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# Millimeter-Wave Communications With Non-Orthogonal Multiple Access for B5G/6G

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**ABSTRACT** In order to further improve the system capacity, we explore the integration of non-orthogonal multiple access (NOMA) in millimeter-wave communications (mmWave-NOMA) for future B5G and 6G systems. Compared with the conventional NOMA, the distinguishing feature of mmWave-NOMA is that, it is usually characterized by transmit/receive beamforming with large phased arrays. In this paper, we focus on the design challenges of mmWave-NOMA due to beamforming. Firstly, we study how beamforming affects the sum-rate performance of mmWave-NOMA, and find that with conventional single-beam forming, the performance may be offset by the relative angle between NOMA users. Then, we consider multi-beam forming for mmWave-NOMA, which is shown to be able to achieve promising performance enhancement as well as robustness. Next, we investigate the challenging joint design of the intertwined power allocation and user pairing for mmWave-NOMA. Relevant challenges are discussed and some potential solutions are proposed in detail. We further consider hybrid spatial division multiple access (SDMA) and NOMA in mmWave communications, where some possible system configurations and the corresponding solutions are discussed to address the multi-user issues including multi-user precoding and multi-user interference mitigation. Finally, we present future directions in mmWave-NOMA and summarize the paper.

**INDEX TERMS** Millimeter-wave (mmWave), non-orthogonal multiple access (NOMA), mmWave-NOMA, beamforming.

## I. INTRODUCTION

With the rapid development of the wireless communications, large aggregate capacity has always been one of the most critical issues [1]–[4]. It is foreseen that by 2030, the overall mobile data traffic will be up to 5 zettabytes (ZB) per month, and the individual data rate will reach 100 Gbps [1]. During the past few decades, micro-wave communications over the sub-6 GHz band have been well investigated and developed. However, due to the limited frequency resource and excessive occupation, the sub-6 GHz band becomes extremely congested and cannot support the exponential increase of the communication capacity anymore. For this reason, millimeter-wave (mmWave) communications will be one of the major candidate technologies for beyond the

fifth-generation (B5G) and the sixth-generation (6G) wireless mobile communications [1], [2], [5]–[7]. With the frequency from 30 GHz to 300 GHz at the mmWave band, abundant frequency spectrum resource can be utilized to support the ultra-high data transmission rate [8]–[10].

On the other hand, the Internet of Everything (IoE) system, connecting millions of people and billions of devices, will be one of the essential application scenarios for B5G and 6G [2]. It is predicted that the number of mobile devices worldwide will be more than 125 billion in the 2030s, including the mobile phone, tablet, wearable devices, integrated headsets, implantable sensors and other machine-type users [5], [11]. The conventional orthogonal multiple access (OMA) schemes, e.g., time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency-division multiple access (OFDMA), may face great difficulties to support the huge number of

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mobile devices for B5G and 6G. By contrast, the non-orthogonal multiple access (NOMA) strategy can support multiple users in the same (time/frequency/code) resource block (RB) by using superposition coding in the power domain [12]–[15]. At receivers, multiple users can be distinguished from each other by exploiting successive interference cancellation (SIC). Thus, the number of users can be increased manyfold, which makes NOMA a promising access scheme in 5G and beyond systems [16].

When applying mmWave communications to cellular systems, an important issue that may offset its benefit is multiple access. For mmWave communications, a big challenge is to support massive users. Due to the high power consumption and high hardware cost in the mmWave band, the number of radio-frequency (RF) chains is usually limited, which is much smaller than the number of antennas [6], [9], [17], [18]. In such a case, the number of users that can be served within one RB is no larger than that of RF chains. Hence, NOMA is with significance to be integrated in mmWave communications (mmWave-NOMA) to break this limitation [19]–[22] and greatly increase the number of users. In addition, the highly directional feature of mmWave makes the users' channels highly correlated, which is ideal for the application of NOMA [19], [20], [23]–[27]. Benefiting from these unique advantages, the combination of mmWave communications and NOMA can provide great potentials to support the ultra-high bandwidth and massive connectivity in B5G and 6G [1], [2], [16].

In the literature, some technologies of mmWave communications and NOMA have already been established, respectively. In mmWave communications, large phased arrays are usually adopted to overcome the high propagation loss, via mmWave beamforming, which refers to analog or hybrid beamforming when there is only one or multiple RF chains. Both analog beamforming and hybrid beamforming are subject to the constant-modulus (CM) constraint due to exploiting only phase shifters to control the antenna weights [9], [17], [18], [28]. In NOMA, power allocation between different NOMA users and user pairing are usually studied to improve the system performance [12], [13]. When combining mmWave communications and NOMA, mmWave beamforming is not only for increasing beam gain, but also for covering multiple NOMA users. As a result, multi-directional beamforming may be required with each RF chain, which differs from the conventional mmWave beamforming where usually only one beam is formed with each RF chain, as well as the conventional NOMA where analog/hybrid beamforming is not involved [21]. What further intensifies the unique challenge of mmWave-NOMA is that the multi-directional beamforming is usually entangled with power/beam gain allocation and user pairing in mmWave-NOMA. These considerations differ from the existing technical studies on mmWave-NOMA [19], [20], where either random single-beam forming was adopted [19] or a lens array instead of a phased array was used [20]. Alternatively, multi-directional beamforming with a phased array and its

interplay with power/beam gain allocation and user pairing are not involved in these works [19], [20].

In this paper, we study beamforming-centering issues in mmWave-NOMA. We first study how single-beam forming affects the sum-rate performance of NOMA in Section II, where we consider using multi-beam forming to improve the performance of mmWave-NOMA. As beamforming usually intertwines with power allocation in mmWave-NOMA, we discuss this issue in detail in Section III, where several potential solutions are proposed to solve the challenging joint power allocation and beamforming problem. Next, we consider the more challenging user pairing problem in mmWave-NOMA in Section IV, since it intertwines with both power allocation and beamforming. Then, in Section V, we investigate hybrid spatial division multiple access (SDMA) and NOMA, where the possible system configurations as well as corresponding solutions are discussed to address the multi-user issues. Finally, we present future directions in Section VI and summarize the paper in Section VII.

## II. BEAMFORMING IN MMWAVE-NOMA

### A. MMWAVE-NOMA WITH SINGLE-BEAM FORMING

In conventional mmWave communications, subject to the hardware constraints, usually only a single beam is formed with each RF chain [17], [19], [24]. If TDMA is used for multiple access, beamforming is straightforward and a narrow beam can be easily formed to steer towards the user [17] within its time slot. However, if NOMA is used, the base station (BS) needs to serve multiple users in one time slot, and a narrow beam may not cover all the users. Instead, a wide beam may be required to cover all the served users in that time slot, and the beam width depends on the relative angle between these users. This may reduce the beam gain and in turn offset the benefit of NOMA, because the beam gain is roughly inversely proportional to the beam width.

To illustrate this issue, we give an example in Fig. 1, where the mmWave-NOMA BS with analog beamforming needs to serve two users. When serving Users 2 and 3, the BS only needs to form a narrow beam, because the angle gap between Users 2 and 3 is small. In such a case, the beam gain will be high. However, when serving Users 1 and 4, the BS has to form a much wider beam, because the angle gap between Users 1 and 4 is much larger. As a result, the beam gain of the BS will be much lower, which degrades the performance of mmWave-NOMA.

We compare the performances of mmWave-NOMA (with single-beam forming) and mmWave-TDMA by assuming a typical two-user case, where  $N = 32$  is the number of antennas at the BS. Transmission SNR is the SNR without considering the beam gain at the BS.  $B$  is the required beam width to cover the two NOMA users. A common mmWave channel model that used in [17] and [18] is adopted between the BS and a user, and the number of paths is set to 1 for simplicity. According to [17], the narrowest beam width for the array with  $N$  elements is roughly  $2/N$  in the cosine

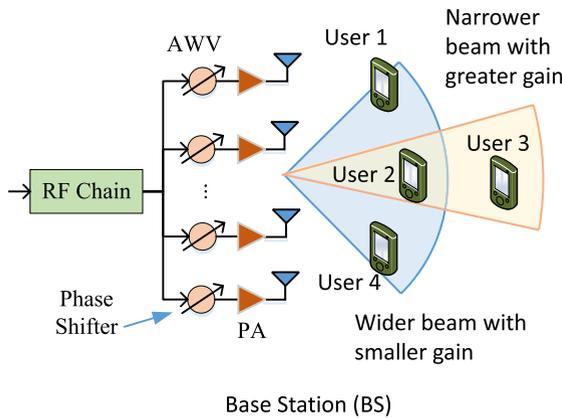


FIGURE 1. MmWave-NOMA with analog beamforming at the BS.

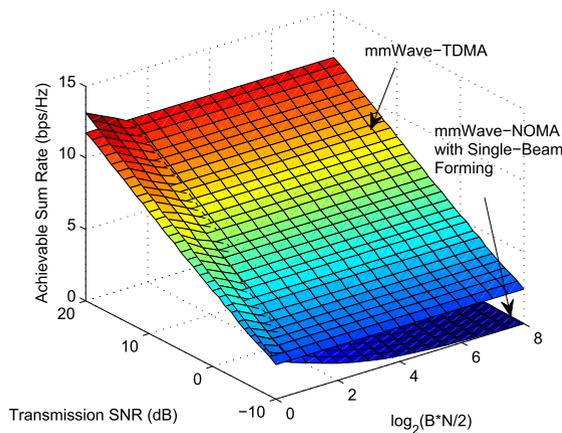


FIGURE 2. Performance comparison between mmWave-NOMA with single-beam forming and mmWave-TDMA.

angle domain, and the beam gain can be roughly computed as  $2/B$ , where  $B$  is the required beam width. For mmWave-TDMA, the beam gain is roughly  $N$ , as a narrow beam can be shaped to steer towards a user in each time slot. For mmWave-NOMA, the beam gain varies as  $B$ . We assume the average channel power of User 1 is 6 dB higher than that of User 2, and in mmWave-NOMA the stronger user and weaker user are allocated with  $1/4$  and  $3/4$  of the total transmission power, respectively. Fig. 2 shows the performance comparison in terms of sum achievable rate. We can find that when the required beam width is  $B = 2/N$ , mmWave-NOMA outperforms mmWave-TDMA. However, as the required beam width becomes larger, the performance of mmWave-NOMA deteriorates, and even becomes worse than that of mmWave-TDMA for large  $B$ , since the beam gain is significantly reduced in this case.

**B. MMWAVE-NOMA WITH MULTI-BEAM FORMING**

As single-beam forming does not behave efficiently and robustly enough, we consider multi-beam forming with a

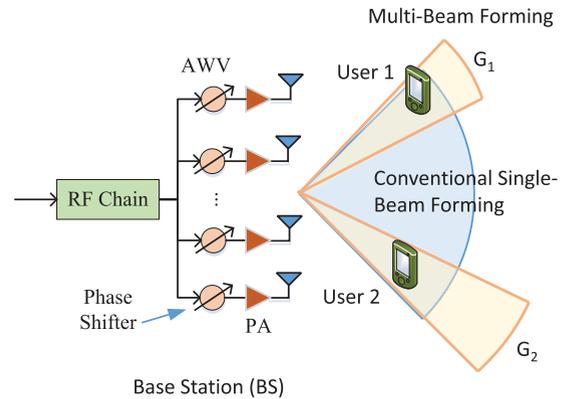


FIGURE 3. Comparison between single-beam forming and multi-beam forming for mmWave-NOMA.

single RF chain, which means that the BS can form multiple narrow beams to steer towards multiple NOMA users simultaneously. As shown in Fig. 3, the BS with multi-beam forming forms two narrow beams to cover two NOMA users (User 1 and User 2) in the same time slot. Intuitively, since multi-beam forming covers a narrower range than single-beam forming, a higher beam gain can be achieved, and the beam gain will not be reduced even when the angles of two users become larger. More importantly, with multi-beam forming, the beam gains for different NOMA users can be different. For instance, in Fig. 3, the beam gains  $G_1$  for User 1 and  $G_2$  for User 2 can be different, where  $G_i = |\mathbf{w}^H \mathbf{a}(\phi_i)|$  for  $i = 1, 2$ ,  $\mathbf{w}$  is the antenna weight vector (AWV), and  $\mathbf{a}(\phi_i)$  is a given steering vector towards the direction  $\phi_i$  [17]. This feature is very important for mmWave-NOMA, because in addition to the degree of freedom in the power domain, it provides another degree of freedom, i.e., beamforming, to improve the performance of mmWave-NOMA, which will be discussed in detail later.

We compare the sum-rate performance of mmWave-NOMA (with multi-beam forming) with that of mmWave-TDMA in Fig. 4, where  $\beta$  is the ratio of the average channel gain of User 1 to that of User 2. In the comparison,  $G_1 = G_2 = 16$  for mmWave-NOMA, i.e., we do not enlarge the difference of channel gains by setting different beam gains. The total average channel power is identical for both mmWave-NOMA and mmWave-TDMA. We can observe that with multi-beam forming, mmWave-NOMA performs better than mmWave-TDMA in general. In addition, as  $\beta$  becomes larger, the superiority of mmWave-NOMA becomes more significant.

As aforementioned, by appropriately setting the beam gains for different users, the performance of mmWave-NOMA can be further improved. We show this in Fig. 5, where  $\beta = 3$ . We assume that the beam widths of User 1 and User 2 are the same, i.e.,  $2/N$  in the cosine angle domain [17]; hence we have  $(G_1 + G_2) \times 2/N = 2$  or  $G_1 + G_2 = N$ . When  $G_2$  is smaller,  $G_1$  becomes larger, and the channel gain difference between these two users is more

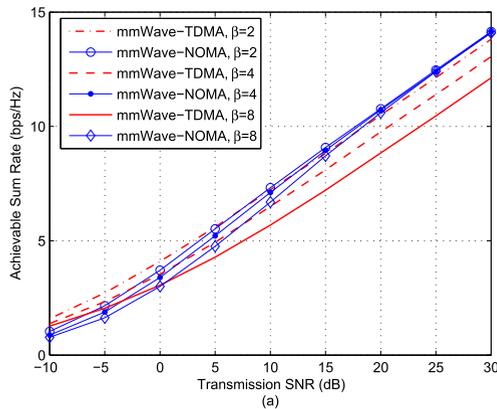


FIGURE 4. Performance comparison between mmWave-NOMA (with multi-beam forming) and mmWave-TDMA.

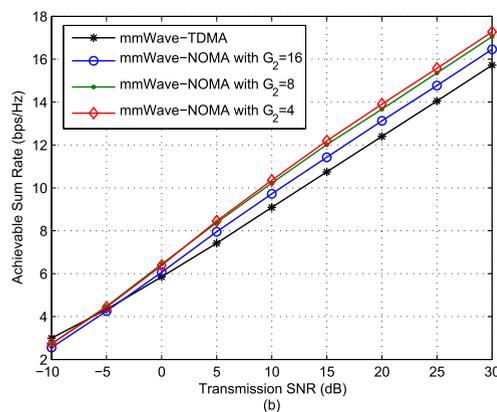


FIGURE 5. Effect of setting different beam gains for different users in mmWave-NOMA with multi-beam forming.

significant. We can find that as  $G_2$  becomes smaller, the sum-rate performance of mmWave-NOMA becomes better, but the improvement becomes slower as  $G_2$  becomes smaller. The results in Figs. 4 and 5 demonstrate that the sum-rate gain of mmWave-NOMA compared with mmWave-TDMA is larger when the channel difference of the users is higher. Thus, the beamforming gains of the users can be elaborated to enlarge the channel difference between the NOMA users, where beam gain allocation and power allocation are coupled in mmWave-NOMA.

### C. TECHNIQUES FOR MULTI-BEAM FORMING

Compared with single-beam forming, multi-beam forming has distinctive advantages, but the AWW design is more challenging. For single-beam forming, only one beam needs to be formed. In comparison, for multi-beam forming, multiple beams with different beam gains need to be formed, and the key challenge is the CM constraint due to phase shifters, which is non-convex and high-dimension in general. To achieve multi-beam forming, there are three promising techniques, i.e., sub-array technique, optimization technique, and intelligent search technique.

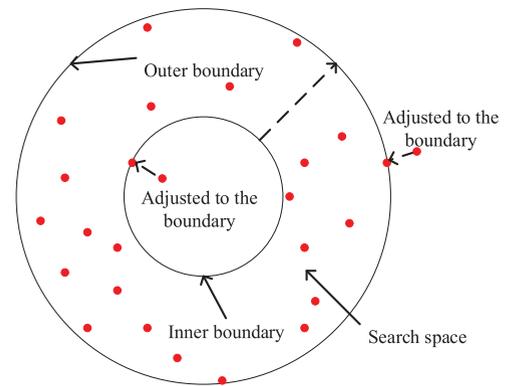


FIGURE 6. Illustration of the principle for BC-PSO.

#### 1) SUB-ARRAY TECHNIQUE

One possible way of multi-beam forming is the sub-array technique [17], [18]. As we need to form multiple beams, a natural method is to divide a large antenna array, with a given number of antennas, into multiple sub-arrays, and let them steer to different directions, i.e., set the AWWs of these sub-arrays to steering vectors associated with different directions. Thanks to the small sidelobe of the large antenna array, the interference between different sub-arrays is small. Thus, the beam gain is roughly linear to the number of antennas for each sub-array.

#### 2) OPTIMIZATION TECHNIQUE

Another possible way is to apply an optimization approach [24], [25]. Since the number of antennas is large in general, the dimension (the number of variables) of the optimization problem will be large. As a result, the formulation of a tractable optimization problem is critical. The key is how to deal with the CM constraint and the beam gain constraints, which are all non-convex. For instance, if we want to design  $\mathbf{w}$  to form two different beams with gains  $G_1$  and  $G_2$ , respectively, it is natural to minimize  $\|\mathbf{w}\|^2$  (or  $\alpha$ ) subject to the CM constraint  $\|\mathbf{w}\| = \alpha$  and gain constraints  $|\mathbf{w}^H \mathbf{a}(\phi_i)| = G_i$  ( $i = 1, 2$ ), where  $\alpha$  is the scaling factor for the AWW,  $\mathbf{w}$  is the AWW and  $\mathbf{a}(\phi_i)$  is a given steering vector towards the direction  $\phi_i$  [17]. However, with these equality constraints, the problem is generally difficult to solve, not only because they are non-convex constraints, but also because the equality constraints are usually too strict to find an appropriate CM AWW. In such a case, some relaxation may be induced to ease the problem. For instance, we may relax the CM constraints to minimize the maximal absolute weight of the antenna weights, i.e., to minimize  $\alpha$  subject to  $|\mathbf{w}| < \alpha$  where  $<$  is componentwise inequality. Meanwhile, we may relax the beam gain requirements from equality to inequality, i.e.,  $|\mathbf{w}^H \mathbf{a}(\phi_i)| \geq G_i$ . Then, by searching the optimal phases of the two beam gains  $\mathbf{w}^H \mathbf{a}(\phi_i)$ , the problem can be transformed into several standard convex optimization problem [24], [25].

### 3) INTELLIGENT SEARCH TECHNIQUE

Since the dimension of the AWV is very high for mmWave antenna array, it is computation prohibitive to directly search the optimal solution. Alternatively, we can introduce the intelligent search methods, e.g., particle swarm optimization (PSO) and artificial bee colony (ABC) algorithm [26], [29]. Due to the interference between the multiple users, the formulation of the achievable rate is not convex in general. Besides, the CM constraint on the AWV is also highly non-convex. As a result, PSO algorithm may converge to a sub-optimal solution very fast and the globally optimal solution is missed. To improve the search capacity, some improvements can be conducted for PSO. As shown in Fig. 6, first, the search space defined by the CM constraint can be relaxed as a convex set, i.e.,  $\{|\mathbf{w}|_n \leq \frac{1}{\sqrt{N}}\}$ . Then, we can define the boundaries of the relaxed search space, the inner boundary  $\{|\mathbf{w}|_n = \frac{t}{T} \frac{1}{\sqrt{N}}\}$ , and the outer boundary  $\{|\mathbf{w}|_n = \frac{1}{\sqrt{N}}\}$ , where  $t = 1, 2, \dots, T$  is the iteration index and  $T$  is the total number of the iteration. As we can see, the inner boundary is dynamically increasing from zero to the outer boundary during the iteration, while the outer boundary is fixed and indeed equivalent to the CM constraint. For each iteration, the positions and velocities of the particles (AWVs) are updated according to the PSO principle. If one particle moves out of the boundaries, and it should be adjusted to the closest boundary. With this operation, the particles can move around the whole search space and finally converge to the outer boundary to satisfy the CM constraint. Since the particles in the proposed boundary-compressed PSO (BC-PSO) algorithm has a more opportunities to perceive the global information, it outperforms the classical PSO algorithm in terms of multi-beam forming [26], [29].

The proposed three multi-beam forming techniques can achieve an increasing beamforming performance, with the expense of a higher computational complexity. Sub-array technique has the lowest computational complexity, but it results in the beam-gain loss due to the beam broadening. Optimization technique can achieve a tradeoff between the computational complexity and the beam-gain performance. However, it requires an elaborate optimization design for different system models. Intelligent search technique has the near-optimal beamforming performance, while the computational complexity may be high when the dimension of the AWV is large.

In addition to the techniques above, where the CM constraint causes the main difficulty for multi-beam forming, another possible way is to explore new antenna structures. For example, by employing double phase shifters in each antenna branch, the CM constraint on the AWV can be relaxed as a convex constraint [27]. Although the signal of each phase shifter has a the same modulus, the superposition of two signals can achieve different modulus in each antenna branch, which can be realized by adjusting the phases of the conjugated phase shifters. With the double-phase-shifter implementation, the design of multi-beam forming can acquire

higher degree of freedom (DoF) and reduce the computational complexity [27].

### III. JOINT POWER ALLOCATION AND BEAMFORMING

In conventional NOMA, power allocation can be seen as a degree of freedom to tune user rates so as to maximize the sum rate. In mmWave-NOMA, in addition to power allocation, beamforming constitutes a new degree of freedom. Specifically, the effective channel gains of the users can be artificially changed by beamforming. For instance, considering the 2-user mmWave-NOMA system in Fig. 3, where the channel gains and beam gains for these two users are  $h_1, G_1$  and  $h_2, G_2$ , respectively, i.e., the effective channel gains of the two users are  $h_1 G_1$  and  $h_2 G_2$ , respectively. Thus, by changing the user gains via beamforming, i.e.,  $G_1$  and  $G_2$ , the effective channel gains can be changed accordingly.

Now we have two degrees of freedom to improve the performance, i.e. power allocation and beamforming. In most cases, power allocation intertwines with beamforming, because the achievable rates of the users depend on them both. As a result, we usually need to consider a joint power allocation and beamforming problem. For example, we still consider the 2-user mmWave-NOMA system in Fig. 3. A problem is how to maximize the sum rate of the two users, where the power allocation intertwines with beamforming. Similar challenges applied to downlink/uplink transmission with the target of maximizing the sum rate or maximizing the minimal user rate.

As this kind of problem is non-convex, it may be infeasible to make use of the existing optimization tools. A potential solution is to decompose the original joint power allocation and beamforming problem into two sub-problems: one is a power and beam gain allocation problem, and the other is a beamforming problem under the CM constraint, i.e., to determine  $\{P_1, P_2, G_1, G_2\}$  first, where  $\{P_1, P_2\}$  are powers for these two users, and then determine their beamforming vectors using the approaches introduced in the previous section [24], [25]. Although the original problem is difficult to solve, the two sub-problems are relatively easy to solve, and thus we can obtain a sub-optimal solution [24], [25].

In addition to the optimization method, some intuitive approaches can also be considered. For instance, to maximize the sum rate, most power or beam gain should be allocated to User 1, which has better channel quality, while only necessary power or beam gain should be allocated to User 2 to satisfy the rate constraint. Besides, for User 2, although its achievable rate increases with both  $P_2$  and  $G_2$ , increasing  $P_2$  is more efficient, because increasing  $G_2$  also increases multi-user interference (MUI), i.e., the signal of User 1 at User 2, while increasing  $P_2$  reduces MUI on the contrary, since  $P_1$  is reduced accordingly. Using these intuitive observations, we may set appropriate powers and beam gains for the two users, and then determine the beamforming vector.

For a multi-user mmWave-NOMA system, the optimization method may face great challenges, due to the high dimensional variables [24], [25]. In such a case, alternating

optimization may be used to find a solution, i.e., alternatively optimize the power allocation with a fixed beamforming vector and the beamforming vector with fixed user powers. In addition, the dimension of the power allocation variables is much lower than that of the AWV, and the power allocation variables have linear or convex constraints in general, which is more tractable compared with the CM constraint on the AWV. It is a possible way to first optimize the power allocation variables under fixed AWV, and then substitute the power allocation solution as the function of the AWV. It has been proved that the closed-form optimal power allocation for mmWave-NOMA can be obtained in both max-sum-rate and max-min-rate problems [26], [27]. As thus, the joint problem can be transformed into an equivalent beamforming problem, where the multi-beam forming techniques in Section II can be utilized [26], [27], [29].

#### IV. USER PAIRING IN MMWAVE-NOMA

In conventional NOMA, user pairing is used to enable hybrid multiple access [30]–[32], where NOMA is combined with OMA. Generally, it is difficult to find the optimal user pairing strategy [30] due to its enumeration feature, except applying exhaustive search with high computational complexity. In general, intuitive approaches with lower complexity can be adopted, e.g., weaker users are usually paired with strong users [30], [32], but the challenge of user pairing is still intensified by user power allocation [30], [31].

In mmWave-NOMA, user pairing also faces similar challenges, including the enumeration feature as well as entangling with power allocation. A new issue that also affects user pairing in mmWave-NOMA is beamforming. In particular, the channel gains of the users are the main factors to affect user pairing in conventional NOMA. However, in mmWave-NOMA the relative angles between the users also affect user pairing, because they affect the beam gains. We take the mmWave-NOMA system shown in Fig. 7 for instance, where the left sub-figure shows the situation with conventional single-beam forming, while the right sub-figure shows the situation with multi-beam forming. We first see the middle sub-figure, where we need to select two users as a NOMA group. Clearly, User 3 can be paired with either User 1 or User 2 if only channel gain is considered. However, when using conventional single-beam forming in mmWave-NOMA, a wide beam, i.e., Beam 2, needs to be formed to cover the group of Users 3 and 2, because the relative angle between them is large. In contrast, a narrower beam, i.e., Beam 1, needs to be formed to cover the group of Users 3 and 1, because the relative angle between them is smaller. As a result, the achievable beam gain when pairing Users 3 and 1 is higher than pairing Users 3 and 2.

The situation is different when using multi-beam forming in mmWave-NOMA, as shown in the right sub-figure of Fig. 7. With multi-beam forming, two narrow beams are formed to cover the two NOMA users. In such a case, it is almost the same to pair Users 3 and 2 as to pair Users 3 and 1, provided that the channel gains of Users 1 and 2 are

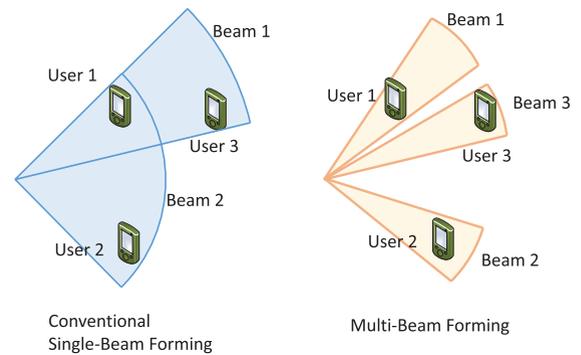


FIGURE 7. Beamforming affects user pairing in mmWave-NOMA.

similar, because the beam gains to cover Users 3 and 1 with Beams 3 and 1 are the same as those to cover Users 3 and 2 with Beams 3 and 2. However, when the relative angle between User 3 and 1 is very small, e.g., smaller than  $2/N$  in the cosine angle domain, the BS may not form two different beams to cover them, because the smallest beam width is  $2/N$  [17]. Instead, the BS may form only one narrow beam to cover both users. In such a case, both users can achieve a higher beam gain.

#### V. HYBRID SDMA AND NOMA

In conventional mmWave communications, to serve multiple users with SDMA, a BS needs to exploit hybrid analog/digital beamforming. There are typically two architectures for hybrid beamforming, i.e., the phase-shifter based array and lens antenna array [6]. The former has a higher DoF for beamforming design, in which a higher array gain and lower interference for the mmWave-NOMA users. In contrast, the latter has a lower DoF, but a lower hardware cost and power consumption, where the users should select the fixed beams to perform NOMA [20]. In this section, we consider the full-connected phase-shifter based structure, as shown in Fig. 8. The hybrid structure has  $M$  RF chains, and thus can support at most  $M$  users by using SDMA. Thanks to the NOMA technology, multiple users now can be served in the same RB with analog beamforming as introduced in Section II. However, the number of NOMA users is limited in general, because the achievable rates of the users with weak channel gains decrease as the number of NOMA users due to MUI. In such a case, a potential method to increase the total number of users in mmWave-NOMA is to use hybrid SDMA and NOMA. In particular, the BS may have a hybrid beamforming structure with  $M$  RF chains, and exploit NOMA with each RF chain and SDMA between different RF chains. If each RF chain can serve  $K$  NOMA users, the hybrid SDMA and NOMA strategy can support at most  $MK$  users.

We show an example for the hybrid SDMA and NOMA strategy. Suppose  $M = K = 2$  in Fig. 9 (Left), i.e., there are two RF chains and each RF chain supports two NOMA users. We call this configuration Mode 1, as shown in the middle sub-figure. The BS sets beamforming vector of the first RF chain, i.e., RF 1, to form two narrow beams to

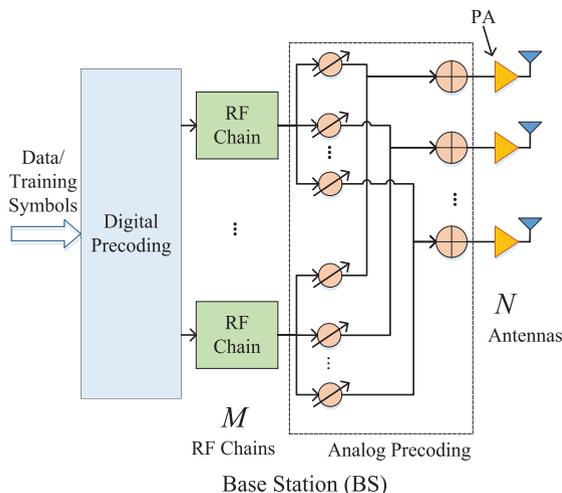


FIGURE 8. System structure of hybrid analog/digital beamforming in mmWave communications.

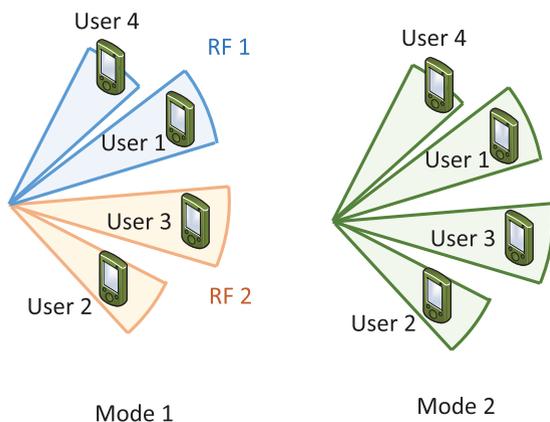


FIGURE 9. Two modes for hybrid SDMA and NOMA in mmWave communications.

cover Users 4 and 1, belonging to a NOMA group. In this process, multi-beam forming is adopted. Meanwhile, the BS sets beamforming vectors of the second RF chain, i.e., RF 2, to form another two narrow beams to cover Users 2 and 3, belonging to another NOMA group. Power allocation is performed among only the users of the same group. When designing the beamforming, power allocation and user pairing issues, the methods introduced in Sections II, III and IV may be used.

It is noteworthy that the above manipulations have implicitly ignored the MUI from different NOMA groups. This is reasonable only when the number of users is small such that the MUI from other NOMA groups is negligible. However, when the number of users is not small, the MUI from other NOMA groups needs to be considered, and the design will become more complicated due to MUI.

For the case that the MUI cannot be ignored, we propose the configuration of Mode 2, as shown in Fig. 9 (Right). In this mode, all RF chains jointly serve all users. In particular, the BS forms four narrow beams to cover the four users

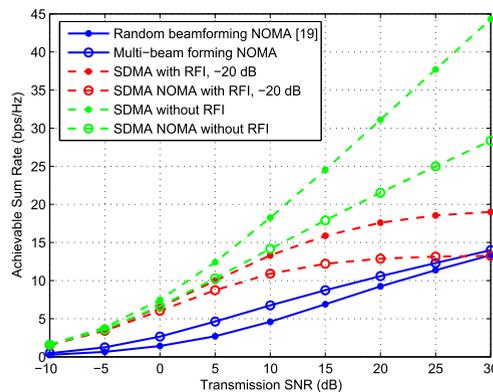


FIGURE 10. Comparison of the sum-rate performance between different beamforming approaches.

using the hybrid beamforming structure, and power allocation is performed among the four users. In fact, Mode 2 can be seen as an overloaded SDMA system, where the number of users is larger than that of the RF chains. Compared with the beamforming and power allocation in analog-beamforming mmWave-NOMA, the digital-domain processing adds a new degree of freedom to optimize the system performance. To be specific, in analog-beamforming mmWave-NOMA, we design analog beamforming and power allocation, while in hybrid-beamforming mmWave-NOMA, we need to jointly design digital precoding, analog precoding and power allocation.

We compare the sum-rate performance between different beamforming approaches in Fig. 10, where the number of users is 4. The power allocated to the users has a ratio of 1:3:5:7 as decreasing channel gains. The number of RF chains for random beamforming NOMA (and multi-beam forming NOMA), SDMA NOMA and SDMA is 1, 2 and 4, respectively. The beam gain settings are as follows: for multi-beam forming  $G_1 = G_2 = G_3 = G_4 = 8$ ; for random beamforming, the beam gain of the randomly pointed user is  $G_0 = 32$  and those of the other users is 20 dB lower than  $G_0$ ; for SDMA, the beam gain is  $G_0 = 32$  for each user; while for SDMA NOMA, the beam gains are  $G_1 = G_2 = G_3 = G_4 = 16$ . For each RF chain, the RF interference (RFI) to other RF chains for SDMA and SDMA NOMA is  $-20$  dB relative to its transmission power, and the case of no RFI is also considered in Fig. 10. We can see that the proposed multi-beam forming outperforms random beamforming NOMA [19], and SDMA NOMA can further improve the achievable rate compared with multi-beam forming NOMA owing to using more RF chains. It is worthy noting that in the presence of RFI, the performances of SDMA and SDMA NOMA increase slowly as SNR, which indicates that interference suppression in digital domain is necessary.

According to the analysis above, we can find that there are two directions to improve the sum-rate performance. One way is to increase the beam gains of the target signals, and the other way is to decrease the beam gains of the interference signals. With the larger number of RF chains and antennas, higher beam gains and lower interference can be obtained

**TABLE 1.** Summary of beamforming-centering issues in mmWave-NOMA for B5G and 6G.

Research Directions	Challenges	Possible Solutions
Multi-beam forming	The CM constraint with a single RF chain	Sub-array technique; Optimization technique with tractable problem formulation; Intelligent search technique with reasonable improvement; Relax the CM constraint through double-phase-shifter implementation
Joint power allocation and beamforming	Entangled power/beam gain allocation and multi-beam forming	Optimization approach with problem decomposition; Alternating optimization; Substitute the power allocation with the function of AWV and reduce as an equivalent beamforming problem; Intuitive methods.
User pairing	Intertwines with power allocation and beamforming	Intuitive methods may work, e.g., to pair the users with quite different channel gains and small angles.
Hybrid SDMA and NOMA	Multi-user precoding and MUI mitigation	Low MUI: to use Mode 1 in Fig. 9, and the aforementioned methods can be adopted. High MUI: to use Mode 2 in Fig. 9, joint optimization is required; Optimize the user pairing/grouping and hybrid beamforming to suppress the MUI

due to the higher DoF, in which the hybrid analog/digital beamforming should be well designed [29]. An alternative way is to first design the analog beamforming to maximize array gain, where the proposed multi-beam forming techniques in Section II can be utilized. Then, the digital beamforming can be designed by using some classical algorithms to minimize the inter-beam interference, such as zero-forcing (ZF), minimum mean square error (MMSE). Particular for uplink mmWave-NOMA with hybrid beamforming, parallel interference cancellation (PIC) can also be utilized at the receiver (BS) to further decrease the MUI. In addition to suppress the MUI in the beamforming domain, user pairing/grouping can also be elaborated, due to the directivity of the mmWave channels. For instance, the users with high channel correlation can be assigned to different groups to minimize the inter-group interference, while the users with high channel correlation can be assigned to the same group to make full use of the array gain [29].

## VI. FUTURE DIRECTIONS

The above introduced beamforming-centering challenges and possible solutions in mmWave-NOMA for future B5G and 6G systems are summarized in Table 1. In addition to these issues, some other important directions of mmWave-NOMA are highlighted as follows for future study.

*Performance analysis:* As mmWave-NOMA is a new research branch, relevant performance analysis is necessary to provide some insights for system design. Achievable rate of multiple access is a key metric to analyze, which involves beamforming, beam gain and power allocation, etc. Due to the existence of side lobes and the CM constraint, the multi-beam forming cannot be ideal, and thus some approximations can be used to simplify the derivation and computation. In addition, some practical factors, such as the channel model, beam misalignment and imperfect SIC, should be considered in a real scene.

*Channel Estimation:* Although the sum-rate performance of mmWave can outperform mmWave-OMA, it is required that the BS has a complete knowledge of the channel state information (CSI) between the BS and all the users. Then,

beamforming, power allocation and user pairing can be designed accordingly. However, the channel estimation in mmWave communications is difficult due to the large number of antennas. In addition, massive users result in high overhead at the BS. Thus, it is necessary to investigate the transmission scheme for mmWave-NOMA under the partial/imperfect CSI. The channel estimation for mmWave-NOMA system should be elaborately designed to achieve the tradeoff between the accuracy and complexity.

*Fairness in mmWave-NOMA:* Fairness is an important issue in all NOMA systems. In conventional NOMA, many fairness indices, like max-min rate fairness, proportional fairness, etc., have been adopted to guarantee fairness between different NOMA users [21]. In mmWave-NOMA, these indices are also applicable [27]. Differences are that in addition to power allocation, beam gain allocation provides another degree of freedom to improve the user fairness, but meanwhile intensify the design challenge. Unlike the max-sum problem for mmWave-NOMA, the fairness problem should ensure the achievable-rate requirements of the users. For instance, more beam gains and transmission power may be allocated to the far user in a max-min problem, and in consequence the sum-rate may decrease.

*Cooperative mmWave-NOMA:* It would be also interesting to induce BS cooperation to improve the performance of the NOMA users at the cell edge in mmWave-NOMA, just like [33]. The coordinated BSes not only need to use Alamouti code, but also need to perform coordinated beamforming for the cell-edge user. In addition, if a phased array is used at the cell-edge user, multi-directional CM beamforming can also be used at the user to further increase its achievable rate, where beam gain allocation towards different coordinated BSs needs substantial study. On the other hand, the cooperative mmWave-NOMA can also be utilized in a pair of users in the same cell, i.e., the cooperative device to device (D2D) communications. Since the near user should employ SIC to decode the signals of the far user, it is a possible way for the near user to forward the signals through the D2D link. Then, the multi-beam forming, power allocation and control should be designed accordingly.

**Delay in mmWave-NOMA:** Since mmWave-NOMA can significantly improve the throughput of the mobile network, it provides great opportunities to decrease the end-to-end delay. The waiting time of the sequence can be shortened with the implementation of mmWave-NOMA or cooperative mmWave-NOMA. Further more, mmWave-NOMA can be combined with short-package communications [34], where the user pairing, power allocation and beamforming in physical layer should be jointly designed with the protocol and routing design in network layer.

## VII. CONCLUSIONS

In this paper, we have investigated many design challenges on the beamforming issues of mmWave-NOMA. We first showed that with conventional single-beam forming, the sum-rate performance of NOMA may be offset by the angular separation between the NOMA users. We then discussed multi-beam forming for mmWave-NOMA, which is shown to be able to achieve improved sum-rate performance and robustness. Meanwhile, we showed that the design of multi-beam forming is more challenging than single-beam forming, and the sub-array, optimization, and intelligent search techniques would be applicable. As for mmWave-NOMA beamforming usually intertwines with power allocation, the formulation of an optimization problem was shown to be critical for joint power allocation and beamforming design. Problem decomposition, alternating optimization, and some intuitive methods may help to find sub-optimal solutions. A more challenging issue in mmWave-NOMA is user pairing. Besides power allocation, we showed that beamforming also affects user pairing. Finally, for hybrid SDMA and NOMA, it was shown that the strength of MUI determines the system configuration. When MUI can be ignored, the system may be configured as multiple independent analog-beamforming mmWave-NOMA, such that the strategies for analog-beamforming mmWave-NOMA are applicable. When MUI cannot be ignored, the system may be configured as an overloaded SDMA structure, where jointly design of digital precoding, analog precoding and power allocation is required to optimize the performance.

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