

TOUSE: A Fair User Selection Mechanism Based on Dynamic Time Warping for MU-MIMO Networks

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Abstract

Multi-user Multiple-Input and Multiple-Output (MU-MIMO) has potential for prominently enhancing the capacity of wireless network by simultaneously transmitting to multiple users. User selection is an unavoidable problem which bottlenecks the gain of MU-MIMO to a great extent. Major state-of-the-art works focus on improving network capacity by using Channel State Information (CSI), however, the overhead of CSI feedback becomes unacceptable when the number of users is large. Some work does well in balancing tradeoff between complexity and achievable capacity but lack of consideration of fairness. Current works universally ignore the rational utilizing of time resource, which lead the improvement of network throughput to a standstill. In this paper, we propose TOUSE, a scalable and fair user selection scheme for MU-MIMO. The core design is dynamic time warping based user selection mechanism for downlink MU-MIMO, which could make full use of concurrent transmitting time. TOUSE also presents a novel data-rate estimation method without any CSI feedback, which provide supports for user selection. Simulation result shows that TOUSE significantly outperforms traditional contention-based user selection schemes in both throughput and fairness in an indoor condition.

Keywords: MU-MIMO, user selection, fairness, dynamic time warping

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1. Introduction

Multi-user Multiple Input Multiple Output (MU-MIMO) has already attracted a huge amount of attention because it enables better spatial reuse. The network capacity is enhanced by sending frames to multiple single-stream users concurrently. Prior to 802.11ac, traditional 802.11 protocol limited every transmission only sent to a single user, which cannot full utilize spatial resources supported by multiple antennas AP. Multi-user transmission is a new technology within 802.11. By using MU-MIMO [1], AP is equipped with multiple antennas, and could transmit to multiple users at one time. Due to these abilities, MU-MIMO has the potential to change the way in which Wi-Fi networks are built and achieve improved capacity gains.

A MU-MIMO downlink system, in theory, its capacity gains increases linearly with the number of transmitting and receiving antennas. But in practice, the number of antennas is limited by several reasons, and the inter-user interference could not be ignored. These lead to a series of important problems. First, how could an AP select a beamforming group of users and transmit simultaneously. Second, how to determine the size of the beamforming group. Different beamforming group selection leads to variant transmitting rate, then influences the overall network performance. Unwise selecting method may results in a huge waste of space-time at any single transmitted slot, and causes the problems of fairness and complexities. To make an optimal selection, we should choose a metric like sum rate as a criterion to process the feedback information like CSI (Channel State Information) or SNR (Signal-Noise Ratio), design an efficient scheduling scheme based on various data we obtained.

Substantial researches [2] have provided the solving methods to the user selection problem for MU-MIMO. Most solutions select the optimal beamforming group based on understanding the full CSI of all potential users. CSI reflects the characteristics of the channel including fading distribution, average channel gain and spatial correlation, all are important for beamforming group select. However, CSI is calculated by estimating the training sequence from AP, then

users feed it back to the AP. Reducing the CSI overhead becomes an important issue in MU-MIMO since this is a long and complex process [3]. Although numerous optimization schemes of feedback have been proposed, like compression algorithms [4], the overhead of CSI feedback is still huge sometimes and severely affects the performance of network, since the overhead grows linearly with the number of users. Even worse, infrequent CSI feedback results in outdated, which may leads to the inter-user interference. It is convenient to select beamforming group within CSI, but intolerable for MU-MIMO system with unacceptable feedback overhead.

In fact, these challenges have motivated previous works to find better possible solutions for user selection. In [3], the author proposed a distributed contention mechanism that singles out the best user to feed back its CSI. Narendra [5] present pre-sounding user selection algorithm only using available pre-sounding information instead of posting channel sounding information, and solved the problem of feedback overhead to a certain extent.

In this paper, we propose *Time Optimal User Selection based on Effective SNR* (TOUSE), a scalable and fair user selection scheme for MU-MIMO networks to achieve higher capacity. To sum up, our main contributions are as follows:

- We design a novel dynamic time warping based user selection mechanism to increasing throughput under the fairness constraints, and propose a algorithm to solve it.
- We adopt a low complexity feedback mechanism to obtain the available channel information and presents a novel data-rate estimation method base on the information of effective SNR [6] without any CSI feedback.
- TOUSE has abilities to adapt to different network channel qualities, no matter low SNR region or high link qualities. It is also suitable to dynamic network, since it selects users after channel sounding is completed and acquires real-time information.

- Finally we experimentally evaluate the performance of TOUSE. Result shows that, on average, the gain of TOUSE is $1.5\times$ over traditional Random user selection scheme in 3-antennas AP scenarios. Compared with PUMA scheme [5], network capacity gain is similar but TOUSE provides users with fair selection opportunities.

The rest of this paper is organized as follows. In Section II, we present background of user selection in MU-MIMO. Section III provides an overview of the components of TOUSE. Section IV evaluates the performance of TOUSE with experimentations. Then we describe related works in Section V and Section VI concludes the paper.

2. BACKGROUND AND CHALLENGES

2.1. MU-MIMO System Model

In a downlink MU-MIMO system, consider a single-cell MIMO with a single base station serving N users. The base station is equipped with M antennas and the client with one or more receive antennas. We assume that AP sends frames to a set of selected single antenna users S called beamforming group at the same time, which satisfies $K = |S|$, $K \leq M$. Due to the bad effect of multi-user interference at the client side, it is essential for AP to precode outgoing signals to minimize interference among simultaneous streams. Owing to its low complexity, AP applies ZFBF (Zero-forcing beamforming) [7]. In ZFBF, user streams are separated by different beamforming directions. Let x_k denotes the data symbol sending to user k , \mathbf{w}_k be the beamforming weight vector, and p_k presents the transmit power. Assume \mathbf{h}_k is the $1 \times M$ channel state vector between transmission antennas and receiver k . Define $\mathbf{W} = [\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_K]$, $S = \{s_1, s_2, \dots, s_K\}$, the transmitted signal $\mathbf{X} = \sum_{k=1}^K \sqrt{p_k} \mathbf{h}_k \mathbf{w}_k x_k$. Then, let n_k denotes the noise level of user k , and the received signal vector is:

$$y_k = \sqrt{p_k} \mathbf{h}_k \mathbf{w}_k x_k + \sum_{j \neq k, j \in S} \sqrt{p_j} \mathbf{h}_k \mathbf{w}_j x_j + n_k, k \in S. \quad (1)$$

To eliminate the interference from other beamforming frame streams, ZFBF should satisfy the zero-interference condition: $\mathbf{h}_k \mathbf{w}_j$ for all receivers $j \in S, j \neq k$. So that receiver k only gets its symbol x_k . Let the channel state matrix $\mathbf{H} = [\mathbf{h}_1^T, \mathbf{h}_2^T, \dots, \mathbf{h}_K^T]^T$ and the beamforming weight matrix $\mathbf{W} = [\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_K]$. One optimal choice of \mathbf{W} that satisfies zero-interference condition is the pseudo-inverse of \mathbf{H} :

$$\mathbf{W} = \mathbf{H}^+ = \mathbf{H}^*(\mathbf{H}\mathbf{H}^*)^{-1}. \quad (2)$$

Thus, another problem that needs to be considered is power allocation. For simplicity, we adopted ZFBF-EP scheme where the transmitter allocates equal power to its users.

75 2.2. Impact of User Selection Mechanism

From above section, the performance of ZFBF is highly dependent on the channel vectors from transmitter to receiver. When the channel vectors of different receivers are uncorrelated with each other, it is most likely to improve the network capacity gains. It has been proved by the experimental [8] for indoor wireless network. The network spatial multiplexing gain of ZFBF can be increased by a high number of transmitter antennas, wherever the location of receivers in indoor environment.

Selecting beamforming group is one of the key issues which are related to the performance of MU-MIMO system. From Eq. (1), the SNR of each receivers depends on its group member. If one receiver's channel vector is orthogonal to another, it will cause limited interference when transmitting together. The research [8] also proved that the SNR or the size of beamforming group has great influence to the performance of ZFBF. The optimal size of beamforming group depends on the link state of the members. The state of queue and other information should be taken into account as well.

2.3. Challenges in User Selection

User selection is a complicated process. Although optimal transmission beamforming group can improve the network capacity, high computational over-

head is unacceptable. Before each downlink transmit, the AP need obtaining the
 95 CSI from the users' feedback. During the feedback process, AP sends a training
 sequence to the target users, users calculate the CSI by the training sequence
 and send the feedback of CSI to AP in order/sequence. Due to this mechanism,
 overhead by CSI feedback also increased with number of users. Researches [3]
 present that even with 20 users, the channel time cost of existing schemes can
 100 be comparable to or even competitive with that of actual data transmission.

There are a number of factors which a user selection mechanism should be
 considered. First, how to determine the size of beamforming group. In a trans-
 mission time slot, AP beamforming to send frame to a set of users S , which the
 size of set K satisfy $K \leq M$. In [8], it proved that maybe $K = 3$ have a better
 105 network performance than the case of $K = 4$. The authors of [5] proposed an
 aggregate throughput to select the combination mode. Second is the complexity
 reduction. Instead of exhaustive search over all possible combinations, most re-
 searches adopt the local optimal methods to solve this problem, which performs
 inefficiently. It is hard to achieve both low complexity and high performance.
 110 So the tradeoff between performance and complexity is essential [9] . Another
 solution is to reduce the feedback overhead, which is not the way to the under-
 lying problem. The last challenge is how to realize fairness. A simple way to
 improve the network throughput is just selecting the users which have a high
 link quality. But it might not be fair for all users [3]. Sometimes, it will cause
 115 starvation.

3. TOUSE DESIGN

3.1. Design Overview

The design inherits the advantages of throughput fairness and low com-
 plexity in user selection, it also improves the network capacity gain. TOUSE
 120 presents a new preference metric which aims to make full use of time resource
 and guarantees fairness. Besides, instead of requiring CSI feedback, TOUSE
 provides a mechanism in which AP just obtained effective SNR from users to

make decision. This mechanism has limited time overhead compared to the CSI feedback.

125 Before giving the details of TOUSE, there are some available pre-sounding information to introduce. In MU-MIMO system, AP owns the information of system state and queue state before channel sounding or communication. For each transmission, AP knows the hardware configurations, like available number of transmission antennas M , the number of clients' receiving antennas. 130 AP is also aware of the queue state information for each users, like each user's backlog or queue size. The amount of available data directly affects the data transmission time in each transmission, which is used for user selection. By leveraging this information, we design a performance metric to select optimal beamforming group. The TOUSE works as follows:

135 1) First, the AP announces its intention for MU-MIMO downlink transmission through the NDP Announcement frame, and it is the time to start the MU-MIMO sounding process for users. AP randomly selects a first user into the optimal beamforming group, which can achieve channel access fairness.

2) Then, each user estimates its own CSI-independently based on the NDP 140 Announcement frame. AP obtains the effective SNR feedback which is calculated by each client from the CSI. This is the first round of TOUSE user selection.

3) In subsequent round, AP estimates the potential data rate for each competitors based on the effective SNR and current beamforming group. Then it calculates time of data transmission for each users combined with the pre- 145 sounding information, and gets global time of transmission slot based on selected users and candidate users.

4) Given transmission time of each data transmission and information of selected users. According to the constraint condition (described in section D), the AP selects the best candidate which can optimise total network capacity for 150 this transmission slot.

5) The one who satisfies the optimal constraint, indicating the ability of the transmission among the members of beamforming group. Then the AP adds it to the beamforming group.

6) Repeat step (3)-(5) until the size of beamforming group reaches the maximum transmission number M , or there exists no any best choice left. Finally, AP would terminate the user selection process.

Next, we are going to present TOUSE in details for better understanding.

3.2. Effective SNR

In order to accurately predict the packet delivery rate, a key point is using effective SNR (ESNR) [6]. It is a simple, easy-to-deploy, broadly useful, and rather accurate method. Effective SNR consider the factors of transmit power and antennas, which makes packet delivery predicted for 802.11n MIMO rates more effective. During the process, CSI is the input, which can provides the SNR values for each subcarrier. It is contains more information than RSSI, and provides the opportunity to of designing an accurate evaluate model.

The effective SNR calculation is not just the average subcarrier SNR. Instead, it is biased towards the weaker subcarrier SNRs because the subcarriers cause most of the errors. The effective SNR is calculated by averaging the subcarrier BERs and finding the corresponding SNR. The formulas are shown as follows:

$$\text{BER}_{eff} = \frac{1}{S} \sum \text{BER}(snr_s); \quad (3)$$

$$\text{ESNR} = \text{BER}^{-1}(\text{BER}_{eff}). \quad (4)$$

BER^{-1} presents the inverse mapping, from BER to SNR, and S is the number of subcarriers. BER_{eff} denotes the average BER across subcarriers, snr_s is the SNR values of each subcarrier.

3.3. MU-MIMO User Datarate Estimate

In TOUSE, the key is to predict the per-user packet delivery rate. During the process ESNR evaluation is essential for each transmission. Then the AP obtains the data rate for each user from the ESNR by using MCS table. However, There is still a problem when it comes to AP transmissions among multi-receivers at

the same time resulting in the inevitable of the inter user interference. As a
 175 result it will influence the total capacity of network.

1) *Traditional Rate Estimation*: One of the classical approach to calculate the aggregate capacity is using channel state matrix. The sum rate (R) [7] is achieved by following scheme:

$$R = \max_{\mathbf{w}_k, P_k} \sum_{k=1}^K \log \frac{1 + \sum_{j=1}^K P_j |\mathbf{h}_k \mathbf{w}_j|^2}{1 + \sum_{j=1, j \neq k}^K P_j |\mathbf{h}_k \mathbf{w}_j|^2} \quad (5)$$

subject to $\sum_{k=1}^K \|\mathbf{w}_k\|^2 P_k \leq P.$

This method is accurate but quite complex. It requires channel state matrix as input which is difficult to obtain. Given the significant overhead of CSI feedback, the AP needs more reasonable utilizations of this information to maximize the network performance. This leads to the system more complicated and hard to
 180 implement, which is opposite to what we originated.

2) *ESNR based Rate Estimation*: TOUSE's rate estimation method is based on theoretical MU-MIMO system scaling. In order to make it facilitate and precise, AP obtain the ESNR which is calculated by users, and estimates the data delivery rate by MCS-SNR table. Besides, qualifying the influence of inter-user
 185 interference when AP transmits to multi-users is also essential. As mentioned before, in ZF model, user only receives its desired symbol owing to the composite effects of precoding and channel distortion. The main features of ZF is complete interference cancellation with full CSI, but it will amplify the noise [10].

Many works [11] provide the analysis to network capacity performance influenced by ZF-precoded system. But most of methods are not suitable for our purposes because too much information is required. By the ZF criterion, there is residual interference due to the imperfect CSI-based beamformers. The SINR for selected user k is (proposed in [12])

$$\text{SINR}_k = \frac{\text{SNR}_k \|\mathbf{h}_k\|^2 \cos^2(\angle(\mathbf{h}_k, \mathbf{w}_k))}{1 + \text{SNR}_k \|\mathbf{h}_k\|^2 \sum_{j \neq k} \cos^2(\angle(\mathbf{h}_k, \mathbf{w}_j))} \quad (6)$$

190 and the corresponding sum rate is $\sum_{k=1}^n \log_2(1 + \text{SINR}_k)$. Where \mathbf{w}_k presents

the precoding unit-norm beamforming vector for user k is chosen in the direction of the projection of \mathbf{h}_k on the nullspace of \mathbf{h}_j , $j \neq k$.

Eq. (6) presents SINR variation for each users, but there is the same problem of using information of CSI as input. As Eq. (6) shows that the interference caused by other receivers in beamforming group is related to per-receiver SNR. Besides, the system state information also has great influence on the SINR, like transmission antennas number M and the size of current transmission users group K . It is also necessary to note that this paper focuses on the users equipped with a single antenna. In [13] and [12], it proved that in order to achieve the full multiplexing gain of M , the transmitters must have perfect channel knowledge in order to choose the zero-forcing beamforming vectors. However due to the imperfection in this knowledge, there will be some multi-user interference, which leads to performance degradation inevitably. Therefore, we proposed a suitable per-receiver SINR estimation method as following.

$$\text{SINR}_k = \frac{\text{ESNR}_k - \text{ESNR}_k \cdot 2^{-B}}{1 + \text{ESNR}_k \cdot 2^{-B}} \quad (7)$$

$$B = ((M - 1)P)/(3(K - 1))$$

Where M is the number of transmitting antennas, presents the degree of freedom of MU-MIMO system. K denotes the size of beamforming group, which leads
195 an exponential increase in the multi-user interference.

In TOUSE, we assume that each transmission antenna has a same transmitting power P . From Eq. (7), the value of per-receiver SINR is inherently less precise than Eq. (5). But it can provide a sufficiently accurate result for TOUSE user selection process as well, and easy to implement. Then the trans-
200 mission data rate $rate_k$ for user k is calculated from the MCS-Rate (Table 1) by the SINR.

3) *TOUSE Rate Estimation Analyse:* In Eq. (7), the TOUSE's SINR estimation method only requires the system hardware configurations M , number of users K and the ESNR calculated by each user. This estimation scheme can
205 accommodate with the network dynamically by using ESNR, and avoid CSI

feedback overhead at the same time. 2^{-B} presents the multiplexing gain of inter-user interference, and it will increase linearly with the increase of transmission power. Thus, the SINR of each user is related to B in MU-MIMO system.

210 During the rate estimation process, TOUSE first measures the channel state information, and calculates the ESNR by each receivers. Then the each user's SINR is calculated based on the size of beamforming group. Finally the data delivery rate (for 90% packet reception rate) is obtained by using the MCS-SNR table provided by the standard (as shown in Table 1).

Table 1: Minimum SNR required

MCS	Rate (Mbps)	SNR (dB)
0	6.5	1.1
1	13.0	4.1
2	19.5	6.7
3	26.0	9.6
4	39.0	12.8
5	52.0	17.2
6	58.5	18.4
7	65.0	19.7

215 3.4. User Selection Mechanism

In this section, we present the user selection mechanism to maximise the aggregate throughput of network, and implementation of the fairness of channel access for each users. In this subsection, the key point is the two types of limiting condition in the selection process.

Previous sections have given the data rate estimation method. In order to calculate the data transmission time for a transport connection, the key point is total delivery data and network overhead (such as channel sounding and ESNR feedback overhead). These pre-sounding information can be obtained by AP queue state or network measurement. So the total throughput R for each

transmission slot can be calculated, which is the performance metric for user selection mechanism. The formula is as follows, L denotes the total transmission data at a time slot, T_s is the maximum transmission time of all transmissions and T_o is the network overhead.

$$R = L/(T_s + T_o). \quad (8)$$

In order to achieve the two design goals: throughput increment and fairness guarantee. We design a similarity matching algorithm for optimal user group selection based on dynamic time warping [14]. Before presenting the time constraint condition, some definitions should be introduced. First, $S = \{s_1, s_2, \dots, s_k\}$ denotes the current selected beamforming group and $|S|$ is the size of S , c denotes a user which is candidate for $k + 1$ solution from the unselected users, but still waiting for checking by constraint conditions. $T(c)$ presents the transmission time requirement that AP transmits the queue data to user c . Here is the first constraint condition : to maximum the aggregate throughput.

$$\begin{cases} \frac{T(c)}{T(\max(S))} < \frac{1}{(ratio(c)-1)} & T(\max(S)) \leq T(c) \\ \frac{T(\max(S))}{T(c)} < \frac{1}{(ratio(\max(S))-1)} & T(\max(S)) > T(c) \end{cases} \quad (9)$$

220 Where $\max(S)$ presents the one with maximum data transmission time in selected group, $T(\max(S)) = \max(L_i/rate_i)$, $i \in S$, $ratio(c)$ is the ratio between the data rate of user c at the mode of $K = |S|$ and $K = |S| + 1$. The size of beamforming group K has a big impact on the transmitting rate of each user. For example, there is a user u from beamforming group of which the size is
225 K , the transmission rate is a , and rate equals b in the mode of $K + 1$, then $ratio(u) = a/b$. Eq. (9) is a throughput constraint for network capacity, which enables to judge the benefits of user c in this transmit time slot. Then this user will judge whether to put it into the beamforming group or just throw it away. As we have mentioned before, increasing the size of beamforming group
230 may lead to inter-user interference. Therefore the total network capacity per-

formance should be considered when putting candidate user c into beamforming group.

The second constraint aims to make full utilization of space-time resource.

$$T(c) \leq \frac{M}{K} \cdot T(\max(S)). \quad (10)$$

$K = |S|$ denotes the size of beamforming group which is received transmit data from AP concurrently. This restriction allows our algorithm to find an
 235 optimal match between given transmission time of selected users. For example, in a transmit slot, AP transmits to *user1* and *user2*, while the transmission time of *user1* is 1s and *user2* is 100s. In this case, compared with *user2*, the transmission time of *user1* is too short, which is not a best choice to bind them together for total network.

240 Based on the idea of dynamic time warping, the algorithm was designed to find an optimal beamforming group which can improved the network capacity. The AP is selected by the correlation of transmission time between candidate user c and current beamforming group. In the process of user selection, AP selects the first user into beamforming group at random, then the other member
 245 of beamforming group is selected by correlation with the set of selected users. This process will go through the total unselected users until no one is detected, which indicates that current beamforming group is an optimal solution at a transmitting slot.

TOUSE user selection mechanism is based on data transmission time, which
 250 leads the contention is fair in term of SNR of users. Next section will present the fairness performance of our mechanism. Eq. (8) shows that the network overhead limits the performance of a MU-MIMO transmission. Along with the increasing of beamforming group size, the amount of total transmit data L grows. The larger amount of network overhead is created meanwhile. So it is
 255 an important issue to get the trade off between aggregate data and network overhead.

3.5. TOUSE Algorithm

Algorithm 1 TOUSE User Selection

Input:

The set of single antenna users, C ;

The number of transmit antennas and transmit power, M and P ;

Output:

The set of solution receivers, S ;

The size of solution group, $k = |S|$;

Begin:

```
1: while  $k \leq M$  and  $C \neq \emptyset$  do
2:   if  $k = 0$  then
3:     Selecting a solution  $s_1 \in C$  at randomly from  $C$ ;
4:      $C = C - s_1$ ,  $S = S + s_1$ ;
5:   else
6:     repeat
7:       Selecting a optimal receiver  $c_k \in C$  matches  $S$ ;
8:       Judging  $c_k$  by two constraint: Eq. (9), Eq. (10);
9:       if  $c_k$  satisfies the two constraint then
10:         $S = S + c_k$ ;  $C = C - c_k$ ;
11:      end if
12:    until Get the solution  $s_k = c_k$  or none of optimal solution  $s_k \notin C$ 
        meets the condition;
13:   end if
14:   if  $s_k \notin C$  then
15:     None of receiver  $c \in C$  matches  $S$ ;
16:     Break, terminate the process of user selection;
17:   end if
18: end while
```

In order to seek an optimal combination to improve the network capacity, TOUSE applies two constraints which have been mentioned. Given the set of candidate receivers $C = \{c_1, c_2, \dots, c_n\}$ which is the total candidate users in one transmission slot. TOUSE selects the best combination as beamforming group for AP to simultaneous downlink transmissions. Here is the TOUSE user selection algorithm.

The algorithm (1) shows the user selection process of TOUSE's. The input of this algorithm is a candidate set of users, and the output is the beamforming group S , $|S| \leq M$. In the first round, AP selects a solution randomly from candidate set, which meets the requirements of competition fairness. The time constraint condition process is repeated until a receiver matching the existing solution group is selected, or none of optimal solutions exists in candidate receivers, as line 6-12 shown in Algorithm 1. During the process of searching solution, each selected user is the best one while group with the concurrent solution group. This searching method can reduce the complexity of TOUSE, and the result was acquired rapidly and exactly.

4. PERFORMANCE EVALUATION

In this section, we further perform simulations to evaluate the performance of TOUSE in indoor environment. The simulations aim to answer the following questions:

- How much capacity gain can TOUSE achieve in comparison with existing schemes?
- How does TOUSE perform in terms of fairness compared with existing schemes?
- How much the number of transmit antennas impact on TOUSE?
- Does TOUSE scale?
- Could TOUSE work in different channel quality region?

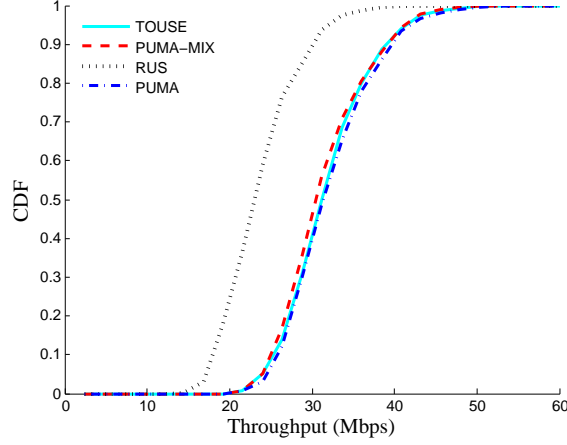


Figure 1: Performance comparison by total throughput

For the performance comparison, we implemented three state-of-the-art user selection schemes: (1) Pre-sounding User and Mode selection Algorithm (PUMA) [5]. PUMA allows MU-MIMO system to efficiently transmit multiple streams by using pre-sounding information. It estimates the throughput of all potential user group combinations. (2) Mixed PUMA algorithm (PUMA-MIX). PUMA employed exhaustively searching method to find the optimal user group. We replaced it with iteration method using for comparison in simulations. (3) Random User Selection (RUS), essentially the default standard of 802.11ac, which randomly selects users with equal probability.

In our simulation, we randomly distribute the users around the AP. The channels are generated according to the rayleigh fading channel model, and the transmit power of each antenna is $15W$. The default number of users is set to 10, packet size is set to 1500 bytes and the number of transmit antennas is 3. The detailed setting will be specified in each simulation.

4.1. Performance Comparison for Continuous Traffic

We evaluate the performance by comparing with other user selection schemes in terms of throughput gain. We set up an AP with 3 antennas and deploy 10 single-antenna users with randomly assignments of locations. Each of ten users

have a different channel quality, and always have packets to receive. Before the transmission, AP obtains the queue information which is totally transmit data
 305 to each candidate users. Then AP estimates the bit-rate of each concurrent packet based on the effective SNR which is calculated by each user.

Fig. 1 plots the CDF of the total throughput in 3 antennas scenarios, and shows the performance compared with other user selection schemes. The result shows that the traditional scheme, RUS, selecting users with an equal
 310 probability, without considering the channel characteristics and other criterions. Compared to RUS, the average throughput gain from enabling concurrent transmissions with TOUSE's user selection is about 50% in three antennas scenarios. This improvement mainly benefits from the following contributions: First, accurate rate prediction mechanism ensures the high packet reception
 315 rate, and reduces the time overhead without CSI feedback. Second, fully utilizing concurrent transmission time by overhead time matches based mechanism. The figure also shows that the PUMA-MIX and PUMA produce a throughput comparable to or even slightly higher than our user selection scheme. The performance of PUMA-MIX is similar to TOUSE's because of the same kind
 320 of scheduling algorithm. Although the PUMA performs slightly better than TOUSE and PUMA-MIX, it causes $10\times$ time overhead in the process of user selection than other two schemes. Besides, this time overhead is growing with the number of users.

4.2. Throughput Fairness Analysis

325 In this section, we analyse the opportunities of user selection in a three antenna AP scenario, which is better to show the performance. In order to analyse the fairness of TOUSE, users should be put into difference scenarios and evaluate the influence. There are five specific regions, where have different channel quality and each region has one user to communicate with AP. In the
 330 simulation, *user1*, *user4* are located in the region with worst and best channel quality, about $5dB$ and $20dB$ respectively. The quality of region *user2* is better than *user1*, but worse than *user3*, and *user5* is a control group with randomly

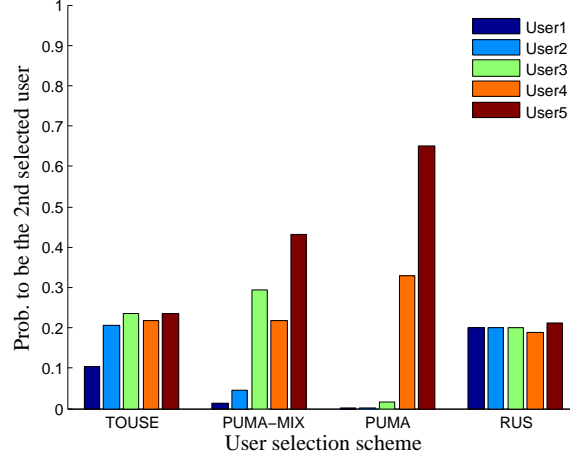


Figure 2: Fairness comparison in a 3-antenna AP scenario

case.

During the user selection process, the user group for downlink transmission was selected one after another. In the first round of simulation, TOUSE chooses a lucky user randomly, which means that TOUSE enables all clients to get almost an equal probability to be selected first. In order to show more convincing results, we plot in Fig. 2. The opportunities is to be second selected for each user in total selection process, which is the metric using for evaluating fairness. The figure shows that both the RUS scheme and our TOUSE enable all users to get almost an equal probability to be the second selected user. This implies that TOUSE enables users to achieve a similar level of fairness compared with fair contention mechanism. The probability of *user1* in TOUSE is slightly lower than other users. Because *user1* is located in a region with the worst channel quality, it results in the lowest throughput rate. In PUMA and PUMA-MIX, it gives little chance to low-throughput users. The user who has higher value of SNR gets more opportunities to be selected. Because these schemes selected concurrent transmit group just depend on throughput of each user.

In order to display the performance of TOUSE more clearly, we introduce one of the most relevant fairness indicators called Jain's fairness index (JFI)

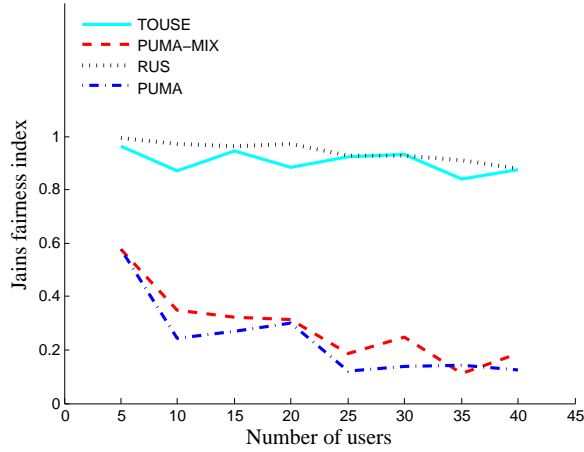


Figure 3: Jain's fairness index versus the number of users for different user selection mechanism

[15]. The definition as follows.

$$JFI = \frac{[\sum_{u=1}^{N_u} X_u]^2}{N_u \sum_{u=1}^{N_u} [X_u]^2}. \quad (11)$$

Where N_u presents the total number of users competing for channel, X_u denotes
 350 channel access times of user u at all time. JFI ranges from $1/N_u$ (only one user
 is served) to 1 (all users are served at the same possibility). Fig. 3 plots the
 Jain's fairness index for TOUSE, PUMA-MIX, PUMA and RUS as a function
 of the number of users in a 3-antenna AP scenario. It shows that the fairness
 performance of the proposed TOUSE clearly outperforms PUMA and almost
 355 close to the ideal case.

4.3. Effect of Number of Transmit Antennas

Here we present the performance by showing the impact of number of trans-
 mit antennas on the throughput. In the simulation, we set that the number
 of transmitting antennas at the AP varies from 2 to 8, and 30 users which
 360 randomly distributed around AP competing for the channel. Fig. 4 plots the
 performance of throughput. It shows that user selection is also important even
 for small scale MU-MIMO system, but it is more necessary for large scale sys-
 tem. Compared with these user selection schemes, all have achieved a similar

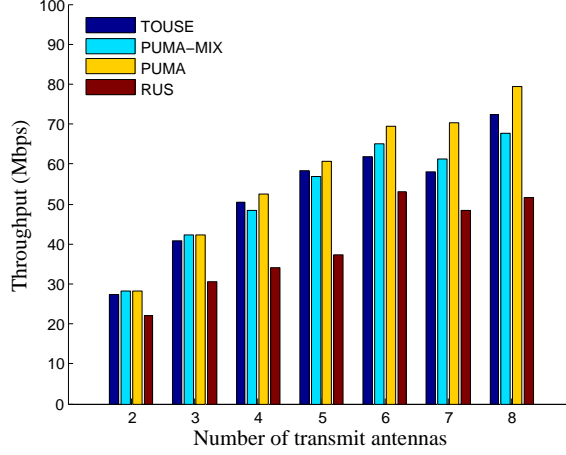


Figure 4: Performance in different AP scenario

capacity gain, when the number of antennas increases. The ceiling of throughput is reached with the antennas number growing, due to a large amount of interference between the inter-user. Besides, the result implies that increasing the number of paralld streams is not always the most efficient transmission scheme. We will prove that whether the TOUSE can perform scalability.

4.4. Impact of Number of Users

Here we evaluate the performance of TOUSE when the number of users varies from 5 to 50. We check the total network throughput gain increased by TOUSE when each user just has limited packet to receive. In each simulation, the AP transmits concurrent queue packets to its matching user, and thereby the throughput is calculated based on the process of transmission.

We plot the Fig. 5 to represent the performance of scalable. The effect of increasing the number of user on TOUSE, PUMA and PUMA-MIX is relatively small, implying that the TOUSE is performing well even when the network scales up. Since the RUS does not consider the channel characteristics and packet queueing status of users, its total network capacity is poor. However its performance is also independent of the number of users. During this simulation, PUMA get higher throughput whatever the network scales up due to the

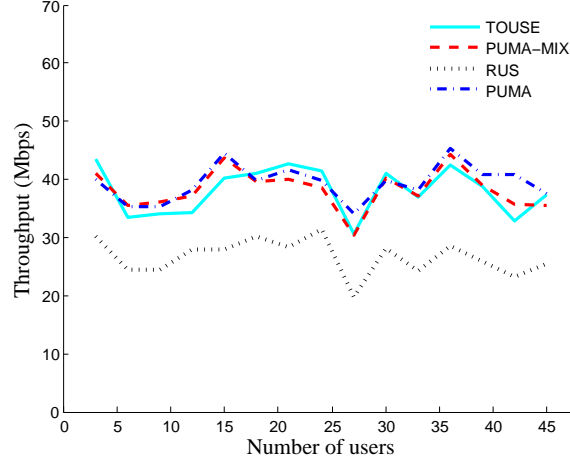


Figure 5: Performance impact by number of users

exhaustively research compared with other schemes. But the total throughput of PUMA-MIX is similar to TOUSE, which means that our user selection has similar level of throughput with a throughput first contention mechanism.

4.5. Performance in Different Channel Quality Regions

In order to evaluate how TOUSE performs where the network has the worst channel quality, we make several simulations which have different channel qualities respectively. In a low SNR region, the value of SNR just varies from 0 to 5dB, and varies from 15 to 20dB in a highest region. We set 10 users located in a region with similar channel quality. Fig. 6 reveals that user selection mechanism is not so significant for MU-MIMO in a low SNR region, because the interference is large enough to each user no matter what the combination of beamforming group is. However, with higher link qualities, these user selection schemes which is considered the channel characteristics of users performs obviously better than RUS. Figure also shows that the TOUSE brings out a capacity improvement over RUS even in a low SNR region. Compared with PUMA and PUMA-MIX, TOUSE performs in the same level or slightly poor in mostly scenario. But TOUSE achieves a similar capacity gain with going bet-

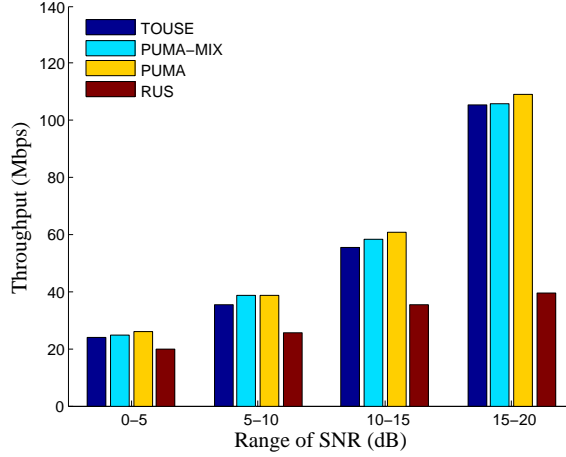


Figure 6: Performance in different channel quality region

ter of the channel quality. Obviously, TOUSE can perform better in different
400 channel quality regions.

5. RELATED WORK

Wireless standards like 802.11ac [16], LTE [17] have recently pushed toward
the use of MU-MIMO for obtaining high-speed and high-throughput wireless
communication. The work [10] presented a study to random access based on
405 MAC mechanisms for MU-MIMO, and gives a survey and categorizes to the
most relevant MU-MIMO MAC proposals. It also identified key requirements
for designing efficient MU-MIMO MAC protocols including de/pre-coding [1]
and scheduling schemes. The potential of MU-MIMO has been investigated
both theoretically [18] and empirically [8], which studied pre-coding techniques,
410 scheduling schemes and practical gain of MU-MIMO in various environments.

Substantial theoretical works [19] assumed that CSI is available and paid
much attention on implementing low-complexity algorithms to approach the
maximum throughput. Xie *et al.*, [3] presented scalable and adaptive user se-
lection which requires several rounds of CSI feedback instead of gathering from
415 all users. However, in reality, the vulnerabilities of CSI [20] still exist due to

its estimation methods, like time overhead. To avoid overwhelming the actual channel time spent on transmission, the schemes of user selection without CSI feedback was proposed. The authors of [21] design an orthogonality evaluation mechanism which enables each user using its own CSI to speculate. But
420 it can only be applied to uplink MU-MIMO. In [5], it proposed a method of user selection prior to channel sounding and exploits theoretical properties of MU-MIMO system to estimate data rate. PUMA achieves better performance in throughput, however, it does not do well in the respect of fairness.

Some other works focus on the scheduling scheme of user selection [22]. Most-
425 ly [23] either iteratively select a user that minimizes the interference, reduces the complexity or maximizes the aggregate throughput. In [9], a novel search and updated strategy was proposed for user selection. It designed a knob to control tradeoff between aggregate capacity and computational complexity. The work [24] presents a low complexity scheduling scheme using block diagonalization
430 with chordal distance.

In addition, some experimental studies emerged, like [25]. Authors realize netMIMO downlink transmission for large-scale wireless network. By organizing a network into clusters, it could manage interference with a decentralized channel-access algorithm, but environment is limited in static network since
435 time-averaged CSI is used as input. In [26], Shen *et al.*, introduced Turbo-Rate, client annotates its packets with single SNR and direction at the AP to obtain the optimal bit rate and could transmit concurrently. Now there are more conditions are considered, like mobility [27] or channel control [28]. The exciting thing is that the team of Xinyu Zhang [29] has optimized MU-MIMO
440 performance in 802.11ac commodity devices.

So far, there are three key points in MU-MIMO MAC protocol design: throughput, complexity and fairness [30]. But most researches only consider two or one of these points. TOUSE is designed a novel metric without CSI feedback benefiting from [12], and presents a fair user selection mechanism based
445 on overhead time matches.

6. CONCLUSION

In this paper, we have presented TOUSE, a scalable and fairness user selection scheme for downlink MU-MIMO. TOUSE is a proportional fair scheduler usually considers both network capacity and fairness. In order to reduce time
450 overhead, we adopt a novel per-user data-rate estimation method without any CSI feedback. TOUSE selects optimal beamforming group by dynamic time warping based on mechanism, which makes full use of concurrent transmitting time and achieves equal opportunity of channel contention. We have simulated TOUSE along with three other user selection schemes. Simulation shows
455 that TOUSE achieves a $1.5\times$ throughput gain over traditional scheme in three antennas AP scenarios, and the similar level of fairness compared with fair contention mechanism. We also proved that TOUSE can always achieve similar performance of throughput compared with throughput contention schemes. More details of QoS will be considered in our future work.

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References

- [1] L.-U. Choi, R. D. Murch, A transmit preprocessing technique for multiuser MIMO systems using a decomposition approach, *IEEE Transactions on Wireless Communications* 3 (1) (2004) 20–24.
- 470 [2] J. Gross, Scheduling with outdated CSI: effective service capacities of optimistic vs. pessimistic policies, in: *Proc. IEEE International Workshop on Quality of Service (IWQoS)*, 2012.

- [3] X. Xie, X. Zhang, Scalable user selection for MU-MIMO networks, in: Proc. IEEE International Conference on Computer Communications (INFOCOM), 2014.
- [4] X. Xie, X. Zhang, K. Sundaresan, Adaptive feedback compression for MIMO networks, in: Proc. ACM International Conference on Mobile Computing and Networking (MobiCom), 2013.
- [5] N. Anand, J. Lee, S.-J. Lee, E. W. Knightly, Mode and user selection for multi-user MIMO w lans without CSI, in: Proc. IEEE International Conference on Computer Communications (INFOCOM), 2015.
- [6] D. Halperin, W. Hu, A. Sheth, D. Wetherall, Predictable 802.11 packet delivery from wireless channel measurements, ACM SIGCOMM Computer Communication Review 41 (4) (2011) 159–170.
- [7] T. Yoo, A. Goldsmith, On the optimality of multiantenna broadcast scheduling using zero-forcing beamforming, IEEE Journal on Selected Areas in Communications 24 (3) (2006) 528–541.
- [8] E. Aryafar, N. Anand, T. Salonidis, E. W. Knightly, Design and experimental evaluation of multi-user beamforming in wireless LANs, in: Proc. ACM International Conference on Mobile Computing and Networking (MobiCom), 2010.
- [9] W.-L. Shen, K. C.-J. Lin, M.-S. Chen, K. Tan, Sieve: Scalable user grouping for large MU-MIMO systems, in: Proc. IEEE International Conference on Computer Communications (INFOCOM), 2015.
- [10] R. Liao, B. Bellalta, M. Oliver, Z. Niu, Mu-mimo mac protocols for wireless local area networks: A survey, IEEE Communications Surveys and Tutorials 18 (1) (2014) 162–183.
- [11] H. Yang, T. L. Marzetta, Performance of conjugate and zero-forcing beamforming in large-scale antenna systems, IEEE.

- 500 [12] N. Ravindran, N. Jindal, Multi-user diversity vs. accurate channel state information in MIMO downlink channels, *IEEE Transactions on Wireless Communications* 11 (9) (2012) 3037–3046.
- [13] N. Jindal, MIMO broadcast channels with finite-rate feedback, *IEEE Transactions on Information Theory* 52 (11) (2006) 5045–5060.
- 505 [14] M. Müller, *Dynamic time warping*, Springer Information retrieval for music and motion (2007) 69–84.
- [15] R. Jain, D.-M. Chiu, W. R. Hawe, A quantitative measure of fairness and discrimination for resource allocation in shared computer system, Vol. 38, Eastern Research Laboratory, Digital Equipment Corporation Hudson, MA, 1984.
- 510 [16] M. S. Gong M X, Hart B, Advanced wireless lan technologies: IEEE 802.11 ac and beyond, *ACM GetMobile: Mobile Computing and Communications* 18 (2015) 48–52.
- [17] S. Deng, R. Netravali, A. Sivaraman, H. Balakrishnan, WiFi, LTE, or both?: measuring multi-homed wireless internet performance, in: *Proc. ACM Internet Measurement Conference (IMC)*, 2014.
- 515 [18] D. Lee, Performance analysis of zf-precoded scheduling system for MU-MIMO with generalized selection criterion, *IEEE Transactions on Wireless Communications* 12 (4) (2013) 1812–1818.
- 520 [19] W. Lim, G. Kim, J. Kim, H. Park, K. Lee, H. Jang, Performance of linear precoding and user selection in IEEE 802.11 ac downlink MU-MIMO system, in: *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, 2014.
- 525 [20] R. Miller, W. Trappe, On the vulnerabilities of CSI in MIMO wireless communication systems, *IEEE Transactions on Mobile Computing* 11 (8) (2012) 1386–1398.

- [21] A. Zhou, T. Wei, X. Zhang, M. Liu, Z. Li, Signpost: Scalable MU-MIMO signaling with zero CSI feedback, in: Proc. ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), 2015.
- 530 [22] T.-W. Kuo, K.-C. Lee, K. C.-J. Lin, M.-J. Tsai, Leader-contention-based user matching for 802.11 multiuser MIMO networks, IEEE Transactions on Wireless Communications 13 (8) (2014) 4389–4400.
- [23] S. Huang, H. Yin, J. Wu, V. Leung, User selection for multiuser MIMO downlink with zero-forcing beamforming, IEEE Transactions on Vehicular
535 Technology 62 (7) (2013) 3084–3097.
- [24] K. Ko, J. Lee, Multiuser MIMO user selection based on chordal distance, IEEE Transactions on Communications 60 (3) (2012) 649–654.
- [25] X. Zhang, K. Sundaresan, M. A. A. Khojastepour, S. Rangarajan, K. G. Shin, NEMOx: scalable network MIMO for wireless networks, in: Proc.
540 ACM International Conference on Mobile Computing and Networking (MobiCom), 2013.
- [26] W.-L. Shen, K. C.-J. Lin, S. Gollakota, M.-S. Chen, Rate adaptation for 802.11 multiuser MIMO networks, IEEE Transactions on Mobile Computing 13 (1) (2014) 35–47.
- 545 [27] O. Bejarano, R. P. F. Hoefel, E. W. Knightly, Resilient multi-user beamforming w lans: Mobility, interference, and imperfect CSI, in: Proc. IEEE International Conference on Computer Communications (INFOCOM), 2016.
- [28] Z. L. Shepard C, Javed A, Control channel design for many-antenna MU-MIMO, in: Proc. ACM International Conference on Mobile Computing and
550 Networking (MobiCom), 2015.
- [29] Z. X. e. a. Sur S, Pefkianakis I, Practical mu-mimo user selection on 802.11 ac commodity networks, in: Proc. ACM International Conference on Mobile Computing and Networking (MobiCom), 2016.

- ⁵⁵⁵ [30] M. Esslaoui, F. Riera-Palou, G. Femenias, A fair MU-MIMO scheme for IEEE 802.11 ac, in: IEEE International Symposium on Wireless Communication Systems (ISWCS), 2012.