Journal of Southeast University (English Edition) Vol. 24, No. 1, pp. 1 – 5 Mar. 2008 ISSN 1003—7985

Employing temporal channel correlation in user selection for MIMO broadcast systems

Wang Jing Jiang Zhanjun Wang Yan You Xiaohu

(National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China)

Abstract: Taking the time varying nature of wireless channels into account, two user selection schemes with lower complexity are developed for multiple-input multiple-output broadcast (MIMO BC) systems. According to the relationship between coherence time and Doppler frequency, an information frame is divided into several segments. At the beginning of each segment, the user selection is carried out with the greedy selection algorithm. In the simplified user selection algorithms employing the temporal correlation (SUSTC), the selection results are applied for all the remaining slots in each segment. But in the improved simplified user selection algorithms employing the temporal correlation (ISUSTC), at the remaining slots, users are kept with favorable channel conditions selected at the previous slot, and other users are updated from the candidate pool to communicate simultaneously. Simulations show that compared with the greedy user selection method, the proposed algorithms can reduce the selection complexity with a little sum capacity loss.

Key words: user selection; multiple-input multiple-output broadcast; temporal channel correlation

The potential for dramatic improvements in spectral efficiency has made multiple-input multiple-output broadcast (MIMO BC) systems receive considerable attention in recent years. It is shown that the capacity region and the sum capacity of MIMO BC systems can be achieved by dirty-paper coding (DPC) [1–2], which is quite sophisticated and challenging to implement in an actual system. On the other hand, linear precoding schemes seem to provide a tradeoff between performance and complexity[3]. In the case where each user has only one antenna, zero-forcing beamforming (ZFBF) has been studied deeply in Refs. [4 – 6].

ZFBF tends to impose a restriction on the number of antennas. When the number of users is greater than the number of transmit antennas, it is impossible to send data streams to all users simultaneously without inter-user interference. In a practical network, there are always more users than transmit antennas, where the base station should select the best set of users to improve system throughput. The optimal subset of users to maximize the sum capacity is achieved by an exhaustive search over all possible user sets, which is a prohibitive task.

To reduce the complexity, several suboptimal schemes have been proposed. A greedy user selection approach was presented in Ref. [7]. In Ref. [8] a semi-orthogonal user selection (SUS) algorithm was given, which shows that as the number of users goes to infinity, the achieved sum capacity is very close to that of DPC. In this method, an orthogonal threshold is used for selecting the users in each step. In Ref. [9], a sequential water-filling (SWF) algorithm was investigated, which achieved a comparable maximum sum rate by ZFBF with lower complexity. These above schemes are based on the block fading channel assumption; i. e., the channels of each user are constant for the duration of a single frame and changed independently frame by frame. For a channel realization, the user selection algorithm is carried out once.

But it is noticeable that the wireless communication channels are ever-changing with time in practical environments. The time-varying nature should also be considered in the process of scheduling. In Ref. [10], the scheduling for time-varying broadcast channels was studied, where all users followed a time division multiple access (TDMA) manner; i. e., only one user was supported in each slot. This paper considers a frequency division duplex (FDD) system, and the inherent feedback delay makes the channel state information (CSI) at the transmitter be outdated. The time correlation of the channel between two slots has been used to obtain an appropriate scheduling order of all users. Unlike Ref. [10], we assume a time division duplex (TDD) system, where the downlink and uplink channels are reciprocal. So, it is reasonable to assume that an instantaneous CSI is available at the transmitter. The main contribution of this paper is that the temporal correlation will be exploited in user selection algorithms in order to reduce complexity with a little sum capacity loss.

1 System Model

Consider a K-user MIMO BC system in which the base station has M antennas, and each user has one antenna. In an actual communication system, signals are usually processed in frame units. Each frame consists of some slots, where a slot duration may be multiple symbol samples. The channel in a slot is assumed to be invariant. We consider the slotted system, where one sample is contained in a slot for convenience. The scheduler decides that users transmit simultaneously in every slot. At the j-th slot, the received signal of user k is described as

$$y_k^j = \boldsymbol{h}_k^j \boldsymbol{x}^j + z_k^j \qquad k = 1, 2, \dots, K \tag{1}$$

where $\boldsymbol{x}^j \in \mathbf{C}^{M\times 1}$ is the transmitted signal with a power constraint of P; $\{z_k^j\}$ is the additive white Gaussian noise (AWGN) with distribution CN(0, 1); $\boldsymbol{h}_k^j \in \mathbf{C}^{1\times M}$ denotes the

Received 2007-10-08.

Biographies: Wang Jing (1977—), female, graduate; You Xiaohu (corresponding author), male, doctor, professor, xhyu@seu.edu.cn.

Foundation items: The National High Technology Research and Development Program of China (863 Program) (No. 2006AA01Z268), the National Natural Science Foundation of China (No. 60496311).

Citation: Wang Jing, Jiang Zhanjun, Wang Yan, et al. Employing temporal channel correlation in user selection for MIMO broadcast systems[J]. Journal of Southeast University (English Edition), 2008, 24(1): 1 – 5.

channel vector between the base station and user k. The channel is assumed to be flat fading; hence, the elements of $\boldsymbol{h}_k^j$ are i. i. d. complex Gaussian variables with zero mean and unit variance. We use the well known Jakes' model to model the time varying channel, and the time correlation about a symbol duration T_s is $J_0(2\pi f_d T_s)$, where $J_0(\cdot)$ is the 0-th-order Bessel function of the first kind; $f_d = f_c v/c$ is the Doppler frequency of user k; f_c is the carrier frequency and c is the velocity of light. The Doppler frequencies of all users can be estimated by the base station.

Because the number of users that ZF can support simultaneously is limited, we assume the maximum achievable sum capacity at the j-th slot is obtained by a subset of users $S_n = \{s_1, \dots, s_n\}$, whose cardinality n is less than or equal to M. For notational simplicity, we ignore the slot index for the moment. Denote the composite channel matrix of these users as $\boldsymbol{H}(S_n) = [\boldsymbol{h}_{s_1}^{\mathrm{H}}, \dots, \boldsymbol{h}_{s_n}^{\mathrm{H}}]^{\mathrm{H}}$, where the superscript H stands for conjugate transpose. In ZFBF, the BF vectors can be obtained by the pseudo-inverse of the downlink channel matrix. Let $\boldsymbol{T}(S_n) = \left[\frac{\boldsymbol{t}_{s_1}}{\|\boldsymbol{t}_{s_1}\|}, \dots, \frac{\boldsymbol{t}_{s_n}}{\|\boldsymbol{t}_{s_n}\|}\right]$ and $\boldsymbol{P}(S_n) = \mathrm{diag}\{P_{s_1}, \dots, P_{s_n}\}$ be the column normalized $\boldsymbol{H}(S_n)^{\dagger}$ and the allocated power matrix, respectively, where the superscript † denotes pseudo-inverse.

Then the transmitted signal can be expressed as $\boldsymbol{x} = \boldsymbol{T}(S_n)\boldsymbol{P}(S_n)\boldsymbol{d}$, where the symbol vector $\boldsymbol{d} = \{d_{s_1}, \dots, d_{s_n}\}^{\mathrm{T}}$ is intended to send to users, whose entries are chosen i. i. d. zero-mean Gaussian variables with unit power. Hence, for the ZFBF system model, the received signal for user i is

$$y_i = \frac{\sqrt{P_i}\, d_i}{\|\boldsymbol{t}_i\|} + n_i \qquad i \in S_n \tag{2}$$

It can be seen that ZFBF decomposes the MIMO BC channel into a series of subchannels without inter-user interference. The sum capacity of this system is

$$C(S_n) = \max_{\sum_{i \in S_n} P_i \leqslant P} \sum_{i \in S_n} \log_2\left(1 + \frac{P_i}{\|\boldsymbol{t}_i\|^2}\right) \tag{3}$$

The optimization problem can be solved by the water-filling strategy.

2 Greedy ZFBF User Selection Algorithm

Let S denote the set containing all possible pairs(n, S_n), $\forall n \leqslant M$. Then the maximum achievable sum capacity of ZF is given by

$$C_{\mathrm{ZF}} = \max_{(n, S_n) \in S,\ \forall n \leqslant M} C(S_n) \tag{4}$$

In general, the optimal subset of users is achieved by exhaustive search in the space with size $\sum_{i=1}^{M} C_K^i$. The computational complexity becomes prohibitive when the number of users K is large. To solve this problem, a reduced-complexity suboptimal solution, named the greedy user selection algorithm, is proposed in Ref. [7]. The user with the largest channel norm is chosen first. At each of the iterations that follows, the algorithm selects the next one which can obtain the maximum sum capacity jointly with the selected users. The algorithm terminates when M users have been selected or the sum capacity stops increasing if more users are chosen.

The algorithm introduced above is based on the block fading assumption, whereas, the time varying should be considered for the scheduling problem. In the following, we want to explain how to utilize the temporal correlation to reduce the complexity of the user selection algorithm.

The time-varying nature of wireless channels is often described by two parameters: the Doppler frequency f_d in the frequency domain and the coherence time T_C in the time domain, respectively. They are inversely proportional to one another. Coherence time is a statistical measure of the time duration over which the channel impulse response is essentially invariant, and quantifies the similarity of the channel response at different times. In general, the Doppler frequency can be estimated by the base station. Thus, the coherence time can be approximately measured.

The basic idea behind this algorithm is as follows. During the coherence time, the channels have a strong potential for amplitude correlation at different slots, which indicates that the channel varies continuously, and the phase also changes slowly. In other words, the channels do not fade suddenly. It is possible that users who are selected in the j-th slot will be re-chosen at the next slot. Thus, we can reduce the complexity of the user selection process using the temporal channel correlation.

3 Simplified User Selection Algorithm Employing the Temporal Correlation(SUSTC)

First, according to the coherence time, divide one frame into L segments, each with the length D; i. e., there are D slots in one segment. A referenced relationship between the coherence time and the Doppler frequency is $T_C = 0.423/f_d$ [11]. The proposed user selection scheme SUSTC is conducted segment by segment, where the user selection performs once at the beginning of each segment. The user selection is updated for every D slot. Let Ω be the candidate set of users and Y be the set of selected users, respectively. Now, we can describe it as follows.

Algorithm 1 SUSTC

For one frame, where L segments are included:

For $l = 1, 2, \dots, L$

At the first slot of the l-th data segment, obtain the appropriate users set according to the greedy algorithm.

Initialization

Let $\Omega = \{k \mid k = 1, 2, \dots, K\}$ and $Y = \varnothing$.

Set $n = 1$, and find a user such that: $s_1 = \arg\max_{k \in \Omega} \|\boldsymbol{h}_k^{(l-1)D+1}\|^2$. Let $\Omega = \Omega \backslash \{s_1\}$ and $Y = Y \cup \{s_1\}$. Denote the achieved sum capacity $C_{\mathrm{temp}} = \log_2(1 + P\|\boldsymbol{h}_{s_1}^{(l-1)D+1}\|^2)$.

for $n = 2, \dots, M$

for every $k \in \Omega$, let $\bar{Y}_k = Y \cup \{k\}$.

Find a user such that $s_n = \arg\max_{k \in \Omega} C(\bar{Y}_k)$.

if $C(Y \cup \{s_n\}) \leqslant C_{\mathrm{temp}}$, the algorithm terminates

else

$C_{\mathrm{temp}} = C(Y \cup \{s_n\})$

Let $\Omega = \Omega \backslash \{s_n\}$ and $Y = Y \cup \{s_n\}$

At other slots of the l-th data segment, the selection result is still applicable.

The algorithm terminates until the end of the frame.

4 Improved Simplified User Selection Algorithm Employing Temporal Correlation (ISUSTC)

In order to improve the performance of algorithm 1, we now present the second scheme exploiting the temporal correlation. Still divide one frame into L segments according to the coherence time, each with the length D. Algorithm 2 is also conducted segment by segment, whereas, there is a difference from algorithm 1 in the selection process of each segment. At the beginning of each segment, the user selection is carried out with the greedy selection algorithm. At the remaining slots, keep users with favorable channel conditions selected at the previous slot, and update the other users from the candidate pool to communicate simultaneously. Taking one segment as an example, the detailed user selection scheme employing temporal channel correlation is given in the following.

Algorithm 2 ISUSTC

For the l-th data segment in one frame, where D slots are included:

$d = 1$

At the first slot of the d-th data segment, obtain the appropriate users set Y^1 according to the greedy algorithm.

for $d = 2, \dots, D$

Let $\Omega^d = \{k \mid k = 1, 2, \dots, K\}$ and $Y^d = \varnothing$.

Keeping the first q users of Y^1, called $\widetilde{Y}$, as the re-selected users in this slot; i. e., let $\Omega^d = \Omega^d \setminus \widetilde{Y}$ and $Y^d = Y^d \cup \widetilde{Y}$. Set $n = q$.

Compute the achieved sum capacity $C_{\text{temp}} = C(\Omega^d)$ according to Eq. (3).

In the candidate pool, perform the greedy algorithm to select other users to maximize the system throughput.

While $n < M$

$n = n + 1$.

for every $k \in \Omega^d$, let $\bar{Y}_k^d = Y^d \cup \{k\}$.

Find a user such that $s_n = \underset{k \in \Omega}{\arg\max}\, C(\bar{Y}_k^d)$.

if $C(Y^d \cup \{s_n\}) \leqslant C_{\text{temp}}$, the algorithm terminates

else

$C_{\text{temp}} = C(Y^d \cup \{s_n\})$.

Let $\Omega^d = \Omega^d \setminus \{s_n\}$ and $Y^d = Y^d \cup \{s_n\}$.

end

The algorithm terminates until the end of the frame.

5 Complexity Analysis and Simulations

If QR decomposition is employed to avoid computing the Moore-Penrose inverse of the channels, the complexity of the greedy user selection algorithm for channel realization is $O(KM^3)$ [9]. In SUSTC, the selection acts once during one segment, so the complexity depends on the length of the segment. The complexity of algorithm 1 is $O(KM^3/D)$. The longer the segment, the more complexity reduction can be obtained. That is to say, if the channel varies slowly, we can save much computation. In algorithm 2, the first q selected users are maintained as at the beginning of one data segment. The QR decomposition results of the corresponding channel can be conserved in a buffer, which is updated at the beginning of each segment. Hence, these calculations can be saved in the remaining slots of one segment, which is a benefit from the temporal channel correlation. The complexity of algorithm 2 is $O((K-q)M^3)$.

Next, we will examine the performance of the proposed user selection schemes in time varying channels. Let the notation $\{M, K\}$ denote an MIMO BC system with M transmit antennas and K one antenna users. All channels are i. i. d. Rayleigh fading and distributed according to $\mathrm{CN}(0, 1)$. We use the normalized Doppler frequency $f_{\mathrm{d}}T_{\mathrm{s}}$ to describe the time varying nature of wireless channels, where T_{s} is the slot period. The number of keeping users during our methods is q. The length of one frame is 50, and the length of segment $D = 10$. The total number of simulated frames is enough to guarantee that the wireless channel is ergodic. The signal-to-noise ratio (SNR) is defined as $10\log_{10}P$ dB.

Four selection schemes are compared in our simulations.

① For every slot in one frame, the perfect greedy user selection is carried out.

② User selection is done at the beginning of each frame. As in the block fading case, at the beginning of each frame, perfect greedy user selection is performed. The selected users are still to be chosen for whole frame.

③ User selection is carried out by algorithm SUSTC. Each frame is divided into segments with D slots, and the user selection is updated for every D slot.

④ User selection is conducted by algorithm ISUSTC.

In all the following figures, these methods are denoted as "Greedy", "Initial", "Segment" and "Segment + keep", respectively. The "Greedy" and "Initial" schemes are shown as references, which are an upper bound and a lower bound of the achieved sum capacity.

The effect of the Doppler frequency on the user selection employing the temporal correlation information is examined first. Fig. 1 shows the sum capacity of the user selection algorithms with $f_{\mathrm{d}}T_{\mathrm{s}}$ ranging from 0.02 to 0.6 and $q = 3$ for the system of $M = 6$, $K = 30$. It can be seen that the "Greedy" algorithm outperforms other methods, because it takes full advantage of the channel state information. The achieved system throughput of the greedy algorithm is invariant versus the increase of $f_{\mathrm{d}}T_{\mathrm{s}}$. The "Initial" algorithm performs the worst, especially at high $f_{\mathrm{d}}T_{\mathrm{s}}$. The "Segment" method performs better than the "Initial"; however, when channels change rapidly, the performance loss is evident. Algorithm ISUSTC approaches the "Greedy" algorithm at low $f_{\mathrm{d}}T_{\mathrm{s}}$. Meanwhile, the sum capacity decreases as $f_{\mathrm{d}}T_{\mathrm{s}}$ increases, larger $f_{\mathrm{d}}T_{\mathrm{s}}$ makes the gap between them loosen. This can be interpreted as follows: the larger the $f_{\mathrm{d}}T_{\mathrm{s}}$ is, the more rapidly the channel varies. The updated speed cannot catch the variation of the channels. For example, when $f_{\mathrm{d}}T_{\mathrm{s}}$ equals 0.06, the sum capacity gap is 0.5 bit/(s·Hz); when $f_{\mathrm{d}}T_{\mathrm{s}} = 0.3$, the gap becomes about 1.6 bit/(s·Hz).

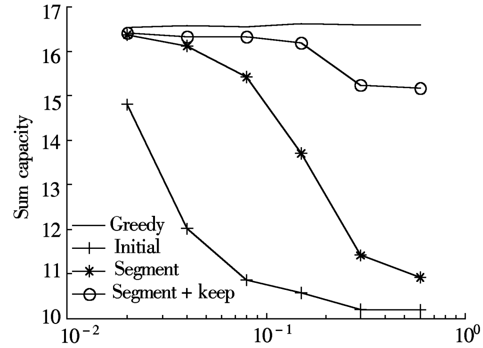

Fig. 1 The sum capacity vs. $F_{\mathrm{d}}T_{\mathrm{s}}$ ($K = 30$, $M = 6$, $q = 3$)

Next, we examine the influence of the number of keeping users on algorithm ISUSTC in Fig. 2, where the system throughput is plotted. Parameters are as follows: $f_d T_s = 0.08$, $q = [1, M-1]$, SNR = 10 dB and 20 dB. Various numbers of keeping users are simulated. It can be seen that the fewer the number of keeping users is, the better the system performance is. The algorithm degenerates into the "Segment" method if we keep all the selected users at previous slots. The number of keeping users is related to the degree of the time varying of channels. In the practical system, to determine the exact number of keeping users, one can follow by the simulation results.

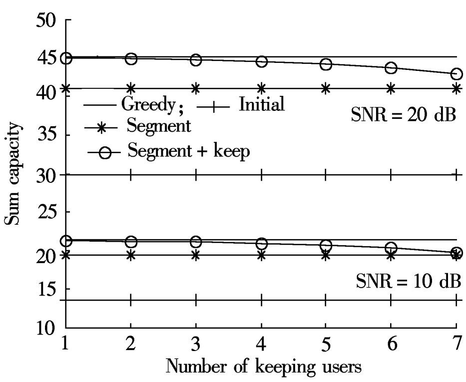

Fig. 2 The sum capacity vs. the number of keeping users ($K = 50, M = 8, f_d T_s = 0.1$)

In Fig. 3, the sum capacity for the system $M = 8$, $K = 50$ vs. the SNR is plotted. The number of keeping users is set as 3. With the increase in SNR, the system throughputs of all schemes increase consistently. Algorithm ISUSTC achieves almost the same performance as the "Greedy" algorithm.

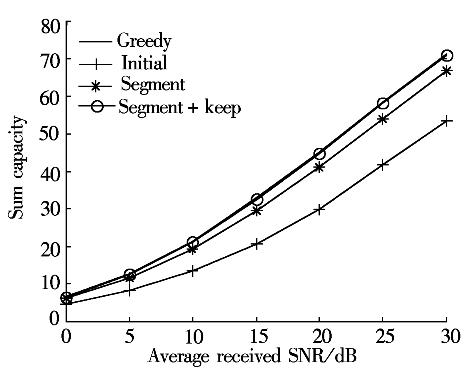

Fig. 3 The sum capacity vs. the average received SNR ($K = 50, M = 8, q = 3, f_d T_s = 0.1$)

In Fig. 4, user selection throughput performance vs. the number of users is depicted under SNR = 10 dB. The settings are: $f_d T_s = 0.08$, $K = [20, 10, 60]$, $M = 8$ and $q = 3$. As the number of users increases, the sum capacity increases also. This is achieved by the gains in multiuser diversity.

6 Conclusion

In this paper, we investigate the user selection algorithm in MIMO BC systems in time varying channels. We base our investigations on the fact that: if the channel varies slowly, the

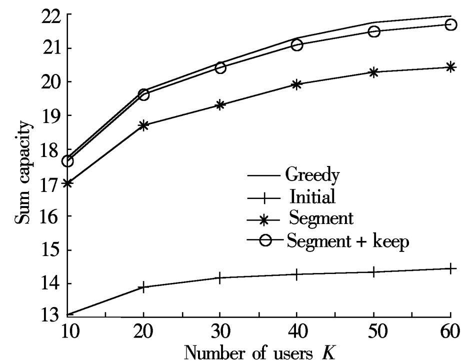

Fig. 4 The sum capacity vs. the number of users ($M = 8$, $f_d T_s = 0.08$)

gain and the angle of the channel vector also vary slowly. Thereby, users with favorable channel conditions selected at this slot will be re-selected with a high probability. Simulation results prove the effectiveness of the proposed user selection schemes.

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多天线广播系统中利用信道时间相关特性的用户选择算法

王　静　蒋占军　王　炎　尤肖虎

（东南大学移动通信国家重点实验室，南京 210096）

摘要：考虑无线信道的时间相关性，提出了 2 种多天线广播系统中降低复杂度的用户选择方案. 根据信道相干时间和多普勒频率的关系，将发送信息序列划分为数据段. 在每个数据段的开始时刻，利用贪婪用户选择算法做选择. 在基于时间相关的用户选择算法 SUSTC 中，其余时隙仍然保持该段开始时刻的选择结果. 而在改进的基于时间相关的用户选择算法 ISUSTC 中，在其余时刻，保留信道条件较好的一些用户仍被选中，然后在备选用户集合中更新其他用户. 仿真结果表明，与贪婪用户选择方法相比，所提出的算法降低了用户选择复杂度而只需损失少许系统和容量.

关键词：用户选择；多天线广播系统；信道时间相关性

中图分类号：TN91