Analog Beamforming mm-Wave Two User Non-Orthogonal Multiple Access

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Abstract. In this paper, the authors aim to design analog beam forming weight vector for two user down link non-orthogonal multiple access (NOMA) scenario. Millimeter wave (mm-wave) channel with one line-of-sight (LOS) path and multiple non line-of-sight (NLOS) paths is considered. The components of beamforming vector vary only in phase whereas their magnitudes are same. This restriction guarantees that power amplifiers need not be designed with different power amplification factors, thereby minimizing the complexity of power amplifier design. In this work, two users located at different angle of departure (AoD) with different gains are considered. The weight vector is designed aiming to minimize the total power requirement. Simulation results show that the proposed approach requires less power with minimum complexity compared with the time division multiple access (TDMA) for the same spectral efficiency requirements.

Keywords: NOMA · mm-wave channel · Analog beamforming · Power minimization · Spectral efficiency · Semi-definite relaxation

1 Introduction

Fifth Generation broadband wireless networks and device to device communication require to establish epidemic hike in the traffic volumes and emerging challenges in user data rate. This can be achieved by the integration of enormous spectrum with a powerful radio access technology [1–3]. Huge bandwidth (30 GHz to 300 GHz) of mm-wave is a crucial factor of using this in 5G mobile network to cater multi-gigabit communication services [4,5].

NOMA is one of the essential practices to cope with the enormous data rate necessities and support massive connectivity in 5G networks and beyond [6]. In the existing 4G orthogonal multiple access (OMA) strategies, orthogonal resources such as time, frequency and code are allotted to diverse users to get rid

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of inter-user interference. Conversely, same resource block with different power levels can be used for multiple users in power domain NOMA. Far user is allotted more power, near user is allotted less power and Superposition Coding (SC) is employed at the transmitter. Consequently, at the receiver of near user, successive interference cancellation (SIC) is applied to decode the far user's data. Then it is subtracted from the near user's received signal to decode its own signal [7,8]. Hence NOMA can be combined with mm-wave band to meet the requirements of future generation networks.

However, severe propagation losses occur in mm-wave carrier frequencies. These losses can be mitigated by the use of array antenna with beam forming technique. It is also feasible to deploy large number of antenna elements due to very small wavelength of mm-wave band [9]. Beam forming is a method in which phases of antenna elements are dynamically varied to produce a narrow beam [10]. This beamforming increases array gain which in turn enhances the signal-to-noise ratio (SNR) and thereby diminishes the propagation path loss.

Beam forming techniques of NOMA in Rayleigh channel is discussed in [11], where power minimization and fairness based beamforming is achieved for perfect channel state information (CSI) condition. In addition to that, robust scheme is discussed under imperfect CSI, targeting to minimize the transmit power. Authors of [12] considered only two users with digital beamforming. They solved power minimization problem with QoS constraints using semi definite relaxation (SDR) as discussed in [13,14].

In [15,16], random steering of single beam forming method is used. This is applicable only when the NOMA users are closer. When the angle between two users is larger, a single wide beam used will reduce the beam gain and in turn decreases the data rate. Hence NOMA with multi beams each targeting towards NOMA users is an efficient method to achieve high data rate. Authors of [17] also use multi beam NOMA with analog beamforming. In this beamforming, single RF chain is connected to number of antenna elements which reduces the hardware complexity and cost. Here, the users which have different AODs and different gains are served by NOMA with analog beamforming weight vector where the absolute value of all the elements of the weight vector is a constant. They discussed how to allocate power among the two NOMA users and design weight vector to boost the sum rate. They solved this non-convex optimization problem in two steps. However, complexity of this algorithm is high for more number of users. Authors of [18] discusses the reduction in achievable data rate for two user two beam mm-wave NOMA under imperfect CSI case. To the best of our knowledge, analog beamforming to achieve the minimization of total power to meet the target spectral efficiency of both the users has not been studied for mm-wave NOMA.

Contribution of our work is as follows:

We consider two user down link mm-wave multiple input single output (MISO) NOMA system. Analog beamforming vector for power minimization problem is solved in our low complex proposed method which is described as follows: We first transform the problem into semi-definite programming (SDP) problem.

Constant Modulus constraint of analog beamforming vector and rank constraint of positive semi-definite (PSD) matrix are relaxed. Problem is solved to compute the unit norm beamforming vector. Then, normalization is done on each component of weight vector. It is again multiplied with a suitable scalar such that all the constraints are satisfied. Obtained analog beamforming vector is the optimum one since the rank of the PSD matrix is one. It is shown that the total power required in our proposed NOMA is less than the conventional TDMA approach.

Rest of the paper is structured as follows. Section 2 illustrates the model of mm-wave channel. Section 3 describes two user analog beamforming down link mm-wave MISO-NOMA system. Proposed algorithm for computing analog beamforming vector to solve power minimization problem is also presented in Sect. 3. Simulation results are discussed in Sect. 4. Conclusion is offered in Sect. 5. Following notations are used. Lower case and upper case bold face letters are adopted for vectors and matrices respectively. Hermitian, transpose, expectation, absolute operation and Euclidean norm operation are denoted by $(.)^H$, $(.)^T$ $E(.)$, $|.|$ and $\|.\|_2$ respectively.

2 mm-wave Channel Model

The channel characteristics of mm-wave LOS and NLOS directional outdoor links in various reference cases are investigated in [19]. The mm-wave channel $\mathbf{h}_\mathrm{j}$ between the base station (BS) and j -th user in the downlink direction as expressed in [20] is given in Eq. (1).

$$\mathbf{h}_\mathrm{j} = \sqrt{\frac{v_\mathrm{j}}{v_\mathrm{j}+1}}\mathbf{a}_{\mathrm{j},0} + \sqrt{\frac{1}{v_\mathrm{j}+1}}\ \sqrt{\frac{1}{L}}\ \sum_{p=1}^{L}\alpha_{\mathrm{j,p}}\,\mathbf{a}_{\mathrm{j,p}} \tag{1}$$

First term in (1) represents the LOS path and the second term denotes L number of NLOS scattered paths, where v_j is the Rician factor of j-th user, which is the power ratio between the LOS component and scattered components.

$\alpha_{\mathrm{j,p}} \sim \mathbb{C}\mathcal{N}\left(0, \sigma_\mathrm{j}^2\right)$ where σ_j^2 is average channel power gain of user j. $\mathbf{a}_{\mathrm{j,p}}$ is given by

$$\mathbf{a}_{\mathrm{j,p}} \ = \ \left[1,\ \mathrm{e}^{\mathrm{i}\pi 1 \mathrm{cos}\theta_{\mathrm{j,p}}}, ...,\ \mathrm{e}^{\mathrm{i}\pi(\mathrm{N}-1)\mathrm{cos}\theta_{\mathrm{j,p}}}\right]^{\mathrm{T}} \tag{2}$$

Spacing between N numbers of antenna elements in Uniform Linear Array (ULA) antenna is $\lambda/2$. $\theta_{\mathrm{j,p}}$ is the AoD of p-th path of user j. $\theta_{\mathrm{j,p}}$ is uniformly distributed over $[0, \pi]$. We assume user 1 is closer to BS compared to user 2. Therefore, $\|\mathbf{h}_1\|_2^2 \geq \|\mathbf{h}_2\|_2^2$.

3 System Model and Problem Formulation

3.1 System Model

Two user mm-wave down link MISO NOMA system with analog beamforming weight vector is considered in Fig. 1.

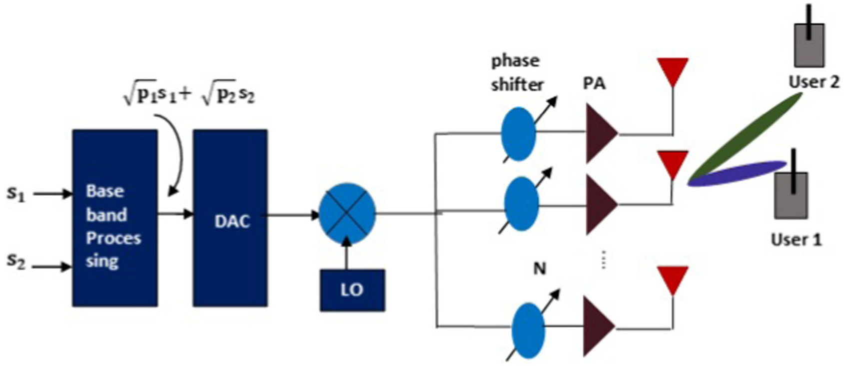

Fig. 1. System model for Two User Analog beamforming down link mm-wave MISO NOMA

BS having N element ULA antenna serves 2 users, each with a single antenna. Each antenna element branch has a phase shifter and a power amplifier (PA). BS produces two concentrated beams pointing towards two NOMA users concurrently. It is achieved by the proper design of phase shifts. Assuming $\mathrm{s_j}$ is the symbol involved for user j and $\mathrm{p_j}$ is the power required for user j with $\mathbb{E}\{|s_j|^2\} = 1$, and $\mathbf{w} \in \mathbb{C}^{\mathrm{Nx1}}$ be the complex beam forming unit normalized weight vector. Signal received by j-th user is

$$\mathrm{y_j} = \mathbf{h}_{\mathrm{j}}^{\mathrm{H}}\mathbf{w}\left(\sqrt{\mathrm{p_1}}\mathrm{s_1} + \sqrt{\mathrm{p_2}}\mathrm{s_2}\right) + \mathrm{n_j} \ \ , \mathrm{j} = 1, 2 \tag{3}$$

where $\mathrm{p_1} + \mathrm{p_2} = \mathrm{P}$, P is the total power transmitted by BS. $\mathrm{n_j}$ is the additive white Gaussian noise (AWGN) at j-th downlink user with unit variance $n_{\mathrm{j}} \sim \mathbb{C}\mathcal{N}(0, 1)$. $\mathbf{h}_{\mathrm{j}}$ is the mm-wave channel from BS to user j.

3.2 Problem Formulation

We assume perfect CSI is available at the BS. Signal to Interference plus Noise Ratio (SINR) required to decode user 2 data at user 2 is given in (4), where user 1 signal is the interference.

$$\mathrm{SINR}_{2,2} = \frac{\mathrm{p_2}\left|\mathbf{h}_2^{\mathrm{H}}\mathbf{w}\right|^2}{\mathrm{p_1}\left|\mathbf{h}_2^{\mathrm{H}}\mathbf{w}\right|^2 + 1} \tag{4}$$

At the near user (user 1), SIC is performed. Therefore SINR required to decode user 2 data at user 1 is mentioned in (5).

$$\mathrm{SINR}_{2,1} = \frac{\mathrm{p_2}\left|\mathbf{h}_1^{\mathrm{H}}\mathbf{w}\right|^2}{\mathrm{p_1}\left|\mathbf{h}_1^{\mathrm{H}}\mathbf{w}\right|^2 + 1} \tag{5}$$

The decoded user 2 data is subtracted from the received SC coded signal and then user 1 data is decoded. Hence the requisite SINR to decode user 1 data at user 1 is specified in (6).

$$\mathrm{SINR}_{1,1} = \mathrm{p}_1 \left| \mathbf{h}_1^{\mathrm{H}} \mathbf{w} \right|^2 \tag{6}$$

Total Power minimization problem with analog beamforming is formulated as follows.

$$\min_{\mathrm{p}_1,\mathrm{p}_2,\mathbf{w}} (\mathrm{p}_1 + \mathrm{p}_2) \tag{7a}$$

$$s.t.\ \log_2 (1 + \mathrm{SINR}_{1,1}) \geq \mathrm{r}_1 \tag{7b}$$

$$\log_2 (1 + \mathrm{SINR}_{2,1}) \geq \mathrm{r}_2 \tag{7c}$$

$$\log_2 (1 + \mathrm{SINR}_{2,2}) \geq \mathrm{r}_2 \tag{7d}$$

$$\|\mathbf{w}\|_2^2 = 1 \tag{7e}$$

$$|[\mathbf{w}]_{\mathrm{n}}| = \text{constant},\ n = 1, 2, ...N \tag{7f}$$

where r_1 and r_2 are the target Spectral Efficiency (SE) of user 1 and user 2 respectively. Non-convex constraint (7f) is removed and then problem (7) is transformed into SDP as mentioned in problem (8).

$$\min_{\mathrm{p}_1,\mathrm{p}_2,\mathbf{Q}} (\mathrm{p}_1 + \mathrm{p}_2) \tag{8a}$$

$$s.t.\ \mathrm{p}_1 tr \left(\mathbf{h}_1^{\mathrm{H}} \mathbf{Q} \mathbf{h}_1 \right) \geq \beta_1 \tag{8b}$$

$$(\mathrm{p}_2 - \beta_2 \mathrm{p}_1)\, tr \left(\mathbf{h}_1^{\mathrm{H}} \mathbf{Q} \mathbf{h}_1 \right) \geq \beta_2 \tag{8c}$$

$$(\mathrm{p}_2 - \beta_2 \mathrm{p}_1)\, tr \left(\mathbf{h}_2^{\mathrm{H}} \mathbf{Q} \mathbf{h}_2 \right) \geq \beta_2 \tag{8d}$$

$$tr(\mathbf{Q}) = 1 \tag{8e}$$

$$rank(\mathbf{Q}) = 1 \tag{8f}$$

$$\mathbf{Q} \succcurlyeq \mathbf{0} \tag{8g}$$

$$where\ \mathbf{Q} = \mathbf{w}\mathbf{w}^{\mathrm{H}}\ \&\ \beta_{\mathrm{j}} = 2^{\mathrm{r_j}} - 1,\ \mathrm{j} = 1, 2 \tag{8h}$$

Constraint (8f) is relaxed and the resultant SDR problem is with 2 scalar variables $\mathrm{p}_1\ \&\ \mathrm{p}_2$ and a PSD matrix $\mathbf{Q}$ with 4 constraints. Rank of $\mathbf{Q}$ in the problem is computed by referring [14].

$$rank^2(\mathbf{Q}) \leq (4 - 2) \tag{9}$$

Hence it is confirmed that the rank of $\mathbf{D}$ is 1 and the solution obtained is always optimal. The optimum beamforming vector $\mathbf{w}^{opt}$ can be obtained from a rank-one $\mathbf{Q}^{opt}$ solution, as

$$\mathbf{w}^{opt} = \sqrt{\mathrm{u}^{opt}}\, \mathbf{v}^{opt} \tag{10}$$

where u^{opt} and v^{opt} are the eigenvalue and the eigenvector of $\mathbf{Q}^{opt}$. Solution obtained satisfies $\|\mathbf{w}^{opt}\|_2^2 = 1$. But the elements of the obtained $\mathbf{w}^{opt}$ do not have constant modulus. Hence normalization is done on $\mathbf{w}^{opt}$ as mentioned in

(11) and then multiplied with α such that all the constraints (7b), (7c) & (7d) are satisfied. Let us call the final solution as $\mathbf{w}^{\mathrm{final}}$.

$$[\mathbf{w}_{NM}]_{\mathrm{i}} = \frac{[\mathbf{w}^{opt}]_{\mathrm{i}}}{\sqrt{\mathrm{N}} \quad |[\mathbf{w}^{opt}]_{\mathrm{i}}|},\ i = 1, 2, ...N \tag{11}$$

$$\mathbf{w}^{\mathrm{final}} = \alpha\ \mathbf{w}_{NM} \tag{12}$$

where α is a positive scaling coefficient.

The achieved SE of user 1 and user 2 are computed from (13) and (14).

$$\mathrm{R}_1 = \ \log_2 \left(1 + \mathrm{p}_1 \left|\mathbf{h}_1^{\mathrm{H}} \mathbf{w}^{\mathrm{final}}\right|^2\right) \tag{13}$$

$$\mathrm{R}_2 = \min \left\{ \log_2 \left(1 + \frac{\mathrm{p}_2 \left|\mathbf{h}_1^{\mathrm{H}} \mathbf{w}^{\mathrm{final}}\right|^2}{\mathrm{p}_1 \left|\mathbf{h}_1^{\mathrm{H}} \mathbf{w}^{\mathrm{final}}\right|^2 + 1}\right),\ \log_2 \left(1 + \frac{\mathrm{p}_2 \left|\mathbf{h}_2^{\mathrm{H}} \mathbf{w}^{\mathrm{final}}\right|^2}{\mathrm{p}_1 \left|\mathbf{h}_2^{\mathrm{H}} \mathbf{w}^{\mathrm{final}}\right|^2 + 1}\right) \right\} \tag{14}$$

The required total transmit power of NOMA users is given in (15).

$$\mathrm{P} = \left\|\mathbf{w}^{\mathrm{final}}\right\|_2^2 (\mathrm{p}_1 + \mathrm{p}_2) \tag{15}$$

Performance of our proposed algorithm is compared with the conventional 2 user TDMA approach. Achieved SE of user k in TDMA is specified in (16).

$$\mathbf{R}_{\mathrm{k-TDMA}} = \frac{1}{2} \log_2 \left(1 + \left|\mathbf{h}_{\mathrm{k}}^{\mathrm{H}} \mathbf{w}_{\mathrm{k-TDMA}}\right|^2\right),\ \mathrm{k} = 1, 2 \tag{16}$$

where the term $\frac{1}{2}$ represents the time slot allotted for each user. $\mathbf{w}_{\mathrm{k-TDMA}}$ is designed to satisfy the maximal ratio combining (MRC) as well as the target SE. It is assumed that the AWGN noise has unit variance.

4 Simulation Results

Simulation has been performed in cvx-matlab [21] for 1000 runs. We assume channel variances of user 1 and user 2 are $\sigma_1^2 = 2$, $\sigma_2^2 = 1$; $N = 32$, $L = 3$. $v_1 = v_2 = 32$; $\theta_{\mathrm{j,p}}$ is uniformly distributed over $[0, \pi]$ for $j = 1,2$ and $p = 1,2,...L$. For attaining user fairness, it is assumed $r_1 = r_2$.

Figure 2 and Fig. 3 show achieved SE versus target SE of near user (user 1) and far user (user 2) respectively. Since the common weight vector for both the users is multiplied with a positive constant, achieved SE of near user is more than the target SE. However far user's achieved SE is same as the target SE. In conventional TDMA, achieved SE is same as target SE in near user as well as in far user. This is due to the fact that the weight vector is designed for a particular user in that dedicated time slot. Figure 4 depicts achieved sum SE vs. target sum SE.

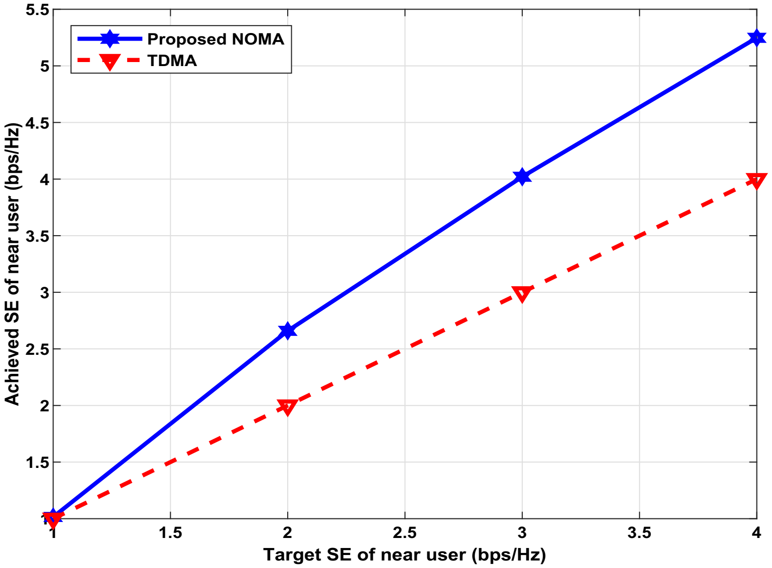

Fig. 2. Achieved SE of near user against target SE

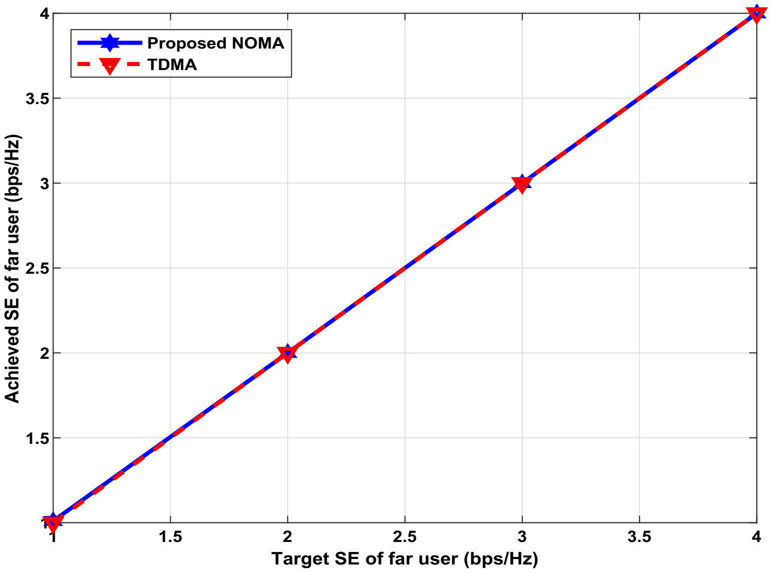

Fig. 3. Achieved SE of far user against target SE

We also evaluate the performance of the proposed approach along with TDMA in terms of power requirement. For that, achieved SE should be same for both the cases. So, target SE of TDMA is kept as the achieved SE of proposed NOMA.

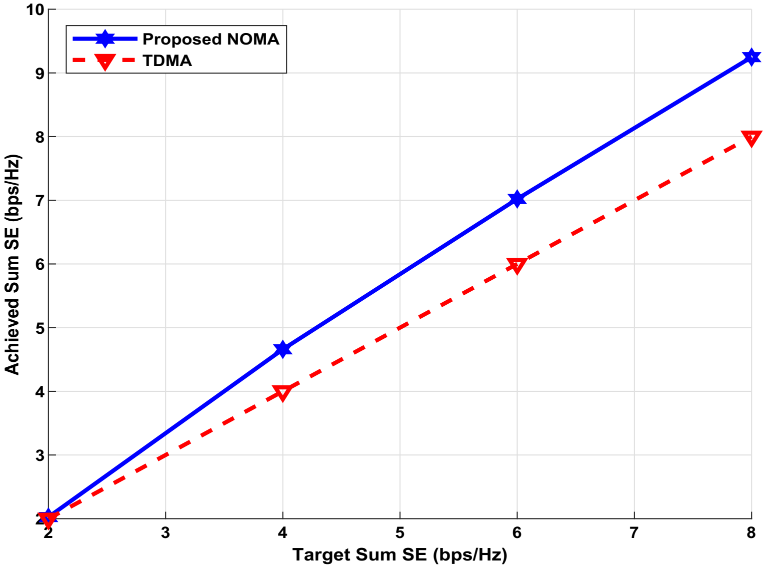

Fig. 4. Achieved sum SE against target sum SE

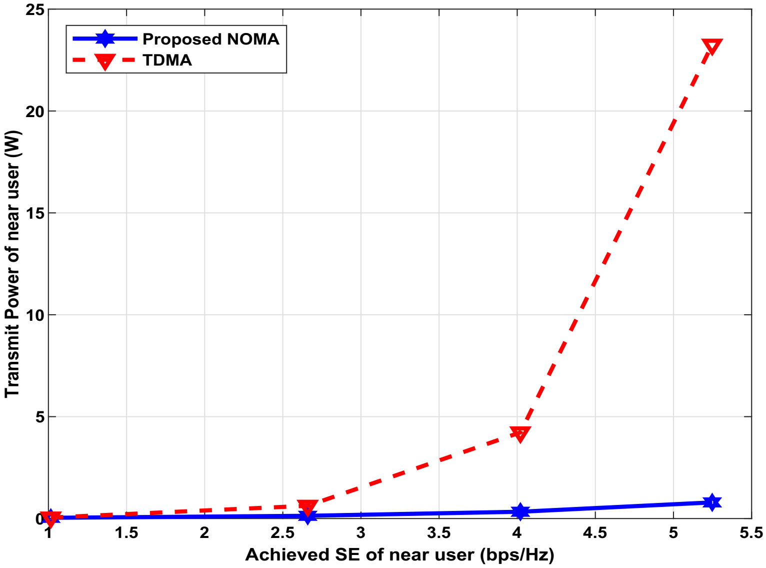

Fig. 5. Required near user's transmit power against achieved SE

The equation for SE of near user NOMA (13) is similar with that of TDMA (16) except the term $\frac{1}{2}$. Hence power required in TDMA i.e. $\|\mathbf{w}_{\mathrm{k-TDMA}}\|_2^2$ is more to meet twice the target SE as shown in Fig. 5. But for the far user, the power

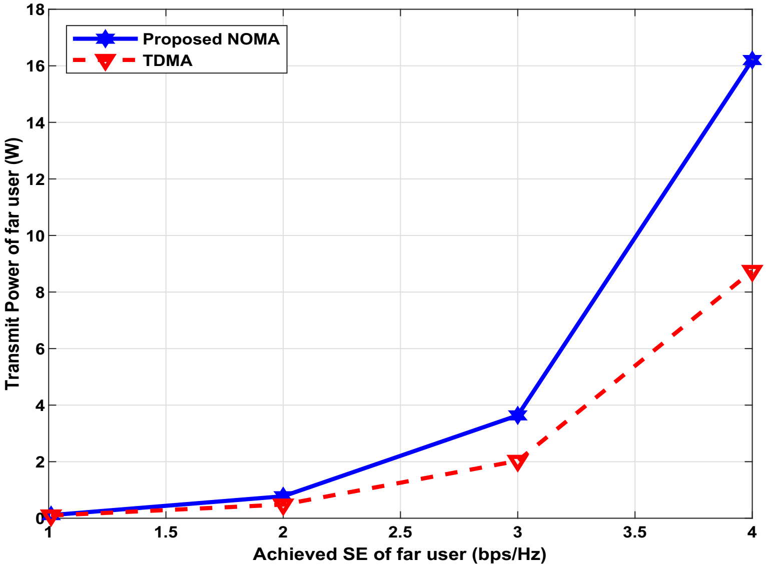

Fig. 6. Required far user's transmit power against achieved SE

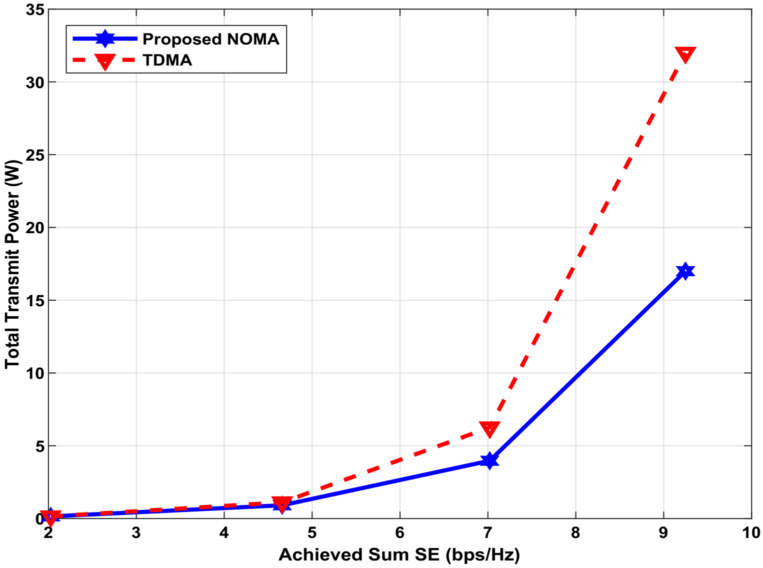

Fig. 7. Required total transmit power against achieved sum SE

requirement in the proposed NOMA approach is more (Fig. 6) to accomplish SIC at near user. From (Fig. 7), it is evident that the proposed approach in NOMA is better compared with the TDMA in terms of the total power requirement for the same achieved sum SE.

5 Conclusion

In this work, we formulated total power minimization problem for two user mm-wave down link NOMA with analog beamforming. SDR method used in this algorithm gives optimum solution since the rank of the PSD matrix involved is always one. Then the weight vector is changed into constant modulus according to the steps discussed in our low complex approach. Moreover, less total power is required in the proposed approach compared with the conventional TDMA to achieve the same sum spectral efficiency. The proposed algorithm can be used in our future work which deals with multi-user NOMA.

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