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Nash Bargaining Solution Based Subcarrier Allocation for Uplink SC-FDMA Distributed Antenna Network

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Abstract

The system capacity of single-carrier frequency division multiple access (SC-FDMA) can be increased by allocating subcarriers to users who are in a good channel condition. However, there is a tradeoff between system capacity and fairness among users. Nash bargaining solution (NBS) in cooperative game theory can be used to solve this tradeoff problem. However, very high computational complexity is required to find the NBS. In this paper, we propose a reduced complexity suboptimal NBS based subcarrier allocation, which requires lower computational complexity while achieving the system capacity and fairness among users similar to the NBS. The proposed suboptimal NBS subcarrier allocation is applied to distributed antenna network (DAN) using frequency-domain space-time transmit diversity (FD-STTD). Numerical computation results show that the proposed NBS based subcarrier allocation achieves the system capacity comparable to Proportionally Fair (PF) map while achieving a higher fairness than PF map.

Keywords: SC-FDMA, distributed antenna network, space-time coding, Nash bargaining solution

1 Introduction

In broadband wireless communications, the transmission quality degrades due to the propagation path loss, shadowing loss, and frequency-selective fading [1]. Distributed antenna network (DAN) [2-5] is a promising network, in which many antennas connected to the signal processing center (SPC) by means of optical link are spatially distributed. In DAN, some distributed antennas can be always visible from a user and therefore, the effect of the propagation path loss and shadowing loss can be eliminated by selecting some antennas close to a user. To further improve the transmission performance, antenna diversity technique is effective [6]. Frequency-domain space-time transmit diversity (FD-STTD) [7] is one of the powerful diversity techniques, which achieves the maximal ratio diversity gain. In FD-STTD, no channel state information (CSI) is required at the transmitter and an arbitrary number of receive antennas can be used while keeping the same coding rate; however, the coding rate reduces if more than 3 transmit antennas are used. Therefore, FD-STTD is suitable for the uplink transmission.

Single-carrier frequency division multiple access (SC-FDMA) [8] is suitable for the uplink transmission because of its low peak-to-average power ratio (PAPR) property compared to orthogonal frequency division multiple access (OFDMA) [9-11]. In SC-FDMA, the system capacity can be increased by allocating subcarriers to users who are in a good channel condition. However, if too many subcarriers are allocated to the single user in a good channel condition, the fairness among users degrades. The system capacity and fairness are in a tradeoff relation.

To solve this tradeoff problem, the resource allocation based on Nash bargaining solution (NBS) in the cooperative game theory has recently been studied [12, 13]. However, to find the NBS, very high computational complexity is required.

In this paper, we propose a reduced complexity suboptimal NBS based subcarrier allocation which achieves the system capacity and fairness similar to the NBS. We apply the proposed method to the multiuser uplink SC-FDMA DAN using FD-STTD and evaluate, by numerical computation, its system capacity and the fairness among users. We also compare the system capacity and fairness of the proposed method with those of Proportionally Fair (PF) map and Max map [14].

2 Multiuser Uplink SC-FDMA DAN using FD-STTD

2.1 Network model

In this paper, the multiuser and single-cell environment is considered. Figure 1 illustrates the network model of the DAN considering in this paper. The SPC is located at the center of a cell and 6 distributed antennas are equidistantly located along a circle of radius $2R/3$, where R denotes the cell radius. They are connected to the SPC by means of optical links (ideal signal transmission between each distributed antenna and the SPC is assumed). It is assumed that there are U users in a cell and each user has N_t transmit antennas. Each user selects N_r distributed antennas which have the highest local average received power and communicate with the SPC by using the allocated subcarriers.

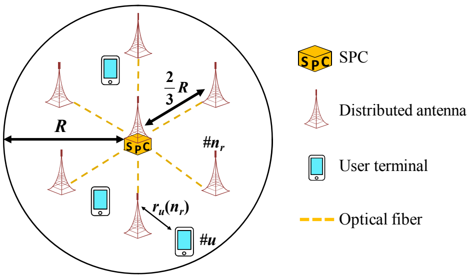
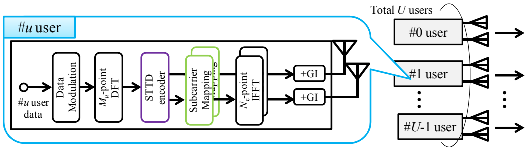
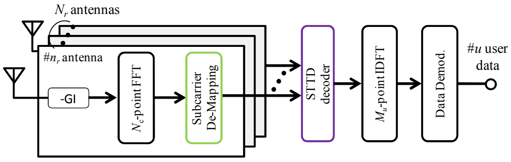


Figure 1 Network model of DAN



(a) Transmitter (user)



(b) Receiver (SPC)

Figure 2 Transmitter and receiver structure.

2.2 Channel model

The propagation channel is characterized by the distance-dependent path loss, the shadowing loss, and the frequency-selective fading. The local average received signal power from the u-th user at the n_r-th distributed antenna is given by

$$\begin{aligned}P_{r,u}(n_r) &= (P'_{t,u}\cdot R^{-\alpha})(r_u(n_r)/R)^{-\alpha}\cdot 10^{-\eta(n_r)/10}\\ &= P_{t,u}\cdot R_u(n_r)^{-\alpha}\cdot 10^{-\eta(n_r)/10}\qquad ,\qquad (1)\\ &= P_{t,u}\cdot\Omega_u(n_r)\end{aligned}$$

where $P'_{t,u}$ denotes the transmit power of the u-th user, $r_u(n_r)$ is the distance between the u-th user and the n_r-th distributed antenna, α is the path loss exponent, and $\eta(n_r)$ is the shadowing loss in dB, and $\Omega_u(n_t,n_r)=R_u(n_r)^{-\alpha}\cdot 10^{-\eta(n_r)/10}$. $\eta(n_r)$ is a zero-mean Gaussian variable with standard deviation σ. $R_u(n_r)=r_u(n_r)/R$ and $P_{t,u}=P'_{t,u}\cdot R^{-\alpha}$ represent the normalized distance and the normalized transmit power, respectively.

The channel impulse response between the n_t-th transmit antenna and the n_r-th distributed antenna is expressed as

$$h_u(n_t,n_r,\tau)=\sum_{l=0}^{L-1}h_{u,l}(n_t,n_r)\delta(\tau-\tau_l),\qquad (2)$$

where L denotes the number of discrete paths, $h_{u,l}(n_t,n_r)$ and τ_l are respectively the complex-valued path gain with $\sum_{l=0}^{L-1}E[|h_{u,l}(n_t,n_r)|^2]=\Omega_u(n_t,n_r)$ and the delay time of the l-th path.

2.3 Signal representation

Figure 2 shows the transmitter and receiver structures of SC-FDMA using FD-STTD. M_u subcarriers are assumed to be allocated to the u-th user. It is assumed that each user transmits M_u data symbols per block and the total number of subcarriers is $N_c=\sum_{u\in\mathbf{U}}M_u$, where $\mathbf{U}=\{0, \ldots, U-1\}$ denotes a set of users.

At the u-th user's transmitter, a sequence of $J\times M_u$ data symbols to be transmitted is divided into a sequence of J blocks of M_u symbols each. Each symbol block $\mathbf{d}_{u,j}=[d_{u,j}(0),\ldots,d_{u,j}(M_u-1)]^T$, $j=0\sim J-1$, is transformed by M_u-point discrete Fourier transform (DFT) into the frequency-domain signal block $\mathbf{D}_{u,j}=[D_{u,j}(0),\ldots,D_{u,j}(M_u-1)]^T$, $j=0\sim J-1$, as

$$\mathbf{D}_{u,j}=\mathbf{F}\mathbf{d}_{u,j},\qquad (3)$$

where $\mathbf{F}$ represents the $M_u\times M_u$ DFT matrix given as

$$\mathbf{F}=\frac{1}{\sqrt{M_u}}\begin{bmatrix}1 & 1 & \cdots & 1\\ 1 & e^{-j2\pi\frac{1\times1}{M_u}} & \cdots & e^{-j2\pi\frac{1\times(M_u-1)}{M_u}}\\ \vdots & \vdots & \ddots & \vdots\\ 1 & e^{-j2\pi\frac{(M_u-1)\times1}{M_u}} & \cdots & e^{-j2\pi\frac{(M_u-1)\times(M_u-1)}{M_u}}\end{bmatrix}.\qquad (4)$$

A sequence of J frequency-domain signal blocks $\mathbf{D}_{u,j}=[D_{u,j}(0),\ldots,D_{u,j}(M_u-1)]^T$, $j=0\sim J-1$, is encoded into N_t streams of Q encoded signal blocks each. For $N_t=2$ ($J=Q=2$), the encoded signal block $\tilde{\mathbf{S}}_{u,q}(n_t)=[\tilde{S}_{u,q}(n_t,0),\ldots,\tilde{S}_{u,q}(n_t,M_u-1)]^T$, $q=0\sim Q-1$, $n_t=0\sim N_t-1$, is expressed as (for $N_t>2$, see [7])

$$\tilde{\mathbf{S}}_{u,q}=\begin{bmatrix}\tilde{\mathbf{S}}_{u,0}(0) & \tilde{\mathbf{S}}_{u,1}(0)\\ \tilde{\mathbf{S}}_{u,0}(1) & \tilde{\mathbf{S}}_{u,1}(1)\end{bmatrix}=\frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{D}_{u,0} & -\mathbf{D}^*_{u,1}\\ \mathbf{D}_{u,1} & \mathbf{D}^*_{u.0}\end{bmatrix}.\qquad (5)$$

For each encoded signal block, the subcarrier mapping is performed. For $N_t=2$, The q-th signal block $\mathbf{S}_{u,q}(n_t)=[S_{u,q}(n_t,0),\ldots,S_{u,q}(n_t,N_c-1)]^T$, $q=0\sim Q-1$, $n_t=0\sim N_t-1$, to be transmitted from the n_t-th antenna is expressed as

$$\mathbf{S}_{u,q}=\begin{bmatrix}\mathbf{S}_{u,0}(0) & \mathbf{S}_{u,1}(0)\\ \mathbf{S}_{u,0}(1) & \mathbf{S}_{u,1}(1)\end{bmatrix}=\begin{bmatrix}\mathbf{A}_u & \mathbf{0}\\ \mathbf{0} & \mathbf{A}_u\end{bmatrix}\tilde{\mathbf{S}}_{u,q},\qquad (6)$$

where $\mathbf{A}_u$ denotes the $N_c\times M_u$ mapping matrix which satisfies

$$\mathbf{A}^T_{u^\star}\mathbf{A}_u=\begin{cases}\mathbf{I}, & if\ u^\star=u\\ \mathbf{0}, & otherwise\end{cases}.\qquad (7)$$

$\mathbf{I}$ and $\mathbf{0}$ denote the $M_u\times M_u$ identity matrix and zero matrix, respectively. The (m, n) element of $\mathbf{A}_u$ is $a_u(m,n)\in\{0,1\}, \forall u\in\mathbf{U}$, $m=0\sim M_u-1$, $n=0\sim N_c-1$.

Finally, N_c-point inverse DFT (IDFT) is applied to $\mathbf{S}_{u,q}(n_t)=[S_{u,q}(n_t,0),\ldots,S_{u,q}(n_t,N_c-1)]^T$, $q=0\sim Q-1$, $n_t=0\sim N_t-1$, to obtain the time-domain transmit signal. After inserting a cyclic prefix (CP) into the guard interval (GI), N_t streams of Q blocks each are transmitted from N_t antenna.

The transmitted signals are received at N_r distributed antennas. The $N_rN_c\times Q$ frequency-domain received signal matrix $\mathbf{R}$ is expressed as

$$\mathbf{R}=\sqrt{\frac{2E_s}{T_s}}\sum_{u\in\mathbf{U}}\mathbf{H}_u\mathbf{S}_u+\mathbf{N}\,, \tag{8}$$

where $\mathbf{H}_u$ denotes the $N_cN_r\times N_cN_t$ channel transfer function matrix given as

$$\begin{cases}\mathbf{H}_u=\begin{bmatrix}\mathbf{H}_u(0,0) & \cdots & \mathbf{H}_u(N_t-1,0)\\ \vdots & \ddots & \vdots\\ \mathbf{H}_u(0,N_r-1) & \cdots & \mathbf{H}_u(N_t-1,N_r-1)\end{bmatrix}\\ \mathbf{H}_u(n_t,n_r)=diag[H_u(n_t,n_r,0),...,H_u(n_t,n_r,N_c-1)]\\ H_u(n_t,n_r,k)=\sum_{l=0}^{L-1}h_{u,l}(n_t,n_r)\exp\left(-j2\pi k\dfrac{\tau_l}{N_c}\right)\end{cases}. \tag{9}$$

$\mathbf{N}$ is the $N_rN_c\times Q$ noise matrix, where each component is i.i.d complex-value Gaussian variable having zero mean and variance $2N_0/T_s$ with N_0 being the single-sided power spectrum density of additive white Gaussian noise (AWGN).

The subcarrier de-mapping is done to pick up the $u^\star$-th user's signal components. The signal components $\widetilde{\mathbf{R}}_{u^\star}$ of the $u^\star$-th user after subcarrier de-mapping can be expressed as

$$\begin{aligned}\widetilde{\mathbf{R}}_{u^\star}&=\begin{bmatrix}\widetilde{\mathbf{R}}_{u^\star,0}(0) & \cdots & \widetilde{\mathbf{R}}_{u^\star,Q-1}(0)\\ \vdots & \ddots & \vdots\\ \widetilde{\mathbf{R}}_{u^\star,0}(N_r-1) & \cdots & \widetilde{\mathbf{R}}_{u^\star,Q-1}(N_r-1)\end{bmatrix}\\ &=\begin{bmatrix}\mathbf{A}_{u^\star}^T & & \mathbf{0}\\ & \ddots & \\ \mathbf{0} & & \mathbf{A}_{u^\star}^T\end{bmatrix}\mathbf{R}\\ &=\sqrt{\frac{2E_s}{T_s}}\begin{bmatrix}\widetilde{\mathbf{H}}_{u^\star}(0,0) & \cdots & \widetilde{\mathbf{H}}_{u^\star}(N_t-1,0)\\ \vdots & \ddots & \vdots\\ \widetilde{\mathbf{H}}_{u^\star}(0,N_r-1) & \cdots & \widetilde{\mathbf{H}}_{u^\star}(N_t-1,N_r-1)\end{bmatrix}\widetilde{\mathbf{S}}_{u^\star}\\ &\quad+\widetilde{\mathbf{N}}\end{aligned} \tag{10}$$

where $\widetilde{\mathbf{H}}_{u^\star}(n_t,n_r)=\mathbf{A}_{u^\star}^T\mathbf{H}_{u^\star}(n_t,n_r)\mathbf{A}_{u^\star}$ and $\widetilde{\mathbf{N}}$ is the $u^\star$-th channel matrix and the noise matrix after de-mapping, respectively.

After subcarrier de-mapping, FD-STTD decoding is carried out to obtain the frequency-domain soft-decision signal vector. Defining $\overline{\mathbf{R}}_{u^\star,q}=[\widetilde{\mathbf{R}}_{u^\star,q}^T(0),...,\widetilde{\mathbf{R}}_{u^\star,q}^T(N_r-1)]^T$ and $\overline{\mathbf{H}}_{u^\star,q}(n_t)=[\widetilde{\mathbf{H}}_{u^\star}^T(n_t,0),...,\widetilde{\mathbf{H}}_{u^\star}^T(n_t,N_r-1)]^T$, the frequency-domain soft-decision signal vector $\hat{\mathbf{D}}_{u^\star,j}=[D_{u^\star,j}(0),...,D_{u^\star,j}(M_u-1)]^T$, j=0~J–1, for N_t=2 can be expressed as (for N_t>2, see [7])

$$\begin{bmatrix}\hat{\mathbf{D}}_{u^\star,0}\\ \hat{\mathbf{D}}_{u^\star,1}\end{bmatrix}=\begin{bmatrix}\overline{\mathbf{R}}_{u^\star,0}^T\overline{\mathbf{H}}_{u^\star}^*(0)+\overline{\mathbf{R}}_{u^\star,1}^H\overline{\mathbf{H}}_{u^\star}(1)\\ \overline{\mathbf{R}}_{u^\star,0}^T\overline{\mathbf{H}}_{u^\star}^*(1)-\overline{\mathbf{R}}_{u^\star,1}^H\overline{\mathbf{H}}_{u^\star}(0)\end{bmatrix}. \tag{11}$$

2.4 Channel capacity

The signal-to-noise power ratio (SNR) $\gamma_u(k)$ of the u-th user at the k-th frequency is given as

$$\gamma_u(k)=\frac{1}{N_t}\frac{E_s}{N_0}\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}|H_u(n_t,n_r,k)|^2\,. \tag{12}$$

Therefore, the channel capacity of the u-th user is expressed as

$$C_u=\sum_{k=0}^{N_c-1}a_u(k)\frac{R_c}{N_c}\log_2(1+\gamma_u(k))\,, \tag{13}$$

where $a_u(k)=\sum_{k'=0}^{M_u-1}a_u(k,k')$ is the mapping indicator that takes 1 if the k-th subcarrier is allocated to the u-th user and 0 otherwise. R_c=J/Q denotes the STTD coding rate. The total capacity of all users are expressed as

$$C_{sum}=\sum_{u\in\mathbf{U}}C_u\,. \tag{14}$$

3 Subcarrier Allocation

3.1 Max map

Max map [14] is the subcarrier allocation which maximizes the total capacity C_{sum} of Eq. (14). In Max map, the k-the subcarrier is allocated to the $u^\star$-th user who satisfies

$$u^\star=\arg\max_{u\in\mathbf{U}}\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}|H_u(n_t,n_r,k)|^2\,. \tag{15}$$

3.2 PF map

Proportionally Fair (PF) map [14] can provide fair subcarrier allocation among users compared to Max map. In PF map method, the k-th subcarrier is allocated to the $u^\star$-th user who satisfies

$$u^\star=\arg\max_{u\in\mathbf{U}}\frac{\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}|H_u(n_t,n_r,k)|^2}{\dfrac{1}{N_c}\sum_{k=0}^{N_c-1}\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}|H_u(n_t,n_r,k)|^2}\,. \tag{16}$$

3.3 NBS based subcarrier allocation

Nash bargaining solution (NBS) based method [12, 13] is known as the resource allocation method which achieves both higher total capacity and higher fairness among users. Defining $\mathbf{C}$=[C_0,…,C_{U-1}], the NBS of subcarrier allocation can be obtained as

$$\mathbf{C}_{NBS}=\arg\max_{\mathbf{C}}f_{NBS}(\mathbf{C})\,, \tag{17}$$

with

$$f_{NBS}(\mathbf{C})=\prod_{u\in\mathbf{U}}(C_u-x_u)\,, \tag{18}$$

where $\mathbf{C}_{NBS}$=[$C_{NBS,0}$,…,$C_{NBS,U-1}$] represents the channel capacity vector obtained by the NBS and x_u denotes the minimum transmission rate requested by the u-th user. In this paper, x_u is set to 0 for all u.

3.4 Proposed suboptimal NBS based subcarrier allocation

NBS based subcarrier allocation requires unacceptably high computational complexity since the optimal solution which satisfies Eq. (18) is found from all possible allocation candidates by exhaustive search. On the other hand, PF map can provide a similar subcarrier allocation to the NBS with low complexity. In this paper, we propose the suboptimal NBS based subcarrier allocation, in which the initial candidate of allocation pattern is found by PF map in the first step and then, the allocation pattern is iteratively changed from the first candidate to approach the NBS.

Figure 3 shows the flowchart of the proposed suboptimal NBS based method. The procedure of the proposed algorithm is as follows.

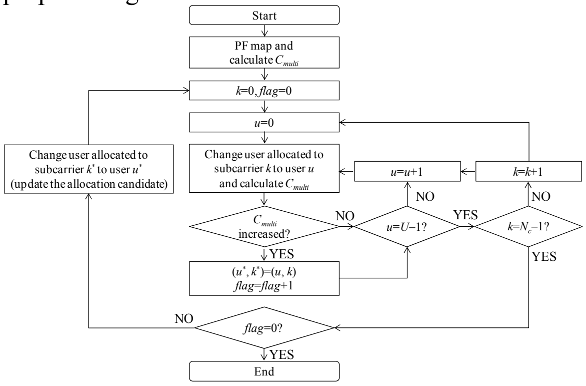


Figure 3 Flowchart of the proposed suboptimal NBS subcarrier allocation

Step 1: Find the initial allocation pattern candidate by using PF map method.

Step 2: Set the index *flag* to 0. Change the user allocated to each subcarrier from the previous allocation candidate and calculate the following cost function C_{multi}.

$$C_{multi} = \prod_{u \in \mathbf{U}} C_u \tag{19}$$

If C_{multi} is increased by changing the user, the index *flag* is incremented by 1. The subcarrier allocation candidate is updated according to the combination of the user u^* and subcarrier k^* which maximizes C_{multi}.

Step 3: Repeat Step 2 until *flag* becomes 0. If *flag*=0, the subcarrier allocation candidate is used as the suboptimal NBS.

Table 1 Simulation condition.

Fading type	Frequency-selective Block Rayleigh fading
Power delay profile	Uniform
No. of path	L=16
Time delay	$\tau_l = l$, l=0~L-1
Path loss exponent	α= 3.5
Shadowing loss standard deviation	σ =7(dB)
No. of transmit antennas	N_t=2
No. of receive antennas	N_r=4
No. of users	U=1, 2, 4, 8, 16, 32, 64, 128, 256
FFT size	256
Normalized transmit E_s/N_0	10(dB)
Channel estimation	Ideal

4 Numerical evaluation results

In this section, we evaluate, by Monte-Carlo numerical computation method, the channel capacity and the fairness among users. Table 1 summarizes the numerical computation condition. The total number of subcarriers is assumed to be N_c=256. A frequency-selective fading channel having symbol-spaced L=16-path uniform power delay profile is also assumed. U users are uniformly distributed in a cell illustrated in Fig. 1.

4.1 Channel capacity

Figure 4 plots the 10% outage total capacity $C_{sum,10\%}$, below which the capacity falls at a probability of 10%, as a function of the number U of users. It can be understood from Fig. 4 that the proposed suboptimal NBS method can achieve almost the same capacity as PF map. In Max map, the subcarrier allocation is done so that the total capacity is maximized. Therefore, Max map achieves the highest $C_{sum,10\%}$.

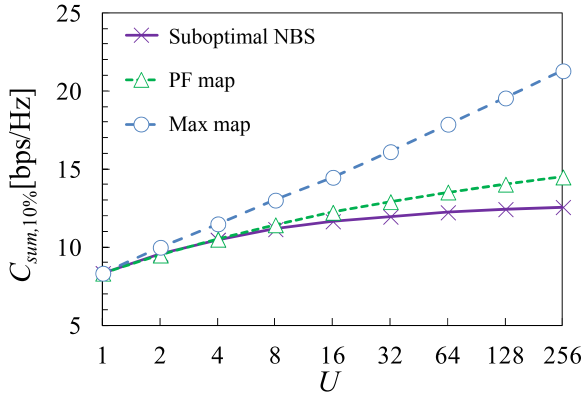


Figure 4 10% outage channel capacity.

When the number of users increases from U=1 to U=16, the channel capacity $C_{sum,10\%}$ of the proposed method increases by about 1.4 times due to the multiuser diversity gain. However, the capacity improvement is limited when U is more than 16. This is because the proposed method also allocates the subcarriers to the users who have bad channel conditions.

4.2 Fairness among users

The fairness among users is evaluated by using the fairness index F [15] defined as

$$F = \frac{\left(\sum_{u=0}^{U-1} C_u\right)^2}{U \cdot \sum_{u=0}^{U-1} C_u^2}. \tag{20}$$

If all users can obtain the same capacity, F becomes 1. If all subcarriers are allocated to only one user, F becomes $1/U$.

Figure 5 plots the 10% outage fairness index $F_{10\%}$ as a function of U. As seen from Fig. 5, the proposed method can achieve higher fairness than PF map and Max map. This is because the proposed method allocates almost the same number of subcarriers to all users. On the other hand, in Max map and PF map, $F_{10\%}$ decreases as U increases.

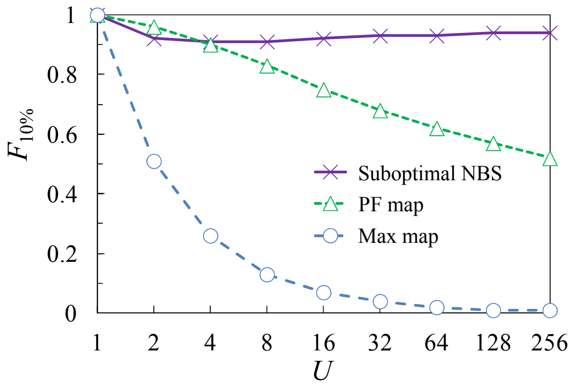


Figure 5 10% outage fairness index

4.3 Comparison of proposed method and optimal NBS method

Figure 6 plots $C_{sum,10\%}$ and $F_{10\%}$ of the proposed method and the optimal NBS when N_c=8. It can be understood from Fig. 6 that the proposed method can achieve almost the same capacity and fairness. Figure 7 shows the average number of comparisons of the channel gain and the channel capacity in each subcarrier allocation method. Comparing with the optimal NBS method, the proposed method requires much smaller computational complexity while achieving almost the same performance as the optimal NBS method.

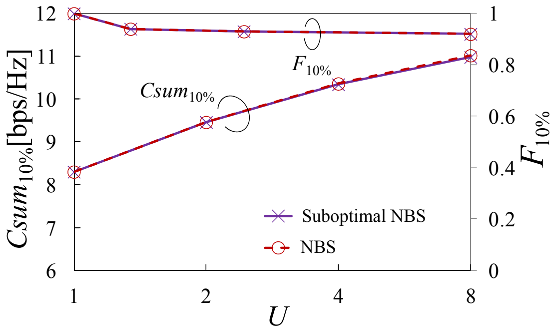


Figure 6 Performance comparison of the proposed method and the optimal NBS.

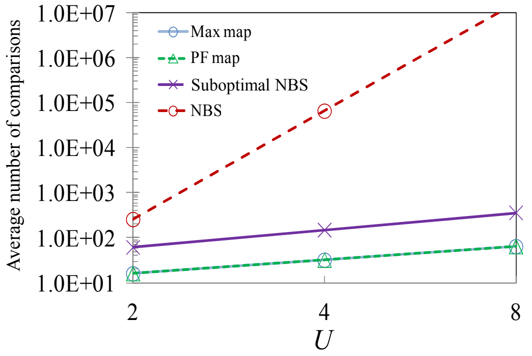


Figure 7 Computational complexity.

5 Conclusions

In this paper, we proposed a reduced complexity suboptimal NBS based subcarrier allocation for the uplink multiuser SC-FDMA DAN. We showed by computer simulation that the proposed NBS based subcarrier allocation can achieve the system capacity comparable to PF map while achieving higher fairness than PF map.

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