# A Massive MIMO User Selection Algorithm Based on Effective Capacity

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**Abstract.** In massive multiple-input multiple-output (MIMO) systems, to maximize spectral efficiency (SE), optimal scheduled user number for a time slot has been investigated. One of the important QoS index is the probability of delay violation, which depends on transmission stableness over a long period rather than the momentary transmission rate. We formulate the relationship between effective SE, QoS constraint, and scheduled user number as a continuous function through employing the effective capacity (EC) theory of wireless channels. Nonetheless, obtaining the definitive solution for optimal scheduled user number is still problematic and unfathomed. Therefore, in this paper, an approach to obtain the suboptimal scheduled user number is presented. Simulation results show that the number of selected users is close to the theoretical value.

**Keywords:** Multiple-input multiple-output systems · Vehicular networks · Quality of experience · Wireless communication · Spectral efficiency

## 1 Introduction

With the expeditious development of next generation networks, many researchers have presented numerous novel network routing algorithm and measurement approaches [1–3]. For optimize the core and edge network, researches about user behavior and traffic analysis methods [4–7] have been conducted. Aiming at enhance user experience [8–11], resources utilization [12–15] and energy-efficiency [16–18], novel scheduling strategies are designed to optimize network efficiency. Meanwhile, the performance evaluation of these scheduling strategies is getting more important. In order to evaluate the performance of these scheduling strategies, traffic reconstruction on flow level has drawn a lot of attention of research [19–21]. To enhance the quality of user service in 5G edge network, massive multiple-input multiple-output (MIMO) systems are proposed. For dealing with massive users and devices, spectral efficiency is critical [22–25]. To guarantee service quality and utilize spectral efficiency of massive MIMO, it is essential to obtain the explicit traffic prediction [2, 26, 27] and resource scheduling according to the traffic model [28–31].

It is indicated by a lot of researches that the spectral efficiency and the experience of end user can be both improved through massive antennas effectively. However, most

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topics of these researches usually focus on the way that the QoS affected by network traffic. Therefore, we put emphasis on how the delay violations caused by the fluctuation of momentary rates in the long term, in this paper. The relationship between the scheduled user number and QoS requirement has been investigated, based on the effective capacity model of wireless communication theory the theory of spectral efficiency model in massive MIMO systems [12]. From our simulation results, it can be drawn that better stableness need to be met to obtained higher QoS requirements. Hence, in each time slot, more users should be scheduled and served transmit signals to by the base station to achieve higher stableness. The momentary transmission rates fluctuation can be diminished by the increment of user scheduling frequency. While it is possible that the SE is reduced with the increasing of the scheduled user number. Hence, in this paper, we mainly formulate a function of effective spectral capacity to indicate the relationship between scheduled user number, SE, and the QoS requirement. Nevertheless, the optimal or explicit solution of relationship between them can not be obtained. Approaches to access the suboptimal solution effectively for the scheduling scheme problem is proposed.

The following content of this paper will be organized in five parts. The system model of the approach will be introduced in the second section. And the third section presents the user selection algorithm for massive MIMO systems. Simulation methodology and results are detailed in the fourth section. Finally, in the fifth section concludes the paper.

## 2 System Model

### 2.1 Spectral Efficiency of Massive MIMO

As proposed in [33], in a typical massive MIMO system model, the BS has an array of $M$ antennas serving it cell. And we consider the mobile terminals have single antenna for receiving signal. The number of mobile terminals is $N$. The sequence number $l$ is assigned to each cell. We use the notation $z_{lk} \in R^2$ to represent the geographical position of each terminal, where the $k \in \{1, \ldots, K\}$ is the sequence number of mobile terminal and $l \in L$ is the cell number of the mobile terminal. The model of the massive MIMO system is described in Fig. 1, where the inverted triangles represent the antennas of the base station and terminals. The arrows between base station and terminal denote the service-providing relationship between them. In Fig. 1, each base station with M antennas serves and communicates with several terminals at the same time. Therefore, the spectral efficiency may be influenced by the scheduled user number. In this paper, the key problem is how to find an optimal or nearly optimal solution of the number of scheduled user number.

The channel response between BS $j$ and UE $k$ in cell $l$ can be denoted by $h_{jlk} \in R^N$. And it can be drawn as realizations from zero-mean circularly symmetric complex Gaussian distributions [32]:

$$h_{jlk} \sim CN\big(0, d_j(z_{lk}\mathrm{I}_M)\big) \tag{1}$$

Where $\mathbf{I}_M$ is the $M \times M$ identity matrix.

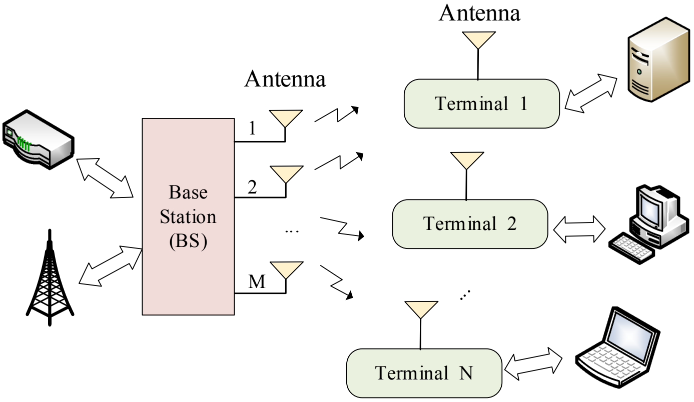

**Fig. 1.** The massive MIMO system

The variance of the channel attenuation from BS $j$ to the positions of any **UE**, $z$ can be obtained by the function $\boldsymbol{d_j}(z)$. We describe the amount of symbols transmitted in each frame as $S$, and reserve $\mathrm{B}'$ out of the $S$ symbols for pilot signaling, allocating the remaining $S - \mathrm{B}'$ symbols for payload data. $p_{lk} = \frac{\rho}{d_{j(z_{lk})}}$ indicates the transmit power of one symbol, in which $\rho$ is a design parameter for the channel attenuation inversion policy, ensuring that the average effective channel gain remains the same for all UEs:$E\{p_{lk}\|\boldsymbol{h}_{llk}\|^2\} = M_\rho$. And at UE $k$ in cell $j$, the received download signal in a frame can be expressed as:

$$y_{jk} = \sum_{l \in L} \sum_{m=1}^{K} \mathrm{h}_{ljk}^{T} \mathbf{w}_{lm} x_{lm} + n_{jk} \tag{2}$$

where $(\cdot)^T$ indicates the transpose operation, the symbol transmitted to UE $m$ in cell $l$ is $x_{lm}$, $w_{lm} \in C^M$ is the vector of corresponding precoding, and $||w_{lm}||^2$ is the power of allocated download transmit, which can be expressed as:

$$w_{lm} = \sqrt{\frac{p_{jk}}{\mathrm{E_h}\left\{||g_{jk}||^2\right\}}} g_{jk}. \tag{3}$$

In Eq. (3), the average power of transmitting $p_{jk} \geq 0$ is a function of the UE position but not of the momentary channel realizations. The spatial directivity of the transmission is defined by vector $g_{jk} \in C^M$ which is based on the acquired CSI. The SNIR is given in [33]:

$$SINR_{jk} = \frac{p_{jk} \frac{\mathrm{E_h}\left\{||\boldsymbol{g}_{jk}\mathbf{h}_{jjk}||^2\right\}}{\mathrm{E_h}\left\{||\boldsymbol{g}_{jk}||^2\right\}}}{\sum_{l \in L} \sum_{m=1}^{K} P_{lm} \frac{\mathrm{E_h}\left\{||\boldsymbol{g}_{lm}\mathbf{h}_{ljk}||^2\right\}}{\mathrm{E_h}\left\{||\boldsymbol{g}_{lm}||^2\right\}} - p_{jk} \frac{\mathrm{E_h}\left\{||\boldsymbol{g}_{jk}\mathbf{h}_{jjk}||^2\right\}}{\mathrm{E_h}\left\{||\boldsymbol{g}_{jk}||^2\right\}} + \sigma^2} \tag{4}$$

In the download of cell *j*, the maximum achievable SE can be expressed by:

$$SE_j = K\left(1-\frac{B'}{S}\right)\log_2\left(1+\frac{1}{I_j^{scheme}}\right) \tag{5}$$

where

$$I_j^{scheme} = \sum_{l\in L_{|}(\beta)\backslash\{j\}}\left(\mu_{jl}^{(2)}+\frac{\mu_{jl}^2+\left(\mu_{jl}^{(1)}\right)^2}{G^{scheme}}\right) + \frac{\left(\sum_{l\in L}\mu_{jl}^{(1)}Z_{jl}^{scheme}+\frac{\sigma^2}{\rho}\right)\left(\sum_{\ell\in L_j(\beta)}\mu_{jl}^{(1)}+\frac{\sigma^2}{B'\rho}\right)}{G^{scheme}}. \tag{6}$$

Here the different receive combining schemes employed determined by the $G^{scheme}$ and $Z_{jl}^{scheme}$. In previous works, the compassion between these two techniques has been conducted in massive MIMO system. As the current research results, $G^{MR}=M$ and $Z_{jl}^{scheme}=K$ with MR combining, whereas $G^{ZF}=M-k$ and

$$Z_{jl}^{ZF}\begin{cases} K\left(1-\dfrac{\mu_{jl}^{(1)}}{\sum_{\ell\in L_j(\beta)}\mu_{jl}^{(1)}+\frac{\sigma^2}{B'\rho}}\right) & if\ l\in L_j(\beta), \\ K & if\ l\notin L_j(\beta). \end{cases} \tag{7}$$

In Eq. (7):

$$\mu_{jl}^{(w)} = \mathrm{E}_{Z_{lm}}\left\{\left(\frac{d_j(z_{lm})}{d_l(z_{lm})}\right)^w\right\} for\ w=1,2. \tag{8}$$

### 2.2 Effective Capacity Model

Generally, we regard the QoS problem for a stable channel as a relationship between the covering of arrival rate and the stable transmission capacity of the system. In order to model a QoE/QoS problem for a stable channel in massive MIMO systems, in each time slot, a threshold of SINR can be set for the small burst data services. Regrettably, the future 5G networks will be consist of many emerging big buffering services, such as speech cloud and remote control based on real-time video. During the transmissions of them, the time-varying capacity, fast-moving users, and low reliability of wireless networks must be considered. How to model the time-varying channel is the key consideration for QoS guaranteeing. Inefficient user scheduling and resource allocation will be caused in traditional QoS/QoE models. Therefore, the EC concept is proposed, which is a function of the nonempty buffer probability and the QoS connection exponent. The EC concepts is more applicable for the description of the delay violation probability of time-varying channels, in many scenarios [34–38].

We denote the QoS requirement as.

$$P_r\left(\max_{1\le i\le N} Q_i(0) > B\right) \le \varepsilon. \tag{9}$$

For a large buffer size $B$, a QoS constraint $\epsilon$ is set and $\theta = -\log(\epsilon)/B$, the QoS requirement can be expressed as an EC problem:

$$\lambda \le \min_{1 \le j \le N} C_k(\theta) \tag{10}$$

where

$$C_k(\theta) = \frac{1}{\theta} \lim_{n \to \infty} \frac{-1}{n} \ln \mathrm{E}\left( e^{-\theta \sum_{t=1}^{n} r_k(t)} \right) \tag{11}$$

and $r_k(t)$ is the rate allocated to user $k$ in cell $j$ at time $t$.

It is assumed that the $K$ users out of a set of $N$ active users is picked by the scheduling scheme at the base station for stochastic transmission with the same probability. Thus, we can denote the $r_k$ as

$$\mathrm{r}_k(t) = \begin{cases} \frac{N_f}{K}\left(1 - \frac{B}{S}\right)\log_2\left(1 + \frac{1}{I_j^{scheme}}\right), & w.p.\frac{K}{N}, \\ 0, & w.p.1 - \frac{K}{N}. \end{cases} \tag{12}$$

## 2.3 Spectral Effective Capacity of Massive MIMO

Higher fluctuation of EC model will account for lower EC, causing higher probability of delay violation. The spectral efficiency model and EC model are combined into spectral effective capacity model for massive MIMO in [33]. In this paper, we compute the outage probability of the QoS constraint due to the difficulty of the predication of a certain momentary CSI and the end users' number who access the cell. For describing the outage probability, one of the effective tools is EC theory. We denote the $\nu = N_f\left(1 - \frac{B}{S}\right)\log_2\left(1 + \frac{1}{I_j^{scheme}}\right)$, $\mathrm{P}\left\{\left(\sum_{t=1}^{n} r_k(t)\right) = \tau\frac{\nu}{K}\right\}$ as the probability of the total transmitted capacity with $\tau$ times scheduled in the future $n$ time slots. Massive MIMO system's effective capacity can be expressed by:

$$\mathrm{E}\left( e^{-\theta \sum_{t=1}^{n} r_k(t)} \right) = \sum_{\tau=0}^{n} \left( e^{-\theta\tau\frac{\nu}{K}} P\left\{ \left( \sum_{t=1}^{n} r_k(t) \right) = \tau\frac{\nu}{K} \right\} \right). \tag{13}$$

We assume that the end devices have same probability to be scheduled and $K$ users for each time slot are scheduled by BS. Therefore, we rewrite the expected transmission capacity of a user in the future $n$ time slots as:

$$\mathrm{E}\left( e^{-\theta \sum_{t=1}^{n} r_k(t)} \right) = \sum_{\tau=0}^{n} \left( \binom{n}{\tau} \left( e^{-\theta\frac{\nu}{K}} \frac{K}{N} \right)^{\tau} \left( 1 - \frac{K}{N} \right)^{(n-\tau)} \right). \tag{14}$$

And we rewrite the effective capacity of user $k$ as.

$$C_k(\theta) = \frac{1}{\theta} \lim_{n \to \infty} \frac{-1}{n} \ln \sum_{\tau=0}^{n} \left( e^{-\theta\tau\frac{\nu}{K}} \binom{n}{\tau} \left( \frac{K}{N} \right)^{\tau} \left( 1 - \frac{K}{N} \right)^{(n-\tau)} \right)$$

$$
\begin{aligned}
&= \frac{1}{\theta} \lim_{n\to\infty} \frac{-1}{n} \ln \sum_{\tau=0}^{n} \left( \binom{n}{\tau} \left( e^{-\theta \frac{\nu}{K}} \frac{K}{N} \right)^{\tau} \left( 1 - \frac{K}{N} \right)^{(n-\tau)} \right) \\
&= \frac{1}{\theta} \lim_{n\to\infty} \frac{-1}{n} \ln \left[ 1 - \frac{K}{N} \left( 1 - e^{-\theta \frac{\nu}{K}} \right) \right]^{n}.
\end{aligned}
\tag{15}
$$

According to L'Hospital's rule, the Eq. (15) can be expressed as [33]:

$$
\begin{aligned}
C_k(\theta) &= \frac{1}{\theta} \lim_{n\to\infty} \frac{-1}{n} \ln \left[ 1 - \frac{K}{N} \left( 1 - e^{-\theta \frac{\nu}{K}} \right) \right]^{n} \\
&= \frac{-1}{\theta} \lim_{n\to\infty} \frac{\frac{\partial \ln \left[ 1 - \frac{K}{N} \left( 1 - e^{-\theta \frac{\nu}{K}} \right) \right]^{n}}{\partial n}}{\frac{\partial n}{\partial n}} \\
&= \frac{-1}{\theta} \ln \left[ 1 - \frac{K}{N} \left( 1 - e^{-\frac{\theta \nu}{K}} \right) \right].
\end{aligned}
\tag{16}
$$

If the $\theta \to \infty$, the EC is zero. While $\theta \to 0$, the EC is $\frac{K}{N}\frac{N_f}{K}\left(1 - \frac{B}{S}\right)\log_2\left(1 + \frac{1}{I_j^{scheme}}\right)$ It is assumed that all users have the same QoS requirements. Therefore, for a fixed $\theta$, at each time slot, we consider the $f(K) = C_k(\theta)$ as function of the scheduled users number $K$. The derivative of this EC function with respect to $K$ is

$$
\nabla f(K) = \frac{K e^{\frac{\nu\theta}{K}} - K - \theta\nu}{(NK\theta)\left( N e^{\frac{\nu\theta}{K}} - K e^{\frac{\nu\theta}{K}} + K \right)}.
\tag{17}
$$

However, it is impractical to obtain the solution of $\nabla f(K) = 0$. Therefore, the optimal users scheduled number is impossible to calculate.

## 3 User Selection Algorithm

Causing the impossibility of obtaining the explicit solution, a fast user selection algorithm is proposed in order to solve the problem by finding a suboptimal solution, which is shown in Table 1.

**Table 1.** User selection algorithm

| | |
|---|---|
| Step1 | Del $= \frac{\mathrm{N}}{20}$, N is the number of candidate users |
| Step2 | n $= 1$, $\Delta$ESC $= \nabla f(1) + \nabla f(1 + Del)$ |
| Step3 | While $\Delta$ESC $> 0$ and $n < N - Del$ |
| Step4 | n = n + Del |
| Step5 | ENDWHILE |
| Step6 | n = n + Del/2 |
| Step7 | RETURN n |

Figure 2 illustrates the calculation process of the proposed fast user selection algorithm. To find a suboptimal solution, we first define a *Del* value, which can be calculated by *N/20*, where *N* denotes the number of candidate users. At the beginning of the algorithm, we assign the *n* as 1 and $\Delta \mathrm{ESC} = \nabla f(1) + \nabla f(1 + Del)$. And the *n* self-increases progressively by *Del*, until the $\Delta \mathrm{ESC} > 0$ and $n < N - Del$. At last, we take $n = n + Del/2$ as the suboptimal solution of the scheduled user number, which will be the approximate solution of the problem.

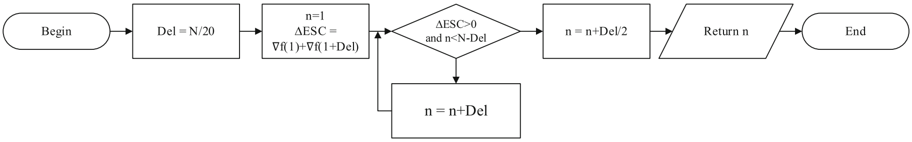

**Fig. 2.** The fast user selection approach.

It can be proved that the algorithm can converge in a few loops. The interval of optimal solution can be found by using Eq. (17), which is the derivative of the EC function. The symbol of the derivative of EC should be different during the two ending intervals. And the suboptimal solution can be obtained as intermediate point after several loops of the interval.

## 4 Simulation and Results

A simple scenario with one cell is simulated, for investigating the relationship between the QoS requirement and the scheduled user number. We set the simulation according the parameters in urban environment. In the simulation experiment, one base station equipped with two hundred antennas servers two hundred users with the same QoS requirement. We set the pilot reuse factor as 1 and the coherence block length to 400. The SNR is set to 5 dB and pathloss factor is set to 3.7. The QoS parameter $\theta$ is in a range from $e^{-10}$ to $e^{10}$, in which low $\theta$ indicates a non-strict demand for real-time transmission, whereas high value of $\theta$ infers that a strict real-time request and high stableness must be satisfied. The unit of EC is bits/S/Hz.

Figure 3 shows the simulation results between theoretical optimal user number and user number obtained from proposed fast algorithm. It can be drawn from the figure that the suboptimal selected user number obtained by the proposed scheduling scheme is very close to the theoretical optimal number.

Furthermore, we conduct the simulation of the comparison between theoretical optimal user number and user number obtained from proposed fast algorithm under different QoS parameter. Figure 4 describes the comparison result of the scheduled user number. It can be seen that with the QoS parameter increasing, the user number will be decreased, which means one base station serve less terminals. With different QoS parameter, the calculation results of proposed fast scheduling algorithm are close to theoretical user number, showing the practicability of our approach.

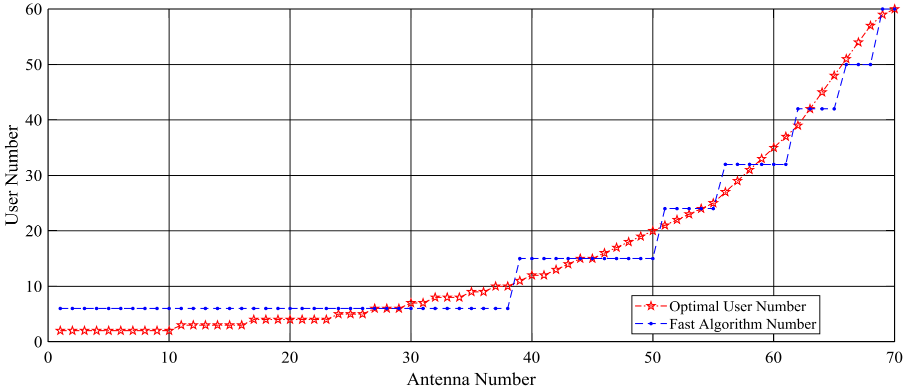

**Fig. 3.** Comparison with different antenna number.

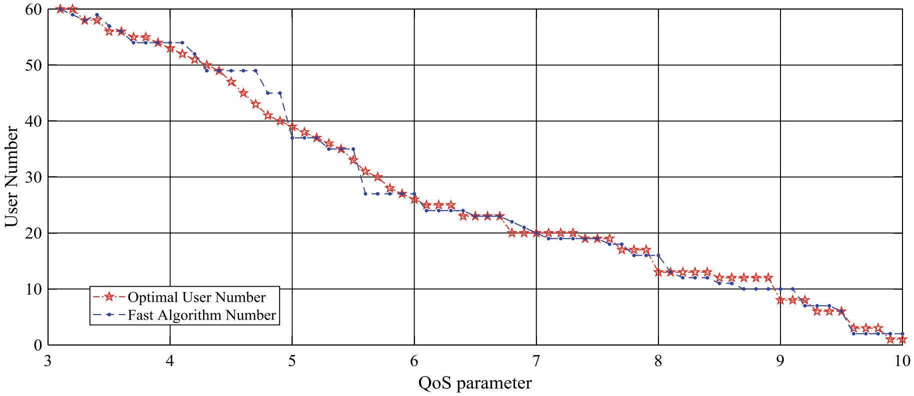

**Fig. 4.** Comparison with different QoS parameter.

## 5 Conclusion

In this paper, the optimal scheduling user number with fixed QoS constraint problem is investigated to obtain the maximum of the effective spectral capacity. Due to the difficulty to seek the explicit user number, a fast algorithm to obtain a suboptimal solution is proposed in this paper. The appropriate and suboptimal user number can be calculated with a low computation cost. The simulation on the massive MIMO system shows that the selected user number from our algorithm is near to the theoretical value, which means our approach is effective and practical.

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