma_{l,m}^2\right)^2\right)\left(\sum_{m=1}^{\mathrm{rank}(\mathbf{H}_l)}1^2\right)\\ &= tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)^2\right]\mathrm{rank}\left(\mathbf{H}_l\right).\end{aligned} \quad (18)$$

Thus, it can be shown that

$$\cos^2\theta_l \leq \frac{\mathrm{rank}\left(\mathbf{H}_l\right)}{N_R}. \quad (19)$$

From (17) and (19), it can be shown that

$$\mathrm{E}\left[\cos^2\theta_l\right] = \frac{\sin\left(2\theta_l^{up}\right)-\sin\left(2\theta_l^{low}\right)}{4\left(\theta_l^{up}-\theta_l^{low}\right)} + \frac{1}{2}. \quad (20)$$

By averaging both sides of (16), it can be expressed as

$$\mathrm{E}\left[tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)^2\right]\right] \approx \frac{1}{N_R\mathrm{E}\left[\cos^2\theta_l\right]}\mathrm{E}\left[\left(tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)\right]\right)^2\right]. \quad (21)$$

Finally, it can be seen from the approximated eigenvalue in [6, Theorem 2.2], (21), and $\mathrm{E}\left[tr\left[\left(\mathbf{H}_l\mathbf{H}_l^H\right)\right]\right] \approx N_R N_{T,sel}$ [1] that

$$\mathrm{E}\left[\overline{\sigma}_l^2\right] \approx \left[1 + \sqrt{\frac{(N_R - M)}{M}\left(\frac{1}{\mathrm{E}\left[\cos^2\left(\theta_l\right)\right]} - 1\right)}\right]. \quad (22)$$

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