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Effects of Beam Configuration on Performances of NOMA System for Millimeter Wave Channels

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Abstract

Non-orthogonal multiple access (NOMA) is a technique that forms a NOMA group composed of two or more users and transmits the superimposed signals of all users in the group through a single beam. In case all users in a NOMA group fall within the main lobe, a high data rate is guaranteed. However, in case not all users in the group fall within the main lobe due to the narrow beam width, the sum data rate decreases, and the data rate disparity between users inside and outside the main lobe widens significantly, leading to reduced fairness. On the other hand, an excessively wide beam might reduce the channel gain which lowers the sum data rate. This paper discusses the effects of beam configuration on the throughput and fairness performances of the NOMA system in the millimeter wave channel environments with simulation results for various channel parameters including the number of antennas and beam directions.

Keywords: *NOMA, mmWave, beam configuration, throughput, fairness.*

1. Introduction

The advancement of smartphones, tablet PCs, high-resolution videos, and games has led to a rapid increase in data-rate demand, necessitating the introduction of 5G (fifth generation) networks. To meet the high performance requirements of 5G networks, there has been a growing interest in research on mmWave in the 30GHz to 300GHz band. The short wavelength of mmWave allows for the accommodation of many antennas

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in the same space, prompting research into massive MIMO, and its strong directivity has been utilized to compensate for severe propagation loss, spurring numerous studies on beamforming structures [1], [2]. Among these, research has predominantly focused on Hybrid Beamforming (HBF), which combines analog beamforming (ABF) with digital beamforming (DBF) [3]-[5]. In [3], two HBF precoding methods using least squares and MMSE are proposed for a single-user system with a BS having a large antenna array and a multi-antenna user. In [4], HBF precoding and combining for a single-user system with multi-antennas are calculated using a convolutional neural network (CNN) applied to a BS with massive MIMO. Despite extensive research on beamforming designs, issues related to multi-user access remain a challenge.

Traditionally, orthogonal multiple access (OMA) has been adopted as a multiple access method, where one radio frequency (RF) chain forms a single beam and includes one user signal. Recently, however, research has been conducted on non-orthogonal multiple access (NOMA), which superimposes multiple user signals onto a single RF chain for simultaneous transmission. In NOMA, different power levels are allocated to multiple users in a NOMA group, and the superimposed signals are recovered at the receiver using successive interference cancellation (SIC). Some of the main challenges in NOMA include clustering multiple users into groups and determining the power allocation (PA) for each user. In mmWave channels, while clustering and PA issues dominate HBF to maximize data rates, ABF research focuses on beam splitting, random beamforming (BF), and beamwidth (BW) control [6]-[8]. Research has been conducted on beam splitting, where the beam is divided if users are far apart and NOMA is used when users are close together, to improve data rates; however, this approach has the drawback of high computational complexity [6]. Random beamforming (BF), which transmits fixed analog beams randomly, has extremely low computational complexity but exhibits a significant drop in data rate below a certain transmission power [7]. Beamwidth control, where the beamwidth is adjusted to ensure users fall within 3 dB of the main lobe channel gain, has achieved low computational complexity and high data rates by allocating antennas and adjusting the beamwidth and direction according to user positions [8].

In mmWave channels, a bigger channel gain is achieved when a user is within the main lobe of the beam formed by ABF. In case of the narrow BW, if users are dispersed over a wide angle to form a NOMA group, the likelihood increases that users will be positioned outside the main lobe, leading to a decrease in data rate or reduced fairness as only a part of users may be within the main lobe. If a wide BW is used to ensure that all users fall within the main lobe, the channel gain decreases, reducing the sum data rate. BW control, where the BW is adjusted to ensure users fall within 3dB of the main lobe channel gain, has achieved low computational complexity and high data rates by allocating antennas and adjusting the BW and beam direction according to user positions [8].

In this paper, the effects of the beam configurations on the performance of the NOMA system are discussed. The optimized BWs and BF directions are experimentally determined for the millimeter wave channels based on user positions. During transmissions, these optimized parameters could be utilized to ensure that all users in the NOMA group are within the beam. Simulations are conducted to compare the fairness and the throughput performances for systems with optimized parameters as well as fixed ones.

2. System Model

Consider a single cell downlink mmWave communication system consisting of one BS and two users, as shown in Figure 1. The BS is located at the center of the cell, with a cell radius of D, and the transmission angles range from $-\theta$ to θ. The BS, equipped with a single RF chain, uses a total of N_{BS} antennas arranged in a commonly adopted Uniform Linear Array (ULA). The RF chain controls N_{BS} phase shifters (PSs), each connected to an antenna, to form an analog beam, transmitting the NOMA signals to the two users. Each user receives the NOMA signal through a single antenna.

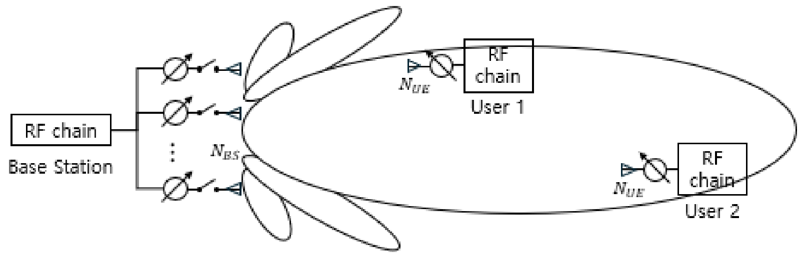

Figure 1. MmWave NOMA scheme with one cluster

The NOMA scheme in Figure 1 forms a NOMA group through BF. The NOMA signal, which superimposes the signals of the two users belonging to a NOMA group, can be expressed as follows.

$$x = \sqrt{p_n}s_n + \sqrt{p_f}s_f \tag{1}$$

Here, s_n and s_f are the normalized and modulated symbols for the near and far users, respectively, and each symbol satisfies $E[s_n^2] = 1$ and $E[s_f^2] = 1$. p_n and p_f are the allocated powers to the near and far user, respectively, satisfying $p_n^2 + p_f^2 = 1$. It is assumed that $p_n < p_f$ to ensure fairness level and also, values of p_n and p_f are fixed to 0.25 and 0.75, respectively.

To transmitting the symbol x described in (1), we assume that a conventional analog beamformer in previous work [8] is adopted. A precoder with coefficients set $\boldsymbol{w}$ is applied which is a function of the BF angle of departure (θ_{BF}) and the number of antennas (N_{BS}):

$$\boldsymbol{w} = \sqrt{\frac{1}{N_{BS}}}\left[1,\ e^{-\frac{j2\pi d}{\lambda}\cos(\theta_{BF})},\ \cdots,e^{-\frac{j2\pi d}{\lambda}(N_{BS}-1)\cos(\theta_{BF})}\right] \tag{2}$$

where, λ is the wavelength of the carrier frequency, and d denotes the spacing between antenna elements, satisfying $d = \frac{\lambda}{2}$. In case of larger values of N_{BS}, the narrower main lobe width can be achieved. Therefore, adjusting N_{BS} allows the formation of a beam with the desired BW. Adjusting θ_{BF} allows the formation of a beam with the desired beam direction.

The symbol x transmitted from the BS to the k-th user via ABF passes through the channel $\boldsymbol{H}_k$. When applying the Saleh-Valenzuela model, which is normally used in mmWave communication channels, $\boldsymbol{H}_k$ is expressed as follows:

$$\boldsymbol{H}_k = a_{k,0}\boldsymbol{H}_{k,0} + \sum_{l=1}^{L-1} a_{k,l}\,\boldsymbol{H}_{k,l} \tag{3}$$

where, $a_{k,0}$ is the line of sight (LoS) complex path gain, and $\boldsymbol{H}_{k,0}$ is the LoS channel matrix between the BS and the k-th user. $a_{k,l}$ and $\boldsymbol{H}_{k,l}$ represent the l-th, $1 \le l \le L$, non-LoS (NLoS) complex path gain and the channel matrix between the BS and the k-th user, respectively. Here, L is the total number of NLoS paths. As mentioned in [7], in mmWave communication, if the LoS link is more than 20dB stronger than the NLoS links, the channel model can be simplified as follows:

$$\boldsymbol{H}_k = a_{k,0}\boldsymbol{H}_{k,0} = \sqrt{\frac{N_{BS}}{1+d_k^{\alpha}}}g_k\boldsymbol{a}(\theta_k) \tag{4}$$

where, d_k denotes the distance between the BS and the k-th user, and α denotes the path loss exponent. g_k represents the channel gain between the k-th user and the BS, which follows a Gaussian distribution, $g_k \sim CN(0,1)$. θ_k is the Angle of Departure (AoD) of the path between the BS and the k-th user:

$$\boldsymbol{a}(\theta_k) = \sqrt{\frac{1}{N_{BS}}}\left[1,\ e^{-\frac{j2\pi d}{\lambda}\cos(\theta_k)},\ \cdots,\ e^{-\frac{j2\pi d}{\lambda}(N_{BS}-1)\cos(\theta_k)}\right] \tag{5}$$

The received signal by the distant user after passing through the channel can be represented as follows.

$$y_f = \boldsymbol{H}_f\boldsymbol{w}x + n = \boldsymbol{H}_f\boldsymbol{w}\left(\sqrt{p_n}s_n + \sqrt{p_f}s_f\right) + n \tag{6}$$

where, n represents the Gaussian white noise with power σ^2. The SINR of the distant user can be expressed as follows.

$$SINR_f = \frac{\left|\boldsymbol{H}_f\boldsymbol{w}\right|^2 p_f}{\left|\boldsymbol{H}_f\boldsymbol{w}\right|^2 p_n + \sigma^2} \tag{7}$$

In the case of the nearby user, the undesired signal is removed from the superimposed NOMA signal using SIC, and it is expressed as follows.

$$y_n = \boldsymbol{H}_n\boldsymbol{w}\sqrt{p_n}s_n + n \tag{8}$$

The SINR of the nearby user is expressed as follows.

$$SINR_n = \frac{|\boldsymbol{H}_n\boldsymbol{w}|^2 p_n}{\sigma^2} \tag{9}$$

Consequently, the total throughput of the system is expressed as follows.

$$R_{tot} = R_f + R_n = \log_2\left(1 + SINR_f\right) + \log_2(1 + SINR_n) \tag{10}$$

where, R_f and R_n represent the throughput of far and near user, respectively.

Along with the throughput, the fairness is also one of the important performance metrics of the system. There are various methods to measure fairness [9], but in this paper, it is measured using Jain’s index. The closer Jain’s index is to one, the higher the fairness, and the closer it is to zero, the lower the fairness. Jain’s index is summarized as follows.

$$F_{tot} = \frac{\left(R_f + R_n\right)^2}{2\left(R_f^2 + R_n^2\right)} \tag{11}$$

3. Effects of Beam Configuration

As described in the previous section, the impacts of users’ location and transmission beam configurations are crucial factors for the system performance. Widening the BW increases the likelihood of two users being covered by the same analog beam leading to the gain enhancement of NOMA scheme. However, this kind of BW control results in an unavoidable power loss at the main BF AoD. As a consequence, a non-trivial tradeoff arises between the BW and the system performance. On the other hand, adjusting the analog BF AoD alters the effective channel gains of the two NOMA users, consequently impacting the SINR of the users and the overall throughput performance.

Fig. 2 shows the impacts of changing the BW via inactivating several antennas. In this figure, maximum throughputs are shown for the given difference of the AoDs of two users and the number of active antennas at the BS. We also assume a fixed distance of 50m and 150m for the near and far user, respectively. The AoD of each user is restricted within a range of -60° to 60°. For each user position, the number of transmitter antennas (N_{BS}) and BF AoD (θ_{BF}) are adjusted to calculate throughputs. Values of N_{BS} and θ_{BF} yielding the highest throughput are stored in a table, indexed by user position.

As shown in the figure, if the two users are located too far from each other which is equivalent to larger values of AoD difference, smaller number of Tx antenna should be activated to improve the throughput performance with a wider beam configuration. For example, in case the AoD difference is 20°, the optimum number of Tx antenna is around 55. On the other hand, in case the AoD difference between users is relatively small, the optimum antenna number is increased which results in a narrower BW. For instance, if the difference is in the range of 5°~10°, the antenna number should be increased to around 215 to 255.

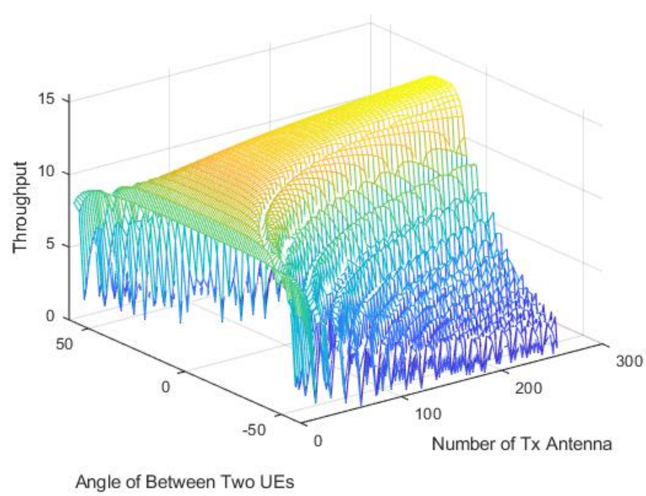

Figure 2. Throughput of far UE for varying N_{BS} and AoD difference between two UEs

4. Simulation Results

In this section, simulation results are discussed to evaluate the effects of the beam configuration on the throughput performance of the NOMA system. The frequency band of the 60GHz mmWave channel is assumed and the channel model is based on the method in [10]. Two users are uniformly distributed within a single cell with a cell radius of $D = 200\text{m}$ and their maximum AoD difference is limited to 20°. The number of antennas equipped at the BS ranges from 1 to 256, while each user has a single antenna. The average throughputs are obtained by conducting 10^5 repeated experiments.

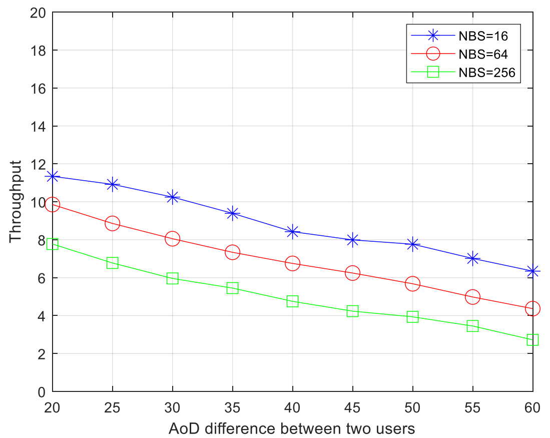

Figure 3. Throughput vs AoD difference between two UEs

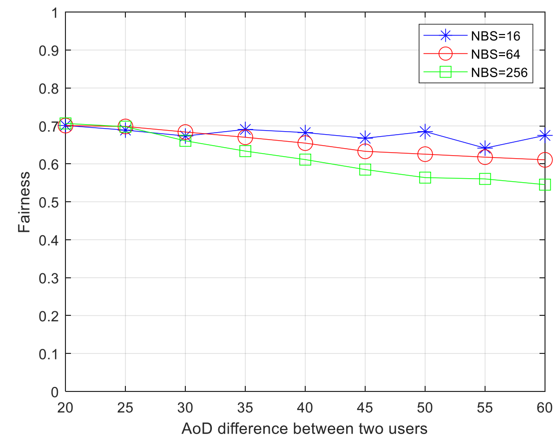

Figure 4. Fairness vs AoD difference between two users

Fig. 3 and Fig. 4 represent throughput and fairness according to the AoD difference between the two users. When the N_{BS} is fixed at 16, 64 and 256, respectively, it can be seen that the larger N_{BS}, the higher the throughput, but the lower the fairness. Since both users of the NOMA group do not enter the main lobe of the analog beam, a difference in throughput occurs, resulting in a decrease in fairness.

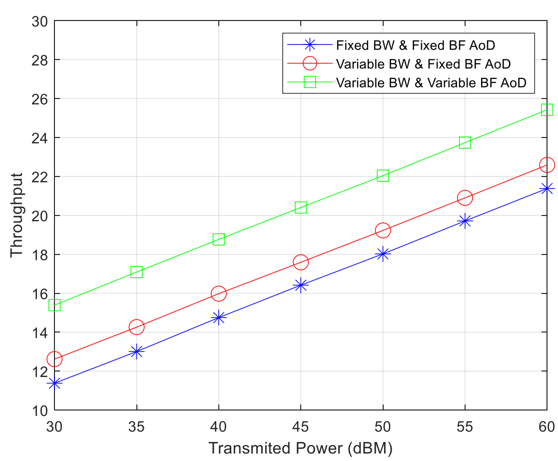

Figure 5. Throughput vs Tx power

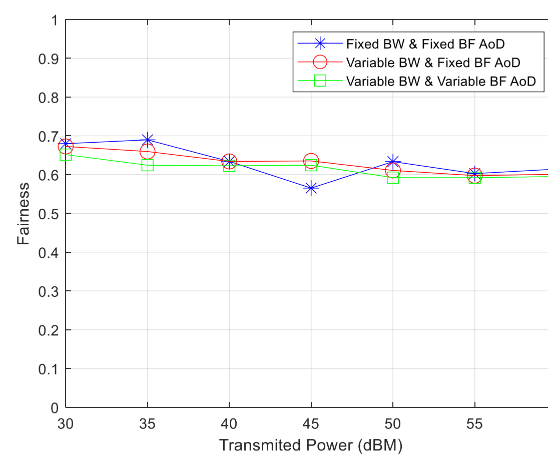

Figure 6. Fairness vs Tx power

Fig. 3 illustrates throughputs of the system in a practical range of transmission power levels. It can be seen that performance enhancements with proper beam configuration can be achieved over the system with the fixed beam. For comparison, we consider three types of ABF. In the case of the first one, both BW and BF AoD are fixed. The second one assumes the variable BW and fixed BF AoD while the last one with variable BW and BF AoD. As shown in Fig. 3, at the transmission power level of 35dBm, the system with variable BW and BF AoD achieves 31.28% gain compared to the fixed BW and BF AoD scheme and 9.69% gain compared to the scheme with variable BW and fixed BF AoD. Additionally, the fairness of the system is investigated as summarized in Fig. 4. The fairness suffers an insignificant loss in all cases.

5. Conclusion

In this paper, we discuss the effects of beam configuration on the throughput and fairness performance of the NOMA system in the millimeter wave channel environments with simulation results for various channel parameters including the number of antennas and BF AoDs. Impacts of users' location and transmission beam configurations are crucial factors for the system performance. To compare the effects of beam configuration, three different types of beam configurations are considered. The simulation results show a significant performance improvement when both BW and BF AoD are adjusted compared to the case where only the BW parameter is adjusted. Additionally, this improvement can be achieved without compromising fairness within a practical range of transmission power levels. According to the research results, the possibility of a precoder that improves throughput by controlling BW and BF AoD in the case of the NOMA system using analog beamforming in a millimeter wave channel was confirmed.

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