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Limited Feedback Design for Massive Full Dimension MIMO Systems

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***Abstract*—Massive Multiple-input Multiple-output (MIMO) systems serve simultaneously multiple users to increase spectral efficiency in wireless communication systems. Using two dimension antenna design for massive MIMO systems namely massive FD-MIMO, the overall system performance is further improved. For the massive FD-MIMO systems, the availability of channel state information (CSI) at the base station is essential to achieve overall performance gain. In this paper, we design limited feedback link for massive FD-MIMO by designing two separate codebooks for horizontal and elevation domains to reduce the feedback load. The simulation results are provided for the proposed scheme by considering 3-dimension wireless channel models.**

***Index Terms*—Massive MIMO, Limited Feedback design, Full Dimension MIMO, Codebook design**

I. INTRODUCTION

Massive Multiple-input Multiple-output (MIMO) is one of the key candidate technologies to satisfy high data rate requirements supporting spectrum and energy efficient systems for the wireless communications [1]. In order to increase the number of antennas in a limited area, two-dimensional antenna arrays such as uniform planar arrays (UPAs) and cylindrical arrays, that put antennas in both vertical and horizontal dimensions are considered in practice instead of Uniform Linear Array (ULA) case. Among various two-dimension (2D) array solutions, UPAs are of great interest since they requires simplified signal processing than cylindrical arrays. Massive MIMO with a UPA structure is known as massive full-dimension (FD) MIMO since it employs beamforming at both vertical and horizontal domain [2]. For FD-MIMO systems, three-dimensional (3D) spatial channels are considered as an extension of 2D spatial channels [3]. In [4], a very comprehensive overview of FD-MIMO systems in 3GPP LTE Advanced Pro has been given by focusing on antenna configurations, transceiver architectures, 3D channel model, pilot transmission, and CSI measurement and feedback schemes.

To fully harvest the benefit of excessive BS antennas, the knowledge of channel state information (CSI) is an essential requirement. However, it is challenging to obtain accurate CSI. Without accurate CSI, the sum data rate of massive MIMO systems is effected strongly [5]. Therefore, in the multiuser massive MIMO systems, one of the challenge is to scale channel estimation and feedback strategies to provide CSI at the BS effectively. In order to maintain the same level of channel quantization error, the codebook size must be increased proportional to the number of transmit antennas, which is not feasible for implementation. Therefore, it is difficult to scale the MIMO codebook design to the multiuser massive MIMO systems.

In conventional MIMO systems, the CSI quantization codebooks have been designed under the assumption of spatially uncorrelated Rayleigh fading channels [6]. In this case, the channel direction information (CDI) which is uniformly distributed on the unit hypersphere, is obtained after normalization of the CSI. For FD-MIMO taking the properties of realistic channels and the UPA, both narrow-band and wideband CSI quantizers have been developed by quantizing a limited number of dominant 2D beams in 3D channel vectors through DFT codebooks in [7]. In order to reduce the complexity of CSI quantization in multiuser massive MIMO systems, in [8], a deep clustering based scheme has been used for a codebook design. In [9], two-stage quantizers approach based on Grassmannian codebook has been examined while it extended to the multi-stage recursive quantization in [10].

In [11], it has been shown that channel correlation in the frequency domain can be exploited to reduce CSI feedback overhead via DFT transformation to a sparse delay domain. In [12], the frequency-domain (FD) basis subset selection in light of the DFT basis transformation has been examined while [11] selected the size of the basis while satisfying a given channel distortion criterion.

In [13] [14], for the FD-MIMO systems, reduced computational complexity codebook based feedback has been given by setting an adaptive reporting interval for the vertical precoding matrix index (PMI) since the angular spread in the vertical domain is small for a typical urban environment. In [15], CSI feedback based on spatial and frequency domains compression using a matrix projection method has been investigated. In [16], 2-stage codebook designs have been provided for the multiuser massive MIMO systems. The first stage codebook provides coarse amplitude quantization information, and the second stage codebook provides phase quantization as well as additional amplitude quantization information that fine-tunes the first-stage quantization. For CSI feedback in massive MIMO system, deep learning based approaches have been

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used while reducing the computational complexity and feedback load [17] [18].

In this paper, we propose a limited feedback design for the massive FD-MIMO communications systems. In Section II, we give the massive FD-MIMO system model including 3D channel model. Section III is dedicated to the proposed feedback design. In Section IV and Section V, the performance results are illustrated and conclusions are given, respectively.

II. System Model

We consider a downlink massive FD-MIMO system with N_t antennas at the BS and K users with one antenna. The BS is equipped with $N_e \times N_a$ dimensional uniform rectangular array having N_e antennas in elevation and N_a antennas in horizontal domains, and $N_{\mathrm{RF}} = N_e N_a = N_t$ radio frequency (RF) chains.

The transmitted vector, $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ is given by:

$$\mathbf{x} = \mathbf{W}\mathbf{s} \tag{1}$$

where $\mathbf{W} \in \mathbb{C}^{N_t \times K}$ with $\mathbf{W} = [\mathbf{w}_1 \dots \mathbf{w}_k \dots \mathbf{w}_K]$ is the generalized precoder matrix which is composed of each user precoder, $\mathbf{w}_k \in \mathbb{C}^{N_t \times 1}$. The data vector is $\mathbf{s} \in \mathbb{C}^{K \times 1}$ with $\mathbf{s} = [s_1 \cdots s_K]^T$. The average transmitted power is $\mathbb{E}[||\mathbf{s}||^2] = P$.

The downlink received signal by the k^{th} user is defined as:

$$\mathbf{y}_k = \sqrt{\Gamma_k}\mathbf{h}_k\mathbf{w}_k\mathbf{s}_k + \sqrt{\Gamma_k}\sum_{j=1; j\neq k}^{K}\mathbf{h}_k\mathbf{w}_j\mathbf{s}_j + \mathbf{n}_k, \tag{2}$$

where Γ_k is the path loss coefficient for the k^{th} user and $\mathbf{n}_k$ is the additive White Gaussian noise (AWGN) whose elements are modeled by $\mathcal{CN}(0, \sigma^2)$.

The overall channel matrix, $\mathbf{H} \in \mathbb{C}^{K \times N_t}$ is given by:

$$\mathbf{H} = [\mathbf{h}_1 \quad \mathbf{h}_2 \cdots \mathbf{h}_K]^T \tag{3}$$

where $\mathbf{h}_k \in \mathbb{C}^{1 \times N_t}$ is the channel vector belonging to k^{th} user.

The received signal-to-interference-noise ratio (SINR) for the k^{th} user is expressed as:

$$\gamma_k = \frac{|\mathbf{h}_k\mathbf{w}_k|^2}{(1/\rho_k) + \sum\limits_{\substack{j=1\\ j\neq k}}^{K}|\mathbf{h}_k\mathbf{w}_j|^2} \tag{4}$$

where $\rho_k = \Gamma_k P/\sigma^2$ is the average signal-to-noise ratio (SNR). It is assumed that all users are the same path loss, and then ρ_k is set to ρ.

The data rate of the k^{th} user is determined by,

$$R_k = \log_2(1 + \gamma_k) \tag{5}$$

The downlink sum data rate is given by,

$$\mathrm{R} = \sum_{k=1}^{K}\mathrm{R}_k \tag{6}$$

In order to determine the precoding matrix, minimum mean square error (MMSE) based linear precoding technique is used:

$$\bar{\mathbf{W}} = \mathbf{H}^H[\mathbf{H}\mathbf{H}^H + (1/\rho)\mathbf{I}_K)]^{-1} \tag{7}$$

In order to keep the power constraint, the precoding matrix is normalized as,

$$\mathbf{W} = \frac{\bar{\mathbf{W}}}{||\bar{\mathbf{W}}||_2} \tag{8}$$

A. Channel Model

The spatial-channel matrix with the dimension of $N_e \times N_a$ is given by [14]:

$$\mathbf{H}_k = \frac{1}{\sqrt{CS}}\sum_{c=1}^{C}\sum_{s=1}^{S}\alpha_{k,c,s}\mathbf{b}(\phi_{k,c,s}, \theta_{k,c,s}) \tag{9}$$

where C is the number of clusters and S is the number of subpath per cluster. $\alpha_{k,c,s}$ represents an instantaneous complex coefficient and modeled by complex Gaussian distribution with zero mean and unit variance. $\mathbf{b}(\phi_{k,c,s}, \theta_{k,c,s})$ denotes array steering matrix with $\theta_{k,c,s}$ and $\phi_{k,c,s}$ indicate respectively the elevation and azimuth angles for c^{th} cluster, s^{th} path and k^{th} user.

The azimuth Angle of Arrival (AoA) of each ray is modeled as $\phi_{k,c,s} = \phi_{k,c} + \Delta_{k,c,s}$ where $\phi_{k,c}$ is the central angle of the rays of cluster c and $\Delta_{k,c,s}$ is the deviation of subpath s from that central angle. $\phi_{k,c}$ is a Gaussian distributed with mean μ_c and variance σ_c^2 and $\Delta_{k,c,s}$ is a Laplacian distribution with variance σ_s^2. The elevation AoA of each ray is modeled as $\theta_{k,c,s} = \theta_{k,c} + \delta_{k,c,s}$ where $\theta_{k,c}$ is the central angle of the rays of cluster c and $\delta_{k,c,s}$ is the deviation of subpath s from that central angle. $\theta_{k,c}$ is a Laplacian distributed with variance $\tilde{\sigma}_c^2$ centered on 90^o and $\delta_{k,c,s}$ is a Laplacian distribution with variance $\tilde{\sigma}_s^2$.

For the uniform rectangular array (UPA), the antenna array response is written by [14],

$$\mathbf{b}(\theta, \phi) = \mathbf{a}_a(\theta, \phi)^T \otimes \mathbf{a}_e(\theta, \phi) \tag{10}$$

where $\otimes$ is the Kronecker product.

The azimuth and elevation array vectors are given, respectively [20]:

$$\mathbf{a}_a(\theta, \phi) = [1, e^{j2\pi\frac{d_a}{\lambda}sin\theta cos\phi}, \dots, e^{j2\pi\frac{(N_a-1)d_a}{\lambda}\sin\theta\cos\phi}] \tag{11}$$

$$\mathbf{a}_e(\theta, \phi) = [1, e^{j2\pi\frac{d_e}{\lambda}sin\theta\sin\phi}, \dots, e^{j2\pi\frac{(N_e-1)d_e}{\lambda}\sin\theta\sin\phi}] \tag{12}$$

where d_a denote the inter-element spacing in horizontal axis and d_e denotes the inter-element spacing in elevation axis.

The channel vector of each user is given by $\mathbf{h}_k = vec(\mathbf{H}_k)$.

For both spatial and time correlated 3D channel model is given by,

$$\mathbf{H}_k(t) = \frac{1}{\sqrt{CS}}\sum_{c=1}^{C}\sum_{s=1}^{S}\alpha_{k,c,s}\mathbf{b}(\phi_{k,c,s}, \theta_{k,c,s})e^{j2\pi\Omega_{k,c,s}t} \tag{13}$$

where t is the time, $\Omega_{k,c,s}$ is the phase shift due to mobility and is determined by

$$\Omega_{k,c,s} = \frac{v cos(\phi_{k,c,s} - \phi_v) cos(\theta_{k,c,s} - \theta_v)}{\lambda} \quad (14)$$

with v is the velocity (m/sn), ϕ_v and θ_v are the travel direction of user in the azimuth and elevation plane respectively.

III. Proposed Limited Feedback Design

In this scheme, our goal is to reduce the feedback load without sacrificing the sum data rate in the massive FD-MIMO. We firstly design codebooks for horizontal and vertical directions separately by using DFT based designs. The angular spread in the vertical direction is low and consequently, the elevation angle is changing slowly for a given time interval. In this work, instead of constructing the codebook by quantizing all directions in the elevation direction, we propose to focus on specific directions to reduce the number of feedback bits.

The codewords of i_a and i_e belonging to horizontal and vertical codebooks are respectively given by,

$$\mathbf{h}^{i_a} = \frac{1}{\sqrt{N_a}}[1, e^{j\frac{2\pi}{O_a N_a} i_a}, \cdots, e^{j\frac{2\pi}{O_a N_a} i_a (N_a - 1)}]^T \quad (15)$$

$$\mathbf{v}^{i_e} = \frac{1}{\sqrt{N_e}}[1, e^{j\frac{2\pi}{O_e N_e} i_e}, \cdots, e^{j\frac{2\pi}{O_e N_e} i_e (N_e - 1)}]^T \quad (16)$$

where O_a and O_e are the oversampling factors and $i_a \in \{0, ..., N_a O_a - 1\}$ and $i_e \in \{0, ..., N_e O_e - 1\}$.

Then, the horizontal and vertical codebooks are constructed respectively by,

$$\mathbf{x}^a = [\mathbf{h}^0, \cdots, \mathbf{h}^{N_a O_a - 1}]^T \quad (17)$$

$$\mathbf{x}^e = [\mathbf{v}^0, \cdots, \mathbf{v}^{N_e O_e - 1}]^T \quad (18)$$

The horizontal codebook includes $N_a O_a$ precoding entries and is represented by $B_a = \log_2(N_a O_a)$ bits while the vertical codebook contains $N_e O_e$ precoding entries and requires $B_e = \log_2(N_e O_e)$ bits. As a result, the total of feedback bits is equal to $B_{FL} = B_a + B_e$.

In order to perform channel quantization to design limited feedback link, firstly, we apply singular value decomposition (SVD) for the 2D channel matrix $\mathbf{H}_k = \mathbf{E}\mathbf{S}\mathbf{T}^H$ with $\mathbf{S}$ is the diagonal matrix consisting of eigenvalues, $\mathbf{E}$ is the left singular matrix and $\mathbf{T}$ is the right singular matrix.

Then, we can write the channel matrix by,

$$\mathbf{H}_k = \sum_{i=1}^{r_k} s_i \mathbf{e}_i \otimes \mathbf{t}_i^H \quad (19)$$

where r_k is the rank of the k^{th} user channel matrix, $\mathbf{e}_i$ and $\mathbf{t}_i$ are the i^{th} column of $\mathbf{E}$ and $\mathbf{T}$ respectively.

The horizontal codebook index based on chordal distance is determined as:

$$i_k^{a^*} = \arg\min_{i_a}(1 - |\mathbf{t}_1^T \mathbf{h}^{i_a}|^2) \quad (20)$$

Similarly, the elevation codebook index based on chordal distance is obtained as:

$$i_k^{e^*} = \arg\min_{i_e}(1 - |\mathbf{e}_1^H \mathbf{v}^{i_e}|^2) \quad (21)$$

After obtaining the codebook indexes, we construct $\tilde{\mathbf{H}}_\mathbf{k}$ based on $i_k^{a^*}$ and $i_k^{e^*}$:

$$\tilde{\mathbf{H}}_k = \mathbf{h}^{i_k^{a^*}} \otimes \mathbf{v}^{i_k^{e^*}} \quad (22)$$

In this work, since the elevation angle is changing slowly, we propose to construct a high-resolution vertical codebook of $\tilde{\mathbf{x}}^e$ by only selecting the most probable $2^{B'_e}$ codewords from the codebook of $\mathbf{x}^e$ where B'_e is less than B_e. Then, the modified high-resolution codebook for the elevation domain is given as:

$$\tilde{\mathbf{x}}^e = [\tilde{\mathbf{v}}^1, \cdots, \tilde{\mathbf{v}}^{2^{B'_e}}]^T \quad (23)$$

After obtaining the codebook indexes for both vertical and horizontal dimension, $\tilde{\mathbf{H}}$ is replaced with $\mathbf{H}$ in (7) to perform MMSE based linear precoding technique to mitigate the inter-user interference for the massive FD-MIMO systems.

The proposed PMI method is described in Algorithm (1) in detail.

Algorithm 1 Proposed PMI Algorithm

1: Obtain the horizontal codebook of $\mathbf{x}^a$ as in (17) having B_a bits.
2: Obtain the vertical codebook of $\mathbf{x}^e$ as in (18) having B_e bits.
3: Construct $\tilde{\mathbf{x}}^e$ as in (23) having B'_e bits.
4: **for** $k = 1 : K$ **do**
5: Obtain the horizontal codebook index by using $\mathbf{x}^a$ as in (20).
6: Obtain the elevation codebook index by using $\tilde{\mathbf{x}}^e$ as in (21).
7: **end for**
8: Construct $\tilde{\mathbf{H}}$ as in (22) and perform MMSE as in (7) and (8).

IV. Performance Results

In this section, we provide the simulation results for the massive FD-MIMO systems based on the parameters given in Table I.

By large number of channel realizations, we examine the distribution of selected codebook indexes in the elevation direction for different number of quantization bits. For $B_e = 6$ and and $N_t = 16$, the distribution of elevation codebook indexes is shown in Figure 1. It is observed that few indexes selected since the variations of elevation angle is slow. Similar behavior is observed when the number of bits is increased to $B_e = 10$ as shown in Figure 2 and the number of antennas is increased to $N_t = 64$ as illustrated in Figure 3. Therefore, we can construct the high-resolution codebook by using B'_e bits rather than B_e bits.

For the case of $B_e = 6$ for $N_t = 16$, the most selected codebook indexes are between 20 and 35 for elevation domain

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Carrier frequency, f_c	3.5 GHz
TTI duration	1ms
TTI	100
Velocity	10km/h
Number of clusters, C	6
Number of paths, S	20
d_e, d_a	$\lambda/2$
Azimuth cluster angle mean μ_c	0 deg
Azimuth cluster angle σ_c,	20 deg
Azimuth subpath angle σ_s	10 deg
Elevation cluster angle mean $\tilde{\mu}_c$	90 deg
Elevation cluster angle $\tilde{\sigma}_c$	5 deg
Elevation subpath angle $\tilde{\sigma}_s$	2 deg

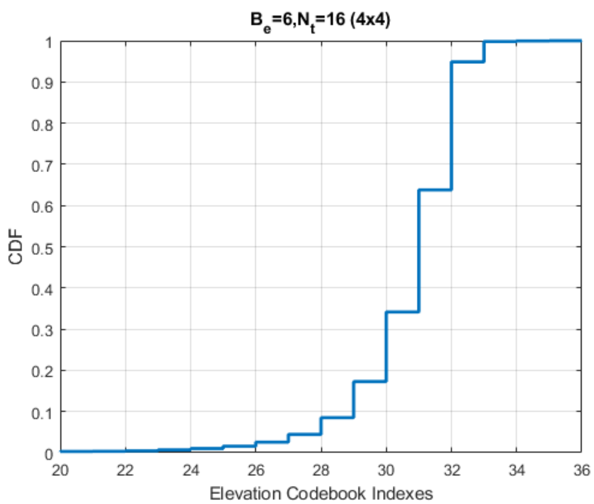

Fig. 1. Distribution of selected codebook indexes in the elevation dimension for $B_e = 6$, $N_e = 4$ and $N_a = 4$.

for the case of $B_e = 6$ for $N_t = 16$. By choosing 16 most probable codebook indexes, the feedback link is represented by 4 bits instead of 6 bits, which reduces the feedback load significantly.

The distribution of codebook indexes in the horizontal direction is shown in Figure 4 for $B_a = 12$ and $N_t = 64$. It is observed that the codebook indexes of horizontal direction span almost all codewords. Based on the observation through different number of bits and different number of antennas, the DFT based codebooks for horizontal direction are employed while for elevation direction, the codebook that includes only most probable codeword indexes rather than all codeworda is constructed in order to reduce the feedback load.

We provide the average sum data rate results of different limited feedback schemes in Figure 5. The proposed codebook design improves the sum data rate up to 0.3bps/Hz compared to the case of DFT based codebook with same number of feedback bits. Besides, the proposed algorithm with $B_{FL} = 10$ gives the same sum data rate with with $B_{FL} = 12$ while reducing the feedback load with 15%.

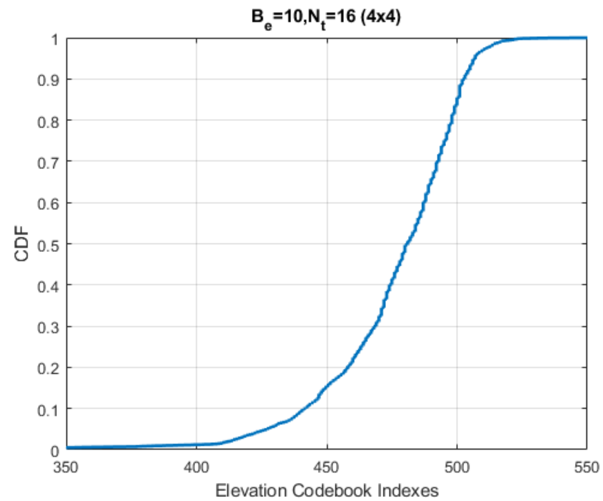

Fig. 2. Distribution of selected codebook indexes in the elevation dimension for $B_e = 10$, $N_e = 4$ and $N_a = 4$.

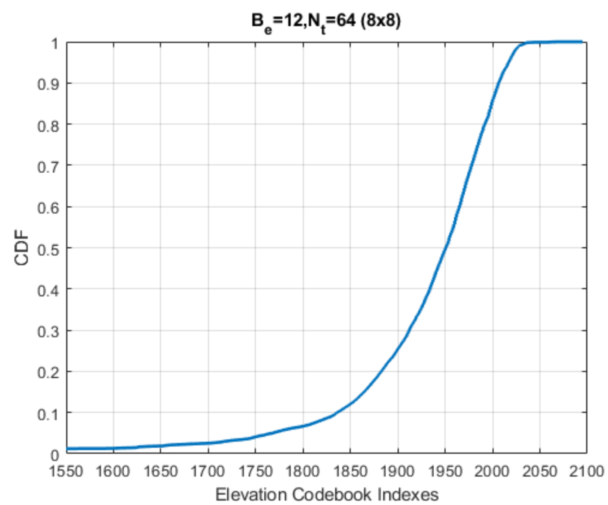

Fig. 3. Distribution of selected codebook indexes in the elevation dimension for $B_e = 12$, $N_e = 8$ and $N_a = 8$.

V. CONCLUSION

In this paper, we have improved average sum data rate for the massive FD-MIMO systems through the proposed limited feedback design. The goal of the algorithm is to reduce the feedback load with higher resolution codebook for elevation dimension. Since the selected indexes do not spread over all codewords for, we have designed high resolution codebook to reduce feedback load. We have compared the sum data rate results considering different number of bits in the limited feedback channel. We have illustrated that the proposed scheme reduces the feedback load by providing the same average sum data rate.

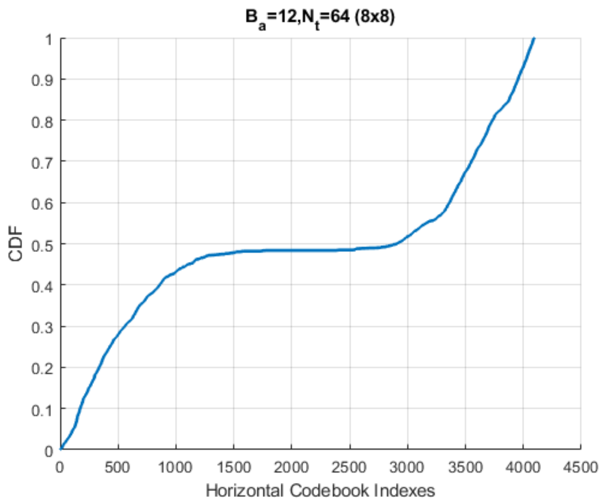

Fig. 4. Distribution of selected codebook indexes in the horizontal dimension for $B_a = 12$, $N_a = 8$ and $N_e = 8$.

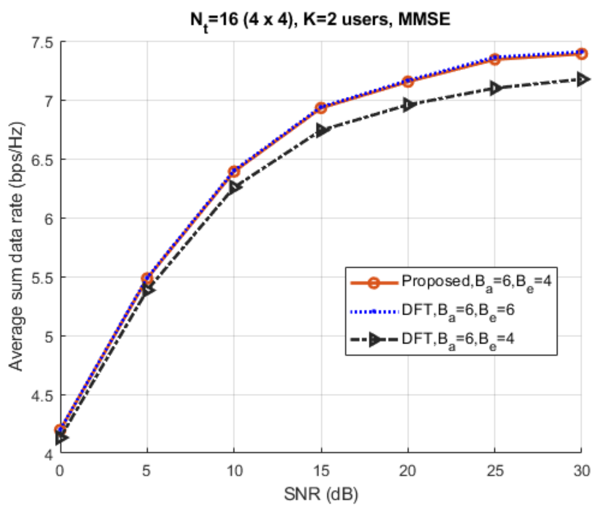

Fig. 5. Comparison on average sum data rate results for $N_t = 16$ transmit antennas and $K = 2$ users.

REFERENCES

[1] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, “Massive mimo for next generation wireless systems,” *IEEE Communications Magazine*, vol. 52, no. 2, pp. 186–195, 2014.

[2] Y. Nam, B. L. Ng, K. Sayana, Y. Li, J. Zhang, Y. Kim, and J. Lee, “Full-dimension mimo (fd-mimo) for next generation cellular technology,” *IEEE Communications Magazine*, vol. 51, no. 6, pp. 172–179, 2013.

[3] X. Li, S. Jin, X. Gao, and R. W. Heath, “Three-dimensional beamforming for large-scale fd-mimo systems exploiting statistical channel state information,” *IEEE Transactions on Vehicular Technology*, vol. 65, no. 11, pp. 8992–9005, 2016.

[4] H. Ji, Y. Kim, J. Lee, E. Onggosanusi, Y. Nam, J. Zhang, B. Lee, and B. Shim, “Overview of full-dimension mimo in lte-advanced pro,” *IEEE Communications Magazine*, vol. 55, no. 2, pp. 176–184, 2017.

[5] Z. Lv and Y. Li, “A channel state information feedback algorithm for massive mimo systems,” *IEEE Communications Letters*, vol. 20, no. 7, pp. 1461–1464, 2016.

[6] N. Jindal, “Mimo broadcast channels with finite-rate feedback,” *IEEE Transactions on Information Theory*, vol. 52, no. 11, pp. 5045–5060, 2006.

[7] J. Song, J. Choi, T. Kim, and D. J. Love, “Advanced quantizer designs for fdd-based fd-mimo systems using uniform planar arrays,” *IEEE Transactions on Signal Processing*, vol. 66, no. 14, pp. 3891–3905, 2018.

[8] J. Jiang, X. Wang, W. Wang, L. Zhen, and J. Wang, “Deep clustering-based codebook design for massive mimo systems,” *IEEE Access*, vol. 7, pp. 172 654–172 664, 2019.

[9] S. Schwarz, M. Rupp, and S. Wesemann, “Grassmannian product codebooks for limited feedback massive mimo with two-tier precoding,” *IEEE Journal of Selected Topics in Signal Processing*, vol. 13, no. 5, pp. 1119–1135, 2019.

[10] S. Schwarz and M. Rupp, “Reduced complexity recursive grassmannian quantization,” *IEEE Signal Processing Letters*, vol. 27, pp. 321–325, 2020.

[11] L. Suárez, N. Ryabov, V. Lyashev, and A. Sherstobitov, “Dft based beam-time delay sparse channel representation for channel state information (csi) compression in 5g fdd massive mimo systems,” in *2018 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*, 2018, pp. 1–5.

[12] R. Ahmed, E. Visotsky, and T. Wild, “Explicit csi feedback design for 5g new radio phase ii,” in *WSA 2018; 22nd International ITG Workshop on Smart Antennas*, 2018, pp. 1–5.

[13] E. Onggosanusi, M. S. Rahman, L. Guo, Y. Kwak, H. Noh, Y. Kim, S. Faxer, M. Harrison, M. Frenne, S. Grant, R. Chen, R. Tamrakar, and a. Q. Gao, “Modular and high-resolution channel state information and beam management for 5g new radio,” *IEEE Communications Magazine*, vol. 56, no. 3, pp. 48–55, 2018.

[14] M. Mussbah, S. Pratschner, S. Schwarz, and M. Rupp, “Computationally efficient limited feedback for codebook-based fd-mimo precoding,” in *WSA 2019; 23rd International ITG Workshop on Smart Antennas*, 2019, pp. 1–5.

[15] Z. Liu, S. Sun, Q. Gao, and H. Li, “Csi feedback based on spatial and frequency domains compression for 5g multi-user massive mimo systems,” in *2019 IEEE/CIC International Conference on Communications in China (ICCC)*, 2019, pp. 834–839.

[16] A. Hindy, U. Mittal, and T. Brown, “Csi feedback overhead reduction for 5g massive mimo systems,” in *2020 10th Annual Computing and Communication Workshop and Conference (CCWC)*, 2020, pp. 0116–0120.

[17] Z. Lu, J. Wang, and J. Song, “Multi-resolution csi feedback with deep learning in massive mimo system,” in *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, 2020, pp. 1–6.

[18] S. Ji and M. Li, “Clnet: Complex input lightweight neural network designed for massive mimo csi feedback,” *IEEE Wireless Communications Letters*, vol. 10, no. 10, pp. 2318–2322, 2021.

[19] S. Sangodoyin, V. Kristem, C. U. Bas, M. Käske, J. Lee, C. Schneider, G. Sommerkorn, C. J. Zhang, R. Thomä, and A. F. Molisch, “Cluster characterization of 3-d mimo propagation channel in an urban macro-cellular environment,” *IEEE Transactions on Wireless Communications*, vol. 17, no. 8, pp. 5076–5091, 2018.

[20] C. L. Miller, P. J. Smith, P. A. Dmochowski, H. Tataria, and M. Matthaiou, “Analytical framework for full-dimensional massive mimo with ray-based channels,” *IEEE Journal of Selected Topics in Signal Processing*, vol. 13, no. 5, pp. 1181–1195, 2019.