Semiorthogonal User Scheduling for Millimeter Wave Using Low-Resolution ADCs

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Abstract —Low-resolution Analogue-to-Digital Converters (ADCs) is a promising solution to reduce power consumption for millimeter wave (mmWave) systems in which the number of antennas at base stations is very large. In this paper, we develop downlink user scheduling for mmWave systems using low-resolution ADCs. Although the sum-rate of Maximum Rate algorithm is very impressive in mmWave systems, it is difficult to use in practice, especially for a large number of users due to exhaustive search. Therefore, we proposed a novel scheduling, termed as NOUS, which selects users who are semi-orthogonal to each other in the beamspace. A closed-form expression for the scheduling criteria in the downlink channel over a mmWave system with low-resolution ADCs and Zero-forcing precoder is derived. The numerical results show that the NOUS algorithm almost achieves the performance of Maximum Rate with lower complexity and outperforms the performance of Proportional Fair in terms of the sum rate.

Index Terms—mmWave MIMO, downlink semi-orthogonal scheduling, low-resolution ADCs

I. Introduction

Millimeter-wave (mmWave) communication systems have many potentials to achieve high throughput in wireless systems [1]–[3]. It is a fact that many researchers try to resolve practical challenges of mmWave systems to get the benefits of very wide bandwidth [4]–[8]. Radio propagation in the mmWave band is highly directional with large path loss due to the very large number of antennas and only has few multi-paths. To compensate for the large path loss, highly directional beamforming is required based on large antenna arrays. As a result of large bandwidth and a high number of bits per sample, high-resolution ADCs coupled with large antenna arrays consume power mainly in the receiver. Therefore, many researchers focus on how to use low-resolution ADC architectures in mmWave communication recently [9].

Many studies show that using large antenna arrays can employ low-resolution ADCs in mmWave systems. Channel state information can be recovered in few bit ADCs [10]-[12]. In [10], an adaptive compressed sensing strategy was designed to rebuild the sparse mmWave channel while requiring a lower number of training pilots. Architectures with ADC bit allocation were proposed to outperform given ADC bit approach in power consumption at the base station in mmWave [13]. Moreover, the optimal number of resolution adaptive ADC bits is logarithmically proportional to the RF chain's signal-to-noise ratio raised to the 1/3 power [14].

The very large number of antennas coupled with low-resolution ADCs pose several challenges to scheduling policy in mmWave systems, including heavy training overhead and incorrect channel state information (CSI). One way to overcome the burden of training overhead is opportunistic random beamforming (RBF) scheduling used in [15]. It shows that the sum rate is proportional with respect to the number of transmit antennas if the number of users also increases linearly with the number of transmit antennas. Then an algorithm is developed for sparse user regime to select users by a beam selection approach [16]. Moreover, conventional algorithms like Maximum Rate (MR) scheduling that maximizes the throughput of the whole system [17], [18] and Proportion Fairness (PF) that tries to provide the same rate for all users [19] cannot be applied directly to RBF in mmWave systems due to exhaustive search [16]. These MR and PF scheduling algorithms also do not exploit the property that channel vectors of scheduled users are almost orthogonal to each other [16]. When the low-resolution ADCs are used, the analysis of the schedule must consider the quantization errors. A user scheduling in the uplink that exploits the orthogonal property of channels was investigated when a BS used low-resolution ADCs [20], [21] to reduce exhaustive search but the downlink user scheduling with low-resolution ADCs is still questionable.

In this paper, we proposed a scheduling algorithm NOUS that aims to select an optimal scheduled group of users by using the semi orthogonality condition of channels to approach the performance of MR with lower complexity. The number of antennas at the user terminal is $N_{\text{MS}} > 1$ that is more practical than the single antenna user case [20], [21]. Our new algorithm has three stages: select the best user in the candidate group, calculate the orthogonal component of its channel to the scheduled group, and eliminate the candidates who are not semi orthogonal with the selected user. The elimination of the candidates by using the orthogonality condition of

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channels helps to reduce a lot of time to find the optimal scheduled users. Moreover, numerical results show that the NOUS can approach the performance of the MR method and outperforms the PF with lower complexity.

This study is organized as follows: Section 2 describes the system model. In Section 3, the user scheduling criteria to select the user set faster than the Maximum Rate are derived, and the user scheduling algorithm is proposed to utilize these criteria. In Section 4, the proposed algorithm is compared with the MR, and PF methods in sum rate. In Section 5 is concludes.

Notation: We use normal letters (e.g., a) for scalars, lowercase and uppercase boldface letters (e.g., $\mathbf{h}$ and $\mathbf{H}$) for column vectors and matrices. $\mathbf{I}_N$ and $\mathbf{0}_N$ are the identity matrix and all-zero matrices of size $N \times N$. For the $\mathbf{A}$ matrix, $\mathbf{A}^T$ is the transpose matrix, $\mathbf{A}^H$ the conjugate transpose, and $\mathrm{tr}(\mathbf{A})$ the trace. $\mathbb{E}[\cdot]$ is the statistical expectation operator.

II. System Model

A. Downlink Transmission

We consider a single-cell multi-user mmWave system consisting of one BS and U users. The BS is equipped with N_{BS} antennas and N_{RF} RF chains. Each user has N_{MS} antennas, and it is assumed that each user connects only one stream with the BS. Furthermore, we assume that the BS only selects a scheduled user set $\mathcal{S} = \{1, 2, ..., N_{\mathrm{S}}\}$ out of U users to serve. Therefore, the total number of streams is N_{S}, and $N_{\mathrm{S}} \le N_{\mathrm{RF}} \le N_{\mathrm{BS}}$.

The BS applies a $N_{\mathrm{S}} \times N_{\mathrm{S}}$ baseband precoder $\mathbf{F}_{\mathrm{BB}} = [\mathbf{f}_1^{\mathrm{BB}}, \mathbf{f}_2^{\mathrm{BB}}, ...\mathbf{f}_{N_{\mathrm{S}}}^{\mathrm{BB}}]$ followed by a $N_{\mathrm{BS}} \times N_{\mathrm{S}}$ RF precoder $\mathbf{F}_{\mathrm{RF}} = [\mathbf{f}_1^{\mathrm{RF}}, \mathbf{f}_2^{\mathrm{RF}}, ...\mathbf{f}_{N_{\mathrm{S}}}^{\mathrm{RF}}]$. Therefore, the transmitted signal as follows:

$$\mathbf{x} = \mathbf{F}_{\mathrm{RF}} \mathbf{F}_{\mathrm{BB}} \mathbf{s} \tag{1}$$

where $\mathbf{s} = [\mathbf{s}_1, \mathbf{s}_2, ...\mathbf{s}_{N_{\mathrm{S}}}]^T$ is the vector of transmitted symbols with $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \frac{1}{N_{\mathrm{S}}} \mathbf{I}_{N_{\mathrm{S}}}$. As the RF is using analog phase shifters, its entries are constant modulus $\left|[\mathbf{F}_{\mathrm{RF}}]_{m,n}\right|^2 = \frac{1}{N_{\mathrm{BS}}}$. In other words, $[\mathbf{F}_{\mathrm{RF}}]_{m,n} = \frac{1}{\sqrt{N_{\mathrm{BS}}}} e^{j\phi_{m,n}}$, where $\phi_{m,n}$ is a quantized angle. The power constraint is applied by $\left|\mathbf{F}_{\mathrm{RF}} \mathbf{F}_{\mathrm{BB}}\right|^2 = N_{\mathrm{S}}$.

Due to the channel model is narrow block-fading, therefore the u -th user will receive the signal [22]-[25]

$$y_u = \sqrt{\rho} \mathbf{w}_u^H \mathbf{H}_u \mathbf{F}_{\mathrm{RF}} \mathbf{F}_{\mathrm{BB}} \mathbf{s} + \mathbf{w}_u^H \mathbf{n}_u \tag{2}$$

where $\mathbf{H}_u$ is the $N_{\mathrm{MS}} \times N_{\mathrm{BS}}$ channel matrix between the BS and the u -th user, $\mathbf{n}_u \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ is the Gaussian noise, ρ represents the transmit power and $\mathbf{w}_u \in \mathbb{C}^{N_{\mathrm{MS}} \times 1}$ is the RF combiner matrix. We assume a geometric channel with L_u scatters for the u -th user [26], [27]. Accordingly, the channel $\mathbf{H}_u$ can be expressed as follows:

$$\mathbf{H}_u = \sqrt{\frac{N_{\mathrm{BS}} N_{\mathrm{MS}}}{L_u}} \sum_{l=1}^{L_u} \alpha_{u,l} a_{\mathrm{MS}}(\theta_{u,l}) a_{\mathrm{BS}}^H(\phi_{u,l}) \tag{3}$$

where $\alpha_{u,l}$ is the complex gain of l -th path, $\theta_{u,l}$ and $\phi_{u,l} \in [0, 2\pi]$ are the l -th path's angles of arrival and departure (AoAs/AoDs) respectively, $a_{\mathrm{MS}}(\theta_{u,l})$ and $a_{\mathrm{BS}}(\phi_{u,l})$ are the antenna array response vectors of the u -th MS and the BS respectively.

Assuming that uniform linear array antennas (ULA) are used, the response vectors are defined as follow:

$$\begin{aligned} a_{\mathrm{MS}}(\theta_{u,l}) &= \sqrt{\frac{1}{N_{\mathrm{MS}}}} [1, e^{j2\pi\epsilon}, ..., e^{j2\pi(N_{\mathrm{MS}}-1)\epsilon}]^T \\ a_{\mathrm{BS}}(\phi_{u,l}) &= \sqrt{\frac{1}{N_{\mathrm{BS}}}} [1, e^{j2\pi\varepsilon}, ..., e^{j2\pi(N_{\mathrm{BS}}-1)\varepsilon}]^T \end{aligned} \tag{4}$$

where $\epsilon = \frac{d \sin(\theta_{u,l})}{\lambda}, \varepsilon = \frac{d \sin(\phi_{u,l})}{\lambda}$, λ is the wavelength signal, and d is the distance between antenna elements. Then, we can denote effective channels as follow:

$$\begin{aligned} \bar{\mathbf{h}}_u &= \mathbf{w}_u^H \mathbf{H}_u \mathbf{F}_{\mathrm{RF}} \\ \bar{\mathbf{H}} &= [\bar{\mathbf{h}}_1^T, \bar{\mathbf{h}}_2^T, ..., \bar{\mathbf{h}}_{N_{\mathrm{S}}}^T]^T \end{aligned} \tag{5}$$

B. Quantization Model

Before digital baseband processing, each real and imaginary component of the complex output $\mathbf{Y}$ is quantized at the ADC pairs. We adopt the additive quantization noise model (AQNM) to characterize the quantization noise. This model can provide sufficiently accurate analysis in the low and medium SNRs [28]. The quantized signal $\mathbf{Z}$ is given as follows:

$$\mathbf{Z} = \vartheta(\mathbf{Y}) = \alpha\sqrt{\rho} \bar{\mathbf{H}} \mathbf{F}_{\mathrm{BB}} \mathbf{s} + \alpha \mathbf{W}^H \mathbf{n} + \mathbf{q} \tag{6}$$

where $\vartheta(.)$ is the element-wise quantizer function, $\alpha = 1 - \beta$ is the quantization gain, β is approximated as $\beta \approx \frac{\pi\sqrt{3}}{2} 2^{-2b}$ for $b > 5$, and the values of β for $b \le 5$ are listed in Table I (are detailed in the ref. [13]).

The noise $\mathbf{W}^H \mathbf{n}$ is distributed as $\mathcal{N}(\mathbf{0}, \mathbf{I})$ because $\mathbf{W}$ is a unitary matrix. The quantization noise is uncorrelated with the $\mathbf{R}$, and $\mathbf{q} \sim \mathcal{CN}(0, \mathbf{R}_{\mathrm{qq}})$ where the covariance matrix $\mathbf{R}_{\mathrm{qq}} = \alpha\beta \mathrm{diag}(\rho \bar{\mathbf{H}} \mathbf{F}_{\mathrm{BB}} (\bar{\mathbf{H}} \mathbf{F}_{\mathrm{BB}})^H + \mathbf{I})$.

C. Two-Stage Multi-user Hybrid Precoding for Single-Path Channels

Survey studies show that, with single path channels, we can omit the subscript l in the channel parameters since $L_u = 1, u = 1, 2, ..., U$. We assumed that continuous beam steering capability is supported, the optimal sum-rate of the system can be found with precoding and combiner vectors [26], we obtained as follows:

$$\begin{aligned} \mathbf{w}_u &= a_{\mathrm{MS}}(\theta_u) \\ \mathbf{f}_u^{\mathrm{RF}} &= a_{\mathrm{BS}}(\phi_u) \end{aligned} \tag{7}$$

The effective channel for the user u -th is

$$\begin{aligned} \bar{\mathbf{h}}_u &= \mathbf{w}_u^H \mathbf{H}_u \mathbf{F}_{\mathrm{RF}} \\ &= \sqrt{N_{\mathrm{BS}} N_{\mathrm{MS}}} \alpha_u a_{\mathrm{BS}}^H(\phi_u) \mathbf{F}_{\mathrm{RF}} \end{aligned} \tag{8}$$

Therefore,

$$\bar{\mathbf{H}} = \mathbf{D} A_{\mathrm{BS}}^H A_{\mathrm{BS}} \tag{9}$$

where $\mathbf{D}$ is a $N_{\mathrm{S}} \times N_{\mathrm{S}}$ diagonal matrix with $[\mathbf{D}]_{u,u} = \sqrt{N_{\mathrm{BS}} N_{\mathrm{MS}}} \alpha_u$. The BS designs the BB precoding as follows:

$$\mathbf{F}_{\mathrm{BB}} = \bar{\mathbf{H}}^H (\bar{\mathbf{H}} \bar{\mathbf{H}}^H)^{-1} \Gamma \tag{10}$$

where Γ is a $N_{\mathrm{S}} \times N_{\mathrm{S}}$ diagonal matrix with $[\Gamma]_{u,u} = \sqrt{\frac{N_{\mathrm{BS}} N_{\mathrm{MS}}}{(A_{\mathrm{BS}}^H A_{\mathrm{BS}})_{u,u}^{-1}}} |\alpha_u|, u = 1, 2, ..., U.$

III. User Scheduling

The achievable rate for the user u -th is given as follows:

$$\begin{aligned} \mathcal{R}_u &= \log_2\left(1 + \frac{\alpha^2 \rho (\bar{\mathbf{h}}_u \mathbf{f}_u^{\mathrm{BB}})^2}{\mathbf{R}_{\mathrm{qq}}(u,u) + \alpha^2}\right) \\ &= \log_2\left(1 + \frac{\alpha^2 \rho N_{\mathrm{BS}} N_{\mathrm{MS}} \alpha_u^2}{\mathbf{R}_{\mathrm{qq}}(u,u) + \alpha^2}\right) \end{aligned} \tag{11}$$

In addition, the sum-rate of the system is:

$$\mathcal{R} = \log_2\left(\det\left(\mathbf{I}_{N_{\mathrm{S}}} + \frac{\alpha^2 \rho (\bar{\mathbf{H}} \mathbf{F}^{\mathrm{BB}})^2}{\mathbf{R}_{\mathrm{qq}} + \alpha^2 \mathbf{I}_{N_{\mathrm{S}}}}\right)\right) \tag{12}$$

Using the achievable rate in Eq. (11), and Eq. (12), the user scheduling problem can be formulated as follows:

$$\mathcal{R} = \max_{\mathcal{S} \subset \{1,2,...,U\}} \sum_{u \in \mathcal{S}} \mathcal{R}_u \tag{13}$$

The optimal performance of ZF precoding in $\mathbf{F}^{\mathrm{BB}}$ is found when the scheduling selects users to satisfy the zero-interference condition $\bar{\mathbf{h}}_u \mathbf{f}_v^{\mathrm{BB}} = 0$ for $u \neq v$. Determining that the optimal set $\mathcal{S}$ and $\mathbf{F}^{\mathrm{BB}}$ is difficult to achieve both the multiplexing gain and the multi-user diversity gain, especially for very large U [29]. However, with a large number of users, it is highly possible to select a nearly orthogonal user set $\mathcal{S}$ [30]; its sum-rate comes close to the optimal performance due to a multi-user diversity effect.

In this work, we proposed a scheduling algorithm (NOUS) as described in ***Algorithm 1*** to maximize the sum-rate in Eq. (12) with low complexity by filtering users with a semi-orthogonal condition in [30] with respect to $\bar{\mathbf{H}}$ which is the projection of the channel matrix onto the beamspace. As it could be seen in ***Algorithm 1***, the scheduling consists of five steps: at first the BS sets the whole users as the candidate group $\mathcal{C}_1, i = 1$ and an empty selected group $\mathcal{S}$, for each round of i the BS will find the best user i -th in the candidate group $\mathcal{C}_i$ to serve to maximize the sum-rate in Eq. (12) and eliminate the selected user $\mathcal{S}(i)$ in the candidate group $\mathcal{C}_i$ in step 2. At step 3, the algorithm calculates the orthogonal component $\mathbf{g}_{\mathcal{S}(i)}$ of new selected user i -th to the current span $\{\mathbf{g}_{\mathcal{S}(1)}, ..., \mathbf{g}_{\mathcal{S}(i-1)}\}$. In step 4, the algorithm will eliminate all users in the candidate group who do not meet the orthogonal criteria with the new selected user $\mathcal{S}(i)$ and finally the algorithm will come back to step 2 with $i = i + 1$ unless the algorithm has selected enough N_S users or there is no candidate user. The *Algorithm 1* is summarized as follows:

Algorithm 1: Near Orthogonal User Scheduling

1: The BS initializes $\mathcal{C}_1 = \{1, 2, ..., U\}, \mathcal{S} = \varnothing, i = 1$

2: Using the sum-rate in 12, the BS select the i -th user as $\mathcal{S}(i) = \underset{k \in \mathcal{C}_i}{\operatorname{argmax}} \; \mathcal{R}([\bar{\mathbf{H}}(\mathcal{S}), \bar{\mathbf{h}}_k])$

and update $\mathcal{S} = \mathcal{S} \bigcup \mathcal{S}(i), \mathcal{C}_i = \mathcal{C}_i \setminus \mathcal{S}(i)$

3: To calculate the orthogonal component of $\bar{\mathbf{h}}_{\mathcal{S}(i)}$ to the span $\{\mathbf{g}_{\mathcal{S}(1)}, ..., \mathbf{g}_{\mathcal{S}(i-1)}\}$

$$\mathbf{g}_{\mathcal{S}(i)} = \bar{\mathbf{h}}_{\mathcal{S}(i)} \left(\mathbf{I} - \sum_{j=1}^{i-1} \frac{\mathbf{g}_{\mathcal{S}(j)}^H \mathbf{g}_{\mathcal{S}(j)}}{\| \mathbf{g}_{\mathcal{S}(j)} \|^2}\right)$$

4: To select the remain users who meet the orthogonal criteria with the user $\mathcal{S}(i)$

$$\mathcal{C}_{i+1} = \{k \in \mathcal{C}_i \mid \frac{|\bar{\mathbf{h}}_k \mathbf{g}_{\mathcal{S}(i)}^H|}{\|\bar{\mathbf{h}}_k\| \, \|\mathbf{g}_{\mathcal{S}(i)}\|} \leq \xi\} \tag{14}$$

5: If $i < N_{\mathrm{S}}$ and $\mathcal{C}_{i+1} \neq \varnothing$, update $i = i + 1$. Otherwise, algorithm finishes.

We compared the NOUS with the MR and PF in terms of sum rate. The MR algorithm must carry exhausted search to select the user who has the highest achievable rate in Eq. (11) in each iteration. As the number of users is very large, the MR carries the burden of computing. Unlike the MR algorithm, the NOUS algorithm enforces the semi-orthogonal condition in Eq. (14) to reduce the size of the remaining user candidate after each iteration, therefore, the NOUS algorithm is more computationally efficient than the MR algorithm. Moreover, the NOUS also outperforms the PF in terms of sum rate because the PF selects the user who has the lowest average rate to serve in each iteration.

IV. Simulation Results and Evaluation

To evaluation the effects of NOUS scheduling, various case studies have been done based on mmWave systems to compare following scheduling policies:

- NOUS
- Maximum Rate
- Proportional Fair
- Single User

In Fig. 1, we compare the spectral efficiency with respect to the SNR. We consider $N_{BS} = 256$ BS antennas, $N_{MS} = 16$ user antennas, $N_S = 20$ scheduled users, $U = 160$ users, $b = 2$ and SNR goes from -20 to 10 dB. It is shown that the NOUS and Maximum Rate algorithm can go to the spectral efficiency of the single user when the SNR is very high. The spectral efficiency of NOUS algorithm almost approximates to the one of the Maximum Rate with lower complexity. The PF focuses on user fairness and cannot get a high spectral efficiency. The gap among methods decreases as the SNR increases because the quantization error will be smaller in the high SNR regime. The proposed NOUS algorithm can work well in the low SNR regime because the high quantization error will decrease the orthogonality among channels.

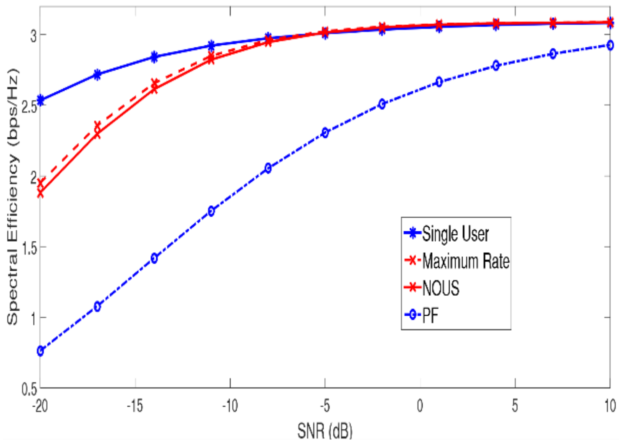

Fig. 1. The spectral efficiency with the respect to the SNR.

In Fig. 2, we compare the spectral efficiency between two cases: one using low-resolution ADC with $b = 2$ while the other does not concern the effects of ADC resolution called No-ADC. It can be seen that if the ADC has a perfect resolution, the spectral efficiency can approach infinity with SNR. In case of low-resolution ADC with $b = 2$, the spectral efficiency improves slowly in the high SNR regime. In both cases, the NOUS algorithm can approximate the performance of Maximum Rate method in terms of spectral efficiency. This result shows that the NOUS algorithm can work in both low-resolution and high-resolution ADC. The gap between the Maximum Rate and the NOUS decreases when the SNR increases because the NOUS will get better performance in low-resolution ADC.

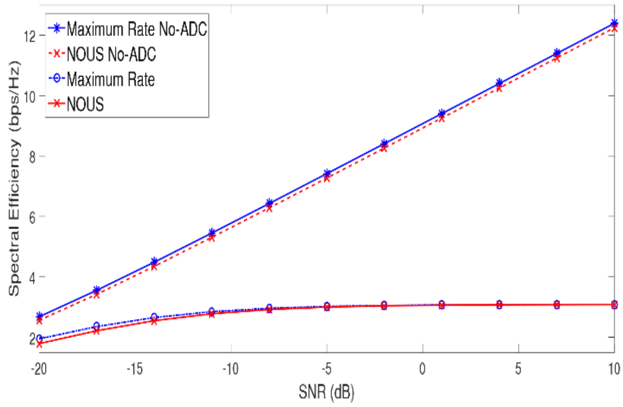

Fig. 2. The comparison of spectral efficiency between low-resolution ADC and No-ADC.

In Fig. 3, we consider the number of antennas at BS N_{BS} increasing from 36 to 256 and the $SNR = 3$ dB. It can be seen that the NOUS algorithm almost achieves the spectral efficiency of the Maximum Rate when the number of transmit antennas is very large. However, the distance of the spectral efficiency between the single-user case and the other cases is high because the increase of N_{BS} cannot compensate for the interference in the low SNR. This result demonstrates that the NOUS work better when the number of antennas increases.

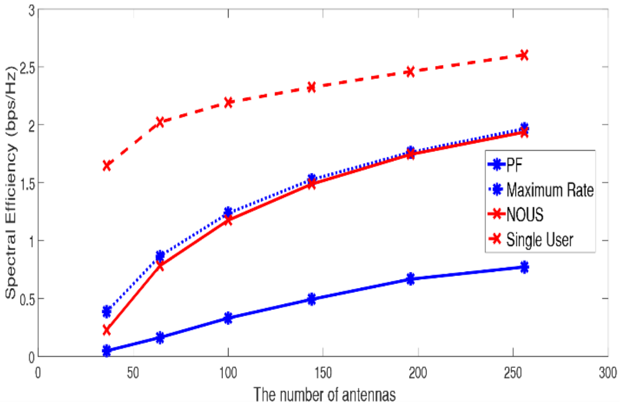

Fig. 3. The spectral efficiency with respect to the N_{BS}.

In Fig. 4, we consider the number of antennas at BS N_S increasing from 20 to 60, $U = 160$ and $\rho = 3$ dB. It shows that if the BS serves more users, the spectral efficiency per user will go down as the power per user also goes down. Moreover, it is more difficult to find high semi-orthogonal users because we keep the total of the number of users U unchanged while serving more users, hence, the spectral efficiency of NOUS goes down slightly compared to Maximum Rate. The gap between the Maximum Rate and the NOUS increases because more scheduled users will make more interference and it is more difficult to find a semi orthogonal group of users to serve.

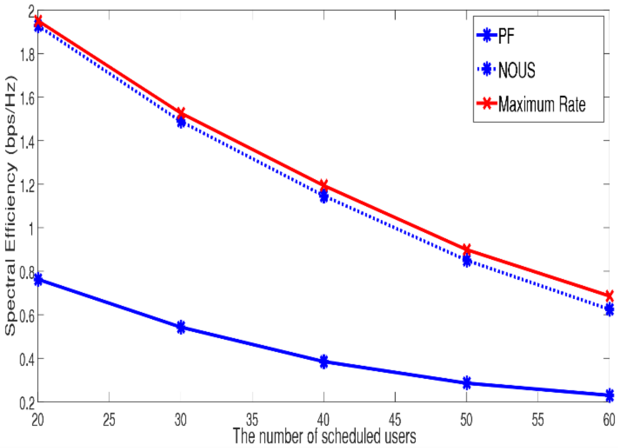

Fig. 4. The spectral efficiency with respect to the N_S.

V. Conclusion

In this study, we proposed a novel scheduling termed as NOUS for downlink mmWave systems with the low-resolution ADCs. It shows that NOUS can reach the performance of the Maximum Rate algorithm while reducing the complexity of choosing the scheduled users. The NOUS uses a derived structure criterion to select a group of semi-orthogonal users and filters users who do not meet this condition in the remaining group. Accordingly, this helps to not only reduce the size of the user set to decrease the time of building the scheduled user list but also reduce the delay of the system. Moreover, it is especially useful for mmWave systems where the number of antennas at BS is very huge and leads to a higher number of serving users.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Professor Ban Nguyen Tien guided and supervised the research; Professor Bac Dang Hoai and Quy Vu Khanh wrote the introduction; Hung Pham made the system model and the simulation; all authors had approved the final version.

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