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PAPER

User and Antenna Joint Selection in Multi-User Large-Scale MIMO Downlink Networks*

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SUMMARY In this paper, we investigate a user and antenna joint selection problem in multi-user large-scale MIMO downlink networks, where a BS with N transmit antennas serves K users, and N is much larger than K. The BS activates only $S(S \leq N)$ antennas for data transmission to reduce hardware cost and computation complexity, and selects the set of users to which data is to be transmitted by maximizing the sum-rate. The optimal user and antenna joint selection scheme based on exhaustive search causes considerable computation complexity. Thus, we propose a new joint selection algorithm with low complexity and analyze the performance of the proposed scheme in terms of sum-rate and complexity. When $S = 7$, $N = 10$, $K = 5$, and SNR=10 dB, the sum-rate of the proposed scheme is 5.1% lower than that of the optimal scheme, while the computation complexity of the proposed scheme is reduced by 99.0% compared to that of the optimal scheme.

key words: *large-scale MIMO, massive MIMO, MU-MIMO, user and antenna joint selection, complexity*

1. Introduction

Mobile data traffic has been exponentially increasing in recent years [1], and the next-generation mobile communication system called 5G is thus receiving much attention from both academic and industrial fields [2]–[4]. The spectral efficiency of the 5G network should be significantly improved over the current mobile communication network because it is difficult to acquire an additional radio spectrum band for mobile communication networks. The large-scale multiple input multiple output (MIMO) is one of the promising technologies that can enhance the spectral efficiency of the 5G network [5]–[7]. In large-scale MIMO networks, a base station (BS) is equipped with hundreds or thousands of antennas and the spectral efficiency can thus be enhanced by transmitting data to multiple users. However, large-scale MIMO networks inevitably cause high complexity in terms of both hardware and computation. As the number of transmit antennas increases, the number of base-band (BB) and radio-frequency (RF) chains increases and the amount of computation to calculate precoders also increases. To reduce the complexity, a BS is equipped with a smaller number of BB and RF chains (S, $S \leq N$) than the number of available antenna elements (N). The BS selects S antennas out of N antennas and then the selected S antennas are only activated to transmit data. This antenna selection (AS) technique can significantly reduce the complexity at the BS with a slight loss in performance [8]–[11]. In addition, the large-scale MIMO networks cause a mismatch of antennas between BS and the user. In contrast to a BS, it is difficult to equip users with a large number of antennas due to the limit in size and cost. The antenna mismatch problem can be mitigated by the multi-user MIMO (MU-MIMO) technique, where a BS transmits data to multiple users simultaneously. In the MU-MIMO technique, the BS can maximize the sum-rate by selecting the optimal set of users [12]–[14].

In summary, a BS in MU large-scale MIMO networks needs to select the optimal set of users and optimal set of transmit antennas for maximizing the sum-rate and reducing the complexity [15]–[20]. In [15], the schemes that select users in two ways and then each selected user selects different transmit antennas were proposed. These schemes use all transmit antennas, i.e. transmit antennas are allocated to selected users equally. In [16], joint user scheduling and one transmit antenna group selection scheme was proposed. The scheme in [16] selects only one user and one antenna group. In [17]–[21], the joint user scheduling and transmit antenna selection schemes were proposed. In these schemes, the number of selected users and transmit antennas is fixed regardless of channel environment. In addition, although these previous studies proposed user and antenna joint selection algorithms and investigated the performance in terms of sum-rate or error probability, the effect of complexity reduction of the proposed schemes was not numerically analyzed, and thus the practical feasibility of the proposed schemes was not verified.

In this paper, we thus propose a new user and antenna joint selection algorithm, in which the number of selected users is fixed according to the channel environment. It offers low complexity even in MU large-scale MIMO networks. In addition, the performance of the proposed scheme is analyzed in terms of sum-rate and is compared with the optimal scheme based on exhaustive search. The complexity of the proposed scheme is numerically analyzed in terms of floating-point operations per second (flops). In addition, the analysis of the flops is verified by computer simulations.

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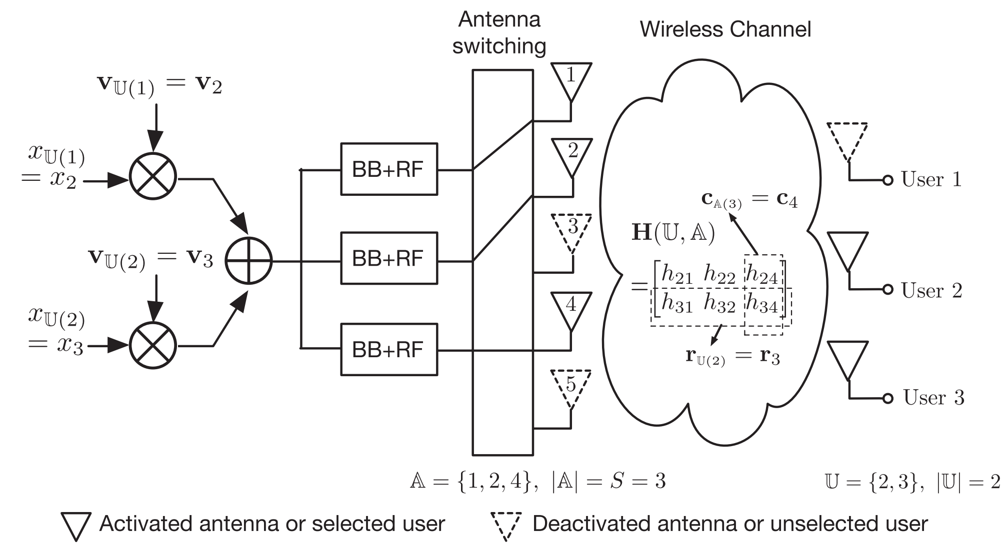

Fig. 1 A multi-user MIMO downlink network where $N = 5$, $S = 3$, and $K = 3$. User 2 and 3 are selected to receive data from BS.

The remainder of this paper is organized as follows. System and channel models are described in Sect. 2 and a user and antenna joint selection algorithm with a low complexity is proposed in Sect. 3. In Sect. 4, the complexity of the proposed scheme is numerically analyzed in terms of flops and is compared with the optimal scheme. Numerical results are shown in Sect. 5 and conclusions are drawn in Sect. 6.

2. System and Channel Models

We investigate a multi-user MIMO downlink network where a base station (BS) with N transmit antennas transmits data to K users with a single receive antenna. The BS is only equipped with $S(S \leq N)$ BB and RF chains to reduce the complexity and hardware cost and thus it selects S transmit antennas to be activated for transmitting data. In addition, the BS determines the optimal set of users to transmit data at each transmission for maximizing the sum-rate. We define $\mathbb{A}$ and $\mathbb{U}$ as the set of activated antennas and the set of users that BS selects to transmit data, respectively. $|\cdot|$ is defined as the cardinality of the set. Fig. 1 illustrates an exemplary multi-user MIMO downlink network, where $N = 5$, $S = 3$, $K = 3$, $\mathbb{A} = \{1, 2, 4\}$, and $\mathbb{U} = \{2, 3\}$.

For the given $\mathbb{A}$ and $\mathbb{U}$, the channel between the activated transmit antennas and selected users can be represented by a $|\mathbb{U}| \times |\mathbb{A}|$ matrix, $\mathbf{H}(\mathbb{U}, \mathbb{A}) = [h_{ij}]_{i \in \mathbb{U}, j \in \mathbb{A}}$, where h_{ij} denotes a channel coefficient between a transmit antenna j and user i. It is assumed that all channel coefficients are circular symmetric complex Gaussian distributed with zero-mean and unit variance to consider Rayleigh fading and they are independent and identically distributed (*i.i.d.*). It is also assumed that they are quasi-static to consider block fading. We consider a time division duplex (TDD) system and thus BS can obtain the perfect information on channel coefficients due to the channel reciprocity. $x_{\mathbb{U}(i)}$ indicates a scalar signal transmitted to user $\mathbb{U}(i)$ and satisfies

$$|x_{\mathbb{U}(i)}|^2 = p_{\mathbb{U}(i)} \text{ and } \sum_{i=1}^{|\mathbb{U}|} p_{\mathbb{U}(i)} = P, \tag{1}$$

where $p_{\mathbb{U}(i)}$ and P denote the transmit power assigned to user $\mathbb{U}(i)$ and total transmit power, respectively. $y_{\mathbb{U}(i)}$ denotes the signal received by user $\mathbb{U}(i)$ and can be described as

$$\begin{aligned} y_{\mathbb{U}(i)} &= \mathbf{r}_{\mathbb{U}(i)} \sum_{k=1}^{|\mathbb{U}|} \mathbf{v}_{\mathbb{U}(k)} x_{\mathbb{U}(k)} + n \\ &= \mathbf{r}_{\mathbb{U}(i)} \mathbf{v}_{\mathbb{U}(i)} x_{\mathbb{U}(i)} + \mathbf{r}_{\mathbb{U}(i)} \sum_{k=1, k \neq i}^{|\mathbb{U}|} \mathbf{v}_{\mathbb{U}(k)} x_{\mathbb{U}(k)} + n, \end{aligned} \tag{2}$$

where $\mathbf{r}_{\mathbb{U}(i)}$ is the i-th row of $\mathbf{H}(\mathbb{U}, \mathbb{A})$ and denotes channel coefficients between S activated transmit antennas in $\mathbb{A}$ and user $\mathbb{U}(i)$. $\mathbf{v}_{\mathbb{U}(i)}$ is the $S \times 1$ beamforming vector for user $\mathbb{U}(i)$ applied to S activated antennas and satisfies $||\mathbf{v}_{\mathbb{U}(i)}||^2 = 1$. In this paper, we consider block diagonalization (BD) precoding technique. The purpose of BD is to precode each user's signal $x_{\mathbb{U}(i)}$ such that

$$\mathbf{r}_{\mathbb{U}(i)} \mathbf{v}_{\mathbb{U}(k)} = 0 \text{ for all } i \neq k \text{ and } 1 \leq i, k \leq |\mathbb{U}|. \tag{3}$$

n denotes the additive white Gaussian noise (AWGN) with zero-mean and variance N_0 at receivers. Then, the signal-to-interference-plus-noise ratio (SINR) perceived at user $\mathbb{U}(i)$ can be obtained as

$$\begin{aligned} \text{SINR}_{\mathbb{U}(i)} &= \frac{p_{\mathbb{U}(i)} |\mathbf{r}_{\mathbb{U}(i)} \mathbf{v}_{\mathbb{U}(i)}|^2}{N_0 + \sum_{k=1, k \neq i}^{|\mathbb{U}|} p_{\mathbb{U}(k)} |\mathbf{r}_{\mathbb{U}(i)} \mathbf{v}_{\mathbb{U}(k)}|^2} \\ &= \frac{\text{SNR}_{\mathbb{U}(i)} |\mathbf{r}_{\mathbb{U}(i)} \mathbf{v}_{\mathbb{U}(i)}|^2}{1 + \sum_{k=1, k \neq i}^{|\mathbb{U}|} \text{SNR}_{\mathbb{U}(k)} |\mathbf{r}_{\mathbb{U}(i)} \mathbf{v}_{\mathbb{U}(k)}|^2}, \end{aligned} \tag{4}$$

where $\mathrm{SNR}_{\mathbb{U}(i)}$ defined by $\frac{p_{\mathbb{U}(i)}}{N_0}$ denotes the signal-to-noise ratio for user $\mathbb{U}(i)$. Finally, the sum-rate for the given $\mathbb{A}$ and $\mathbb{U}$ can be obtained as

$$R(\mathbb{A}, \mathbb{U}) = \sum_{i=1}^{|\mathbb{U}|} \log_2 \left(1 + \mathrm{SINR}_{\mathbb{U}(i)}\right). \tag{5}$$

3. Proposed User and Antenna Joint Selection Scheme

$\mathbb{A}$ and $\mathbb{U}$ maximizing $R(\mathbb{A}, \mathbb{U})$ can be obtained through joint optimization as follows:

$$\{\mathbb{A}^*, \mathbb{U}^*\} = \arg\max_{\mathbb{A}, \mathbb{U}} R(\mathbb{A}, \mathbb{U}), \tag{6}$$

which can only be solved by exhaustive search because it is a combinatorial problem and the corresponding computation complexity exponentially grows as N or K increases.

In this paper, we thus propose a new user and antenna joint selection scheme with a linearly growing computation complexity for N and K. The proposed selection algorithm is described in **Algorithm** 1. Initially, the proposed scheme sets $\mathbb{A} = \{1, \cdots, N\}$ and $\mathbb{U} = \{1, \cdots, K\}$, and obtains the corresponding $\mathbf{H}(\mathbb{U}, \mathbb{A})$. All antennas included in $\mathbb{A}$ are sorted according to $||\mathbf{c}_{\mathbb{A}(i)}||^2 (1 \le i \le |\mathbb{A}(i)|)$ in descending order, where $\mathbf{c}_{\mathbb{A}(i)}$ is the i-th column of $\mathbf{H}(\mathbb{U}, \mathbb{A})$ and denotes the channel coefficients between antenna $\mathbb{A}(i)$ and all users in $\mathbb{U}$. The set of sorted antennas is newly denoted by $\hat{\mathbb{A}}$ and thus it satisfies

$$||\mathbf{c}_{\hat{\mathbb{A}}(1)}||^2 \ge ||\mathbf{c}_{\hat{\mathbb{A}}(2)}||^2 \ge \cdots. \tag{7}$$

Then, we define windows for antenna selection as depicted in Fig. 2. A window for antenna selection consists of S consecutive antennas selected from $\hat{\mathbb{A}}$. Thus, S antennas $\hat{\mathbb{A}}(a)$ through $\hat{\mathbb{A}}(a + S - 1)$ constitute the a-th window and total $(N-S+1)$ windows can be defined. For a given antenna window, all users are sorted according to $||\mathbf{r}_{\mathbb{U}(i)}||^2 (1 \le i \le |\mathbb{U}(i)|)$ in descending order, where $\mathbf{r}_{\mathbb{U}(i)}$ denotes channel coefficients between S antennas included in the given antenna window and all users in $\mathbb{U}$. The set of sorted users is newly denoted by $\hat{\mathbb{U}}$ and it satisfies

$$||\mathbf{r}_{\hat{\mathbb{U}}(1)}||^2 \ge ||\mathbf{r}_{\hat{\mathbb{U}}(2)}||^2 \ge \cdots. \tag{8}$$

Algorithm 1 Pseudo code for the proposed scheme

Initialization:
  $\mathbb{A} = \{1, \cdots, N\}$ and $\mathbb{U} = \{1, \cdots, K\}$
  $\mathbf{H}(\mathbb{U}, \mathbb{A}) = [h_{ij}]_{i \in \mathbb{U}, j \in \mathbb{A}}$
  Sort antennas according to $||\mathbf{c}_{\mathbb{A}(i)}||^2 (1 \le i \le N)$ in
  descending order
for $a = 1 : (N - S + 1)$ **do** %Loop for antenna windows
  $\mathbb{A} = \{\hat{\mathbb{A}}(a), \hat{\mathbb{A}}(a+1), \cdots, \hat{\mathbb{A}}(a+S-1)\}$
  Sort users according to $||\mathbf{r}_{\mathbb{U}(i)}||^2 (1 \le i \le K)$ in
  descending order
  for $u = 1 : \min(K, S)$ **do** %Loop for user windows
    $\mathbb{U} = \{\hat{\mathbb{U}}(1), \cdots, \hat{\mathbb{U}}(u)\}$
    Update $\mathbf{H}(\mathbb{U}, \mathbb{A})$
    for $k = 1 : u$ **do**
      Compute $\mathbf{v}_{\hat{\mathbb{U}}(k)}$ and $\mathrm{SINR}_{\hat{\mathbb{U}}(k)}$
    end for
    Compute the sum rate $R(\mathbb{A}, \mathbb{U})$ for given $\mathbb{A}$ and $\mathbb{U}$
  end for
end for
Find $\mathbb{A}$ and $\mathbb{U}$ maximizing $R(\mathbb{A}, \mathbb{U})$

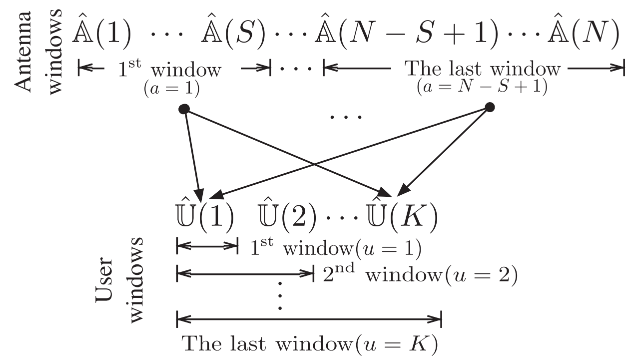

Fig. 2 The windows for antenna and user selections in the proposed scheme.

As depicted in Fig. 2, the length of windows for antenna selection is fixed as S while the length of windows for user selection varies from 1 to K. Thus, the u-th window for user selection consists of u users $\hat{\mathbb{U}}(1)$ through $\hat{\mathbb{U}}(u)$. After $(N - S + 1) \times K$ iterations, the best windows for antennas and users are selected to maximize the sum-rate.

4. Computation Complexity Analysis

In this section, we analyze the computation complexity of the proposed scheme in terms of flops and compare this with the optimal scheme based on exhaustive searching because one of the major motivations for the proposed scheme is to reduce the computation complexity. One flop is defined as one real floating point operation [22]. A real addition, multiplication, or division has one flop while a complex addition and a complex multiplication have 2 flops and 6 flops, respectively. Although the proposed scheme works well regardless of the beamforming schemes, we consider a block diagonalization-based beamforming [23], and transmit power is uniformly allocated to each user. For calculating the beamforming vector of a user i, $1 \le i \le K$, BS first calculates the null space of the remaining $(K - 1)$ users, except user i. The null space of a matrix can be easily obtained by singular value decomposition (SVD). Thus, we only consider the flops required for SVD operations, similarly to [24], because the flops required to calculate beamforming vectors based on block diagonalization is dominated by the SVD operations.

The flop count of the SVD operation for $\mathbf{H} \in \mathbb{C}^{m \times n}$ is given by $24mn^2 + 48m^2n + 54m^3$ [24]. For a given $\mathbf{H}(\mathbb{U}, \mathbb{A})$ satisfying $|\mathbb{U}| = u (1 \le u \le \min(K, S))^\dagger$, the flop count to calculate the beamforming vector for a specific user is given by

†Note that $|\mathbb{A}|$ is constant S while $|\mathbb{U}|$ is variable.

$$\begin{cases} 24S^2 + 48S + 54, & \text{if } u = 1 \\ 24(u-1)S^2 + 48(u-1)^2S + 54(u-1)^3, & \text{if } u \geq 2, \end{cases} \tag{9}$$

because BS calculates the null space of $(u-1)$ users, except for the specific user. This SVD operation is repeatedly carried out u times to calculate the beamforming vectors for u users.

For the optimal scheme, we have $\binom{K}{u}$ combinations to select u users from K users and $\binom{N}{S}$ combinations to select S antennas from N antennas. Then, the flop count required for the optimal scheme can be obtained as

$$F^{\text{Opt}} = \binom{N}{S}\Bigg[\binom{K}{1}(24S^2 + 48S + 54) + \sum_{u=2}^{\min(K,S)} \binom{K}{u} u\Big\{24(u-1)S^2 + 48(u-1)^2S + 54(u-1)^3\Big\}\Bigg]. \tag{10}$$

Contrary to the optimal scheme, the proposed scheme carries out $\min(K, S)$ iterations for user selection and $(N - S + 1)$ iterations for antenna selection. Thus, the flop count required for the proposed scheme can be calculated as[†]

$$F^{\text{Prop}} = (N - S + 1) \times \Bigg[24S^2 + 48S + 54 + \sum_{u=2}^{\min(K,S)} u\Big\{24(u-1)S^2 + 48(u-1)^2S + 54(u-1)^3\Big\}\Bigg]. \tag{11}$$

If $K \leq S$, then (10) and (11) can be simplified by

$$F^{\text{Opt}} = \frac{3}{8}\binom{N}{S}K\Big[9 \cdot 2^K K^3 + 16S \cdot 2^K K^2 (18 - 16S^2) \cdot 2^K + 16(4S^2 + 8S + 9)\Big] \tag{12}$$

and

$$F^{\text{Prop}} = \frac{1}{10}(N - S + 1)\Big[108K^5 + (120S - 135)K^4 + (80S^2 - 80S - 90)K^3 - (120S - 135)K^2 - (80S^2 - 80S + 18)K + 240S^2 + 480S + 540\Big], \tag{13}$$

respectively.

From (12) and (13), it can be shown that for a large-scale antenna network where N is much larger than both K and S, and $K \leq S$, then the computation complexities of the proposed and optimal schemes grow in the order of $O(N)$[††] and $O(\binom{N}{S})$, respectively. If both N and K are much larger than S, the complexity of the proposed scheme has the order of $O(NK^5)$ while the optimal scheme has the order of $O(\binom{N}{S}2^K K^4)$.

[†]Although the proposed scheme requires additional flops for sorting user and antenna sets, they are ignored for simplicity because they are insignificant compared with SVD operations.

5. Numerical Results

The performance of the proposed scheme is investigated in terms of average sum-rate and computation complexity, and it is compared with the optimal scheme based on brute-force searching. In this paper, we show several performances when $N \leq 15$. It is hard to simulate the average sum-rates and the complexity reduction ratio when $N > 10$ and $N > 15$ respectively because of explosively high complexity of optimal scheme.

Figure 3 shows the average sum-rates for K values when $N = 10$, $S = 7$, and SNR $\in$ {0 dB, 10 dB, 20 dB}. The average sum-rate of the proposed scheme is always lower than the optimal scheme. However, the difference in the sum-rate between two schemes is marginal and disappears as K decreases or SNR decreases. When SNR=10 dB, the average sum-rate of the proposed scheme decreases by 5.1% and 11.3% for $K = 3$ and $K = 5$, respectively, compared to the optimal scheme. Figure 4 shows the average sum-rates for S values when $N = 10$, $K = 10$, and SNR=0, 10, or 20 dB. Similarly to that shown in Fig. 3, the average sum-rate of the proposed scheme is slightly degraded compared to the optimal scheme, but the performance degradation is ignorable as S decreases or SNR decreases.

Figure 5 shows the average sum-rates for N values when $K = 7$, SNR $\in$ {0 dB, 10 dB, 20 dB}, and $S = \left[\frac{1}{2}N\right]$, where $[\cdot]$ denotes a rounding operation. The average sum-rate of the optimal scheme is shown only for $2 \leq N \leq 10$ due to

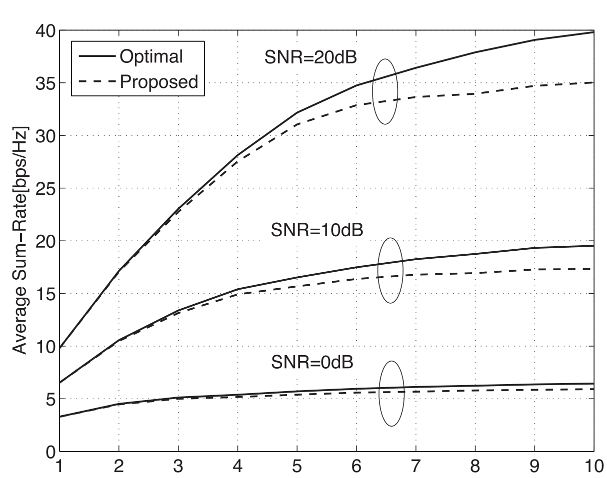

Fig. 3 Average sum-rates for various K values when $N = 10$ and $S = 7$.

[††]$f(x) = O(g(x))$ if and only if there exists a positive real number M and a real number x_0 such that $|f(x)| \leq M|g(x)|$ for all $x \geq x_0$.

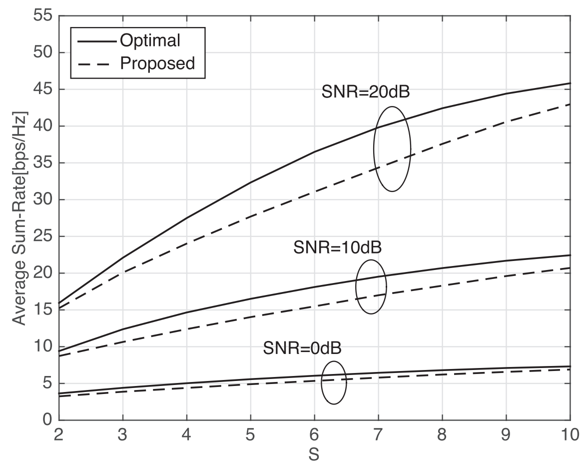

Fig. 4 Average sum-rates for various S values when $N = 10$ and $K = 10$.

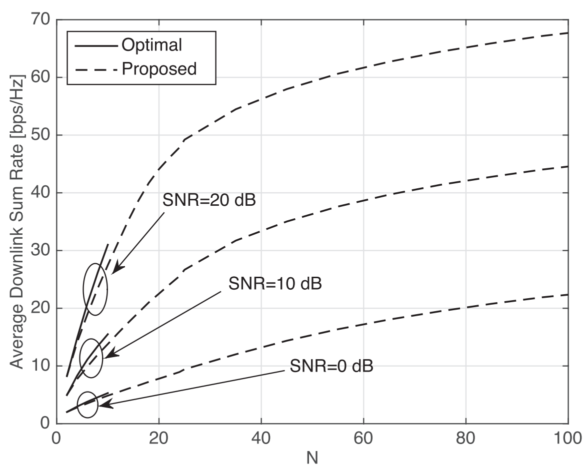

Fig. 5 Average sum-rates for various N values when $K = 7$ and $S = \left[\frac{1}{2}N\right]$, where $[\cdot]$ denotes a rounding operation.

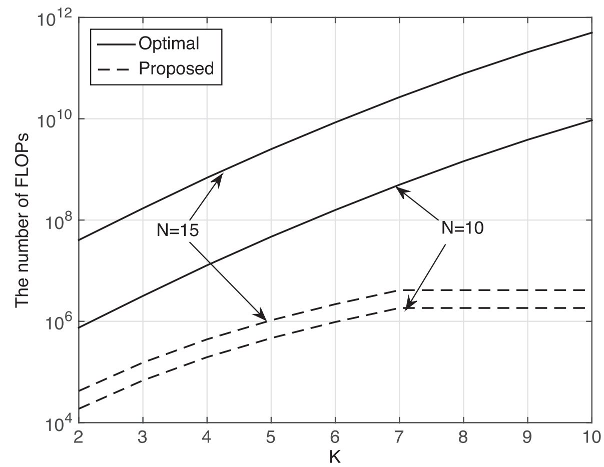

Fig. 6 The number of flops for various K values when $S = 7$.

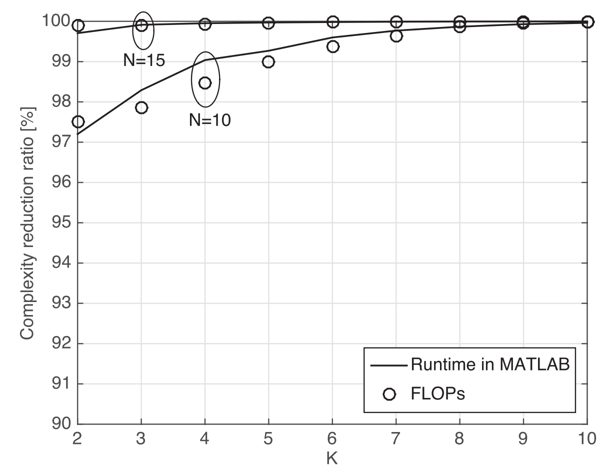

Fig. 7 The complexity reduction ratio η of the proposed scheme obtained by the number of flops and simulation rumtime when $S = 7$.

its catastrophic complexity. It is shown that the proposed scheme works well with large-scale anennas contrary to the optimal scheme. In addition, it is expected that the performance gap between the proposed and optimal schemes is not significant even when a BS is equipped with large-scale antennas.

Figure 6 compares the flops of the proposed scheme with the optimal scheme when N=10 or 15, $S = 7$, $K = 2 \sim 10$. It is shown that the proposed scheme can dramatically reduce the computation complexity compared with the optimal scheme and the flops of the proposed scheme is constant for $K \geq S$ because a BS can not select users larger than S. We define the complexity reduction ratio of the proposed scheme compared to the optimal scheme as

$$\eta[\%] = \frac{F^{\text{Opt}} - F^{\text{Prop}}}{F^{\text{Opt}}} \times 100. \tag{14}$$

When $N = 10$ as shown in Fig. 6, $\eta = 99.0\%$ for $K = 5$ and $\eta = 99.9\%$ for $K = 10$.

Although the flop count can effectively characterize the computation complexity of an algorithm, it cannot reflect the real runtime of the algorithm. In Fig. 7, we thus measure the runtime of the proposed and optimal algorithms in MATLAB, and we substitute the runtime for the flops in Eq. (14) to obtain another ratio depicted by solid lines. It is shown that the η approaches 100% as K or N increases. The flop-based numerical complexity considers the flop count only required for SVD operations, while the runtime in MATLAB includes other operations as well as SVD. As K or N increases, the ratio of SVDs out of total operations also increases, and thus η obtained by the flop count matches well with that obtained by real runtime.

6. Conclusion

In this paper, we studied an MU large scale MIMO network where a BS with N transmit antennas serves K users with a single receive antenna. The BS can transmit data to multiple users simultaneously. In the MU large scale MIMO network, the BS activates only S transmit antennas for each data transmission to reduce the hardware cost and computation complexity. In addition, a subset of total users is selected to transmit data for maximizing the sum-rate. Although the optimal joint selection algorithm can be implemented by exhaustive searching, it is infeasible due to its excessive computation complexity. Thus, we proposed a simple algorithm which can dramatically reduce the computation complexity while only having a slight degradation in sum-rate. Our numerical analysis shows that if both N and K are much larger than S, the complexity order of the proposed scheme is given as $O(NK^5)$, while the complexity order of the optimal scheme is given as $O(\binom{N}{S}2^K K^4)$. Specifically, when $S = 7$, $N = 10$, $K = 5$, and SNR=10dB, the sum-rate of the proposed scheme decreases by 5.1%, while the computation complexity of the proposed scheme is reduced by 99.0% compared with the optimal scheme.

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