A multi-user-hybrid beamforming scheme for dual-band wireless networks

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***Abstract*—To highly increase the system capacity to cater to the ever-increasing mobile service requirements, millimeter wave (mmWave) bands with massive available bandwidth have been envisioned as promising candidates in spectrum extension by the fifth generation (5G) wireless communication networks. Nevertheless, compared with conventional microwave cellular bands, mmWave bands suffer from severer propagation loss and are hard to be directly applied into practical wireless communication systems. With an ability not only to overcome the unfavorable path loss of millimeter wave (mmWave) bands but also to provide spatial multiplexing at economical hardware costs, the hybrid analog and digital beamforming (HBF) technology attracts growing attention recently. Based on the feature of HBF, we propose a multi-user HBF (MU-HBF) precoding scheme for user closely co-located scenarios where users are too close to each other that they cannot be distinguished only by physically-separated directional beams. Considering that the limited coverage scope of mmWave directional beams cannot guarantee the network robustness, the control/user (C/U) plane decoupled network architecture is applied to integrate microwave bands with mmWave bands and form a dual-band wireless network, in which microwave bands provide omnidirectional coverage for mobility-related control plane signaling and mmWave bands provide high-speed transmission rate for user plane data. Analysis and simulations are provided to demonstrate the superior performance of the proposed MU-HBF precoding scheme under user closely co-located scenarios.**

***Index Terms*—multi-user, hybrid beamforming, precoding, dual-band wireless networks, user closely co-located scenarios**

I. Introduction

The rapid developments of mobile multi-media entertainments have put forward higher capacity requirements for wireless communication networks. The most direct and effective way to augment system capacity is spectrum extension. Nevertheless, the conventional microwave cellular bands with high transmission performance have been over-utilized by existing abundant wireless systems. To complement the severe spectrum shortage of cellular communication systems, millimeter wave (mmWave) bands with massive available bandwidth have been envisioned as a promising candidate by the fifth generation (5G) wireless communication systems [1]. Nevertheless, compared with cellular bands, mmWave bands suffer from severe propagation loss, resulting in unacceptable coverage distance. To overcome this challenge, in the industry and academia, it has been widely agreed that the antenna array based beamforming technology will be a necessary component for mmWave communications. Although beamforming can focus the signal energy on desired directions to overcome the unfavorable path loss in mmWave-bands, its directionality makes it less effective in wireless link establishments, user tracking and feedback compared with conventional omnidirectional communication systems [2]. To address this issue, we propose a dual-band solution based on the control/user (C/U) plane decoupled network architecture as shown in Fig. 1 [3], in which small cells operate at mmWave-bands using directional beamforming to transmit high-volume user plane data and omnidirectional macro-cells operating at microwave cellular bands are responsible to transmit the important control signaling and forward it to directional small cells via front-hauls to help them establish and keep reliable connections with users. Moreover, the integration of microwave and mmWave frequency bands can enhance the whole network robustness.

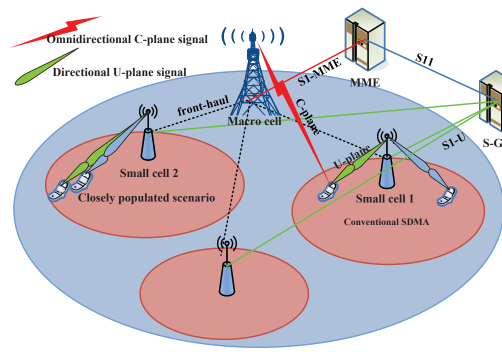

Fig. 1. The user closely co-located scenario in mmWave communications.

In conventional multiple input multiple output (MIMO) systems operating at conventional microwave bands, each antenna is connected to a radio frequency (RF) chain and the number of RF chains determines the maximum supported data streams [4]. As aforementioned, to extend the propagation distance of mmWave signals, massive antennas are required in future mmWave communications to concentrate signal energy and form directional beams. Since the hardware cost increases with the number of configured RF chains, it is impractical to assign each antenna with an exclusive RF chain in mmWave communication systems where the number of antennas is usually in tens or hundreds. To balance the above requirements and the costs, the hybrid beamforming which consists of both analog beamforming and digital beamforming is widely used in practice [5].

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In directional beamforming systems, the user distribution can directly affect the beamforming decisions [2]. As shown in Fig. 1, in small cell 1 the two user equipments (UEs) are so far away from each other that they can be easily distinguished by conventional directional beams when they concurrently communicate with the base station, namely, space division multiple access (SDMA) [6]. Nevertheless, in small cell 2 the two UEs are too closely co-located that they cannot be directly distinguished by directional beams. In other words, they cannot concurrently communicate with the base station due to the high inter-beam interference, thereby resulting in system performance decline. Unfortunately, with exponentially increasing smart devices, this user closely co-located scenario will be a common case. As an emerging technology, hybrid analog and digital beamforming, which can not only form directional beams through analog beamforming but also provide the spatial multiplexing ability through digital beamforming, has attracted growing interests [7], [8]. However, most current researches, such as in [7], [8], mainly focus on precoding schemes for single-user scenarios. Based on the above issues, in this paper, we propose an MU-HBF precoding scheme to mitigate inter-beam interference for the user closely co-located scenario. Considering that UEs have limited capability to manage interference, we leave the task of mitigating inter-beam interference to base stations. Through block diagonalization (BD) [9], [10], every UE's data are put on the null space of other UEs' effective channels. Then, multiple users can concurrently reuse the same radio resources without any inter-beam interference in user closely co-located scenarios, enhancing the system performance. In mmWave communications, both user and base station sides use directional beams for receiving and transmitting. At cell edges, users from different cells usually have a significant beam angle difference as they need to point their narrow beams to the directions of their serving base stations. Therefore, the inter-cell interference under directional communications will not be a significant problem and is not considered in this paper.

The rest of this paper is organized as follows. In Section II, the system model of the proposed MU-HBF precoding scheme for user closely-located scenarios is presented. In Section III, the involved feedback process of the proposed scheme is discussed under the C/U-plane decoupled network architecture, in which the omnidirectional microwave bands provide a dependable tunnel for channel state information feedback. In Section IV, simulation results are analyzed to demonstrate the performance improvements of the proposed scheme. Finally, Section V concludes the whole paper.

II. System Model

The proposed MU-HBF precoding scheme is shown in Fig. 2, where a baseband (BB) precoding module corresponds to digital beamforming to gain space multiplexing, and transmit (TX-) beamformer/receive (RX-) beamformer modules are analog beamforming to compensate the unfavorable path loss of mmWave-bands. A radio frequency (RF) chain contains necessary symbol generation components, such as IFFT/FFT, P/S or S/P and DAC/ADC, which are detailed in [7], [8]. Suppose that there are N UEs and each of them is equipped with an RF chain and N_R^u receiving antennas. N_T^c RF chains and N_T transmitting antennas are deployed in a base station such that $N \leq N_T^c \leq N_T$ [8]. From Fig. 2, we can find that compared with conventional MIMO systems, in mmWave beamforming systems, more antennas are sacrificed to develop an effective beam to compensate the severer path loss. Instead, the number of RF chains determines the achievable space multiplexing gain. Here, as every UE is assumed to be equipped with one RF chain, only one data stream can be established between an UE and a base station. In the following sub-sections, we first present signal processing procedures in base stations and UEs. After the expression of final received signals is obtained, we inversely derive the required precoding matrix. Throughout this paper, we use bold letters to denote vectors and matrices. $(\cdot)^T$ and $(\cdot)^H$ are the transpose operation and conjugate transpose operation of $(\cdot)$.

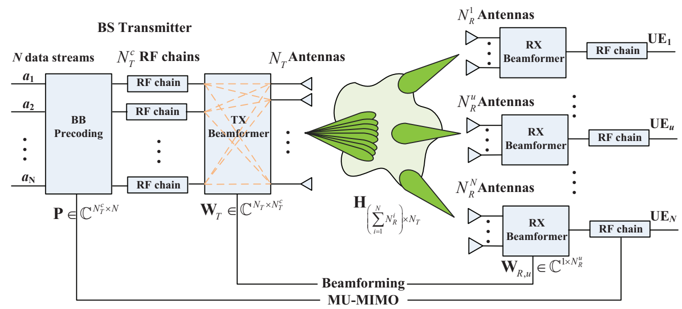

Fig. 2. Proposed MU-HBF precoding scheme.

A. Transmitted signal preprocessing in base stations

In a base station, the transmitted downlink data signals of N UEs are given by

$$\mathbf{s} = [a_1, ..., a_N]^T \tag{1}$$

where a_u is the transmitted data signal of UE u. As shown in Fig. 2, after the BB precoding, the $N \times 1$ dimension data vector $\mathbf{s}$ is mapped to N_T^c RF chains. Therefore, the dimension of the precoding matrix is $\mathbf{P} \in \mathbb{C}^{N_T^c \times N}$, which can be expressed as

$$\mathbf{P} = [\mathbf{p}_1 ... \mathbf{p}_N] \tag{2}$$

where $\mathbf{p}_u \in \mathbb{C}^{N_T^c \times 1}$ is the precoding vector of UE u. After precoding, the data signal of UE u becomes $a_u \mathbf{p}_u$ and the total data signals become

$$\mathbf{P} \cdot \mathbf{s} = [\mathbf{p}_1 ... \mathbf{p}_N] \cdot [a_1 ... a_N]^T = \sum_{i=1}^{N} \mathbf{p}_i a_i \tag{3}$$

In beamforming communication systems, during the beam alignment phase, UEs are required to feed back their selected transmit beam patterns to base stations. Then, base stations focus the signal energy on selected directions to serve UEs. From Fig. 2, we can get the dimension of the TX-beamformer weight matrix as $\mathbf{W}_T \in \mathbb{C}^{N_T \times N_T^c}$, which consists of N_T^c TX-beamformer weight vectors. Let $\mathbf{w}_{T,u} \in \mathbb{C}^{1 \times N_T}$ denote the selected TX-beamformer weight vector of UE u. If $N = N_T^c$, then $\mathbf{W}_T = \left[(\mathbf{w}_{T,1})^T ... (\mathbf{w}_{T,N})^T \right]$. If $N < N_T^c$, then $\mathbf{W}_T = \left[(\mathbf{w}_{T,1})^T ... (\mathbf{w}_{T,N})^T \ \mathbf{0} ... \mathbf{0} \right]$, which means we only need to radiate signals to N directions. For other $N_T^c - N$ directions, no signal is needed to be radiated because there is no user in these directions. After the signal preprocessing of the TX-beamformer module, we can get the final transmitted signals from a base station as

$$\mathbf{X} = \mathbf{W}_T \cdot \mathbf{P} \cdot \mathbf{S} = \sum_{i=1}^{N} \mathbf{W}_T \mathbf{p}_i a_i \tag{4}$$

B. Received signal postprocessing in UEs

Let $\mathbf{H}_u \in \mathbb{C}^{N_R^u \times N_T}$ represent the channel matrix between UE u and a base station. Then, the whole channel matrix between N UEs and a base station is

$$\mathbf{H} = \left[\mathbf{H}_1^H{}_{\left(N_R^1 \times N_T\right)} \cdots \mathbf{H}_N^H{}_{\left(N_R^N \times N_T\right)} \right]^H \tag{5}$$

Accordingly, the received signals of N UEs at antennas before the RX-beamformer modules are given by

$$\begin{aligned} \mathbf{Y} &= \mathbf{H} \cdot \mathbf{X} + \mathbf{N}_0 = \left[\mathbf{H}_1^H \cdots \mathbf{H}_N^H \right]^H \cdot \sum_{i=1}^{N} \mathbf{W}_T \mathbf{p}_i a_i + \mathbf{n}_0 \\ &= \left[\sum_{i=1}^{N} \left(\mathbf{H}_1 \mathbf{W}_T \mathbf{p}_i \right)^H a_i \cdots \sum_{i=1}^{N} \left(\mathbf{H}_N \mathbf{W}_T \mathbf{p}_i \right)^H a_i \right]^H + \mathbf{n}_0 \end{aligned} \tag{6}$$

where $\mathbf{n}_0 \in \mathbb{C}^{\left(\sum_{i=1}^{N} N_R^i \right) \times 1}$ denotes the whole noise vector of N UEs. For UE u, its received signals before the RX-beamformer module can be expressed as

$$\mathbf{Y}_u = \sum_{i=1}^{N} \mathbf{H}_u \mathbf{W}_T \mathbf{p}_i a_i + \mathbf{n}_{0,u} \tag{7}$$

where $\mathbf{n}_{0,u} \in \mathbb{C}^{N_R^u \times 1}$ is the noise vector received by UE u. After multiplying with the RX-beamformer weight vector, denoted by $\mathbf{w}_{R,u} \in \mathbb{C}^{1 \times N_R^u}$, the final received signals of UE u can be written as

$$\begin{aligned} y_u &= \mathbf{w}_{R,u} \mathbf{Y}_u = \sum_{i=1}^{N} \mathbf{W}_{R,u} \mathbf{H}_u \mathbf{W}_T \mathbf{p}_i a_i + \mathbf{w}_{R,u} \mathbf{n}_{0,u} \\ &= \mathbf{w}_{R,u} \mathbf{H}_u \mathbf{W}_T \mathbf{p}_u a_u + \sum_{i \neq u}^{N} \mathbf{w}_{R,u} \mathbf{H}_u \mathbf{W}_T \mathbf{p}_i a_i + \mathbf{w}_{R,u} \mathbf{n}_{0,u} \end{aligned} \tag{8}$$

C. Proposed MU-HBF precoding scheme

From (8), we can find that RX-beamformer can amplify both desired signals and noise without improving the signal to noise ratio (SNR). In fact, the main purpose of RX-beamformer is to prevent receivers from receiving interference from other directions, which euphemistically increases the signal to interference and noise ratio (SINR). In (8), the second item of the final expression is the inter-beam interference, of which $\mathbf{w}_{R,u}$ is determined in the beam alignment phase, $\mathbf{H}_u$ is objectively determined by wireless communication environments and $\mathbf{W}_T$ consisting of N UEs' TX-beamformer weight vectors is also determined in the beam alignment phase. The remaining component $\mathbf{p}_i$ is not determined by objective factors, but generated by base stations with freedom. Therefore, what we can do is to elaborately design the $\mathbf{p}_i$ to mitigate the inter-beam interference, that is,

$$\left(\mathbf{w}_{R,u} \mathbf{H}_u \mathbf{W}_T \right) \mathbf{p}_i = 0, \ \ \forall \ u \neq i \tag{9}$$

For clarity, we define $\mathbf{w}_{R,u} \mathbf{H}_u \mathbf{W}_T$=$\mathbf{h}_{e,u} \in \mathbb{C}^{1 \times N_T^c}$. According to the BD theory in [9], [10], we need to first construct the following effective channel matrix that contains the effective channel gains of all UEs except for UE u

$$\widetilde{\mathbf{H}}_{e,u} = \left[(\mathbf{h}_{e,1})^H ... (\mathbf{h}_{e,u-1})^H (\mathbf{h}_{e,u+1})^H ... (\mathbf{h}_{e,N})^H \right]^H \tag{10}$$

Then, (8) is equivalent to

$$\widetilde{\mathbf{h}}_{e,u} \cdot \mathbf{p}_u = \mathbf{0}_{(N-1) \times 1} \tag{11}$$

which implies that the BB precoding vector of UE u must be designed to lie in the null space of $\widetilde{\mathbf{H}}_{e,u}$. The singular value decomposition (SVD) of $\widetilde{\mathbf{H}}_{e,u}$ can be expressed as

$$\widetilde{\mathbf{H}}_{e,u} = \mathbf{U}_u \cdot \left[\mathbf{\Sigma}_u \ \mathbf{0}_{(N-1) \times \left(N_T^c - (N-1) \right)} \right] \cdot \begin{bmatrix} \left(\mathbf{V}_u{}^{(1)} \right)^H \\ \left(\mathbf{V}_u{}^{(0)} \right)^H \end{bmatrix} \tag{12}$$

where $\mathbf{U}_u \in \mathbb{C}^{(N-1) \times (N-1)}$is a unitary matrix. $\mathbf{\Sigma}_u \in \mathbb{C}^{(N-1) \times (N-1)}$is a diagonal matrix. $\left(\mathbf{V}_u{}^{(1)} \right)^H \in \mathbb{C}^{(N-1) \times N_T^c}$ and $\left(\mathbf{V}_u{}^{(0)} \right)^H \in \mathbb{C}^{(N_T^c - (N-1)) \times N_T^c}$ are composed of right singular vectors that correspond to non-zero singular values and zero singular values, respectively. According to [9], [10], we have

$$\widetilde{\mathbf{H}}_{e,u} \cdot \mathbf{V}_u{}^{(0)} = \mathbf{0} \tag{13}$$

That is, $\mathbf{V}_u{}^{(0)}$ is the null space of $\widetilde{\mathbf{H}}_{e,u}$, and when a signal is transmitted in the direction of $\mathbf{V}_u{}^{(0)}$, all but UE u receive no signal at all. Therefore, we can choose any column of $\mathbf{V}_u{}^{(0)} \in \mathbb{C}^{N_T^c \times (N_T^c - (N-1))}$ as the precoding vector of UE u. If $N = N_T^c$, $\mathbf{V}_u{}^{(0)} \in \mathbb{C}^{N_T^c \times 1}$can be directly used for precoding the UE u signal.

Thanks to the proposed MU-HBF precoding scheme, the final signal received by UE u without interference from other UEs can be expressed as

$$y_u = \mathbf{w}_{R,u} \mathbf{H}_u \mathbf{W}_T \mathbf{p}_u a_u + \mathbf{w}_{R,u} \mathbf{n}_{0,u} \tag{14}$$

III. Feedback Analysis

Based on the above analysis, in order to generate the precoding matrix to mitigate inter-beam interference, a base station requires every UE to feed back its wireless channel matrix $\mathbf{H}_u$, the selected RX-beamformer weight vector $\mathbf{W}_{R,u}$ and the selected TX-beamformer weight vector $\mathbf{W}_{T,u}$. Note that beamforming weight vectors depend on antenna array structures. For example, an uniform linear array gives the beamforming weight vector as

$$\mathbf{\Lambda}\left(\theta, M\right)=\frac{1}{\sqrt{M}}\left[1\ e^{-j\frac{2\pi}{\lambda}d\cos\theta}....e^{-j(M-1)\frac{2\pi}{\lambda}d\cos\theta}\right] \quad (15)$$

where θ is the desired direction. M is the number of antennas. d is the spacing distance between two antennas, and λ is the wave length. For UE u, with a θ_u transmitting direction and a $\varphi_u$receiving direction, its corresponding TX-beamformer and RX-beamformer weight vectors are $\mathbf{w}_{T,u}=\mathbf{\Lambda}\left(\theta_u, N_T\right)$ and $\mathbf{w}_{R,u}$=$\mathbf{\Lambda}\left(\varphi_u, N_R^u\right)$, respectively. Considering the limited feedback resources, all feedbacks can be based on codebooks. Nevertheless, the design of feedback codebooks is beyond this paper.

For mmWave communication systems, directional beamforming is an effective technology to focus the signal energy in desired directions to compensate the unfavorable path loss of mmWave-bands. However, the negative impact of directionality of beamforming is its blindness outside the beam, making it less effective in wireless link establishments, user tracking and feedback processes [2]. Practically, as discussed above, feedback is a crucial stage of the proposed MU-HBF precoding scheme. Therefore, in this paper, the C/U-plane decoupled network architecture is applied to address this issue, in which omnidirectional macro-cells operating at microwave cellular bands are responsible to transmit and receive the important control signaling including feedback, and then forward it to directional mmWave small cells via front-hauls. In this way, the important control signaling, which is omnidirectionally radiated in cellular macro-cells, can be reliably and timely exchanged between UEs and directional mmWave small cells.

IV. Performance Evaluation

According to [1], [2], small-scale wireless channels of mmWave-bands are partial to LOS (Line of Sight) accompanied with low-order scattered non-LOS (NLOS) components. Therefore, the small-scale wireless channel used in the simulation is modeled as $\mathbf{H}_{u,small-scale}=\sqrt{K}\mathbf{H}_{u,LOS}+\mathbf{H}_{u,Rayleigh}$ [10], where K is the Rician factor, $\mathbf{H}_{u,Rayleigh}$ is the NLOS Rayleigh channel of UE u, and

$$\mathbf{H}_{u,LOS}=\begin{bmatrix}1\\ e^{j\frac{2\pi}{\lambda}d\cos\varphi_u}\\ \vdots\\ e^{j\frac{2\pi}{\lambda}d(N_R^u-1)\cos\varphi_u}\end{bmatrix}\cdot\begin{bmatrix}1\\ e^{j\frac{2\pi}{\lambda}d\cos\theta_u}\\ \vdots\\ e^{j\frac{2\pi}{\lambda}d(N_T-1)\cos\theta_u}\end{bmatrix}^T \quad (16)$$

Through the Monte Carlo simulation in MATLAB, the bit error rate (BER) and spectrum efficiency performance comparisons between the conventional SDMA scheme and the proposed MU-HBF precoding scheme under user closely co-located scenarios are conducted. Here, the conventional SDMA scheme means users are distinguished by directional beams without precoding. By mapping the conventional S-DMA scheme to Fig. 2, the corresponding precoding vector of UE u is equivalent to $\mathbf{p}_u\left(1\right)=\frac{1}{\sqrt{N_T^c}}[1...1]^T$. Detailed simulation parameter values are listed in Fig. 3 [8]. The large-scale path loss model used here is $92.4+20\lg f_c\left(GHz\right)+20\lg D\left(km\right)$ [11], where f_c is the center frequency, set as 28GHz. D is the signal propagation distance. For clarity and without loss of generality, here two UEs are taken into account. Nevertheless, the same analysis method can also be generalized to multiple users. They are closely co-located with the same large-scale path loss and an angle difference of $\Delta\theta=\pi/20$. According to [12], only if $\left|\cos\left(\theta_1\right)-\cos\left(\theta_2\right)\right|\geq\frac{\lambda}{N_T d}$ can the two UEs be distinguished by directional beams. Nevertheless, under the parameter values of this simulation, what we can get is $\left|\cos\left(\theta_1\right)-\cos\left(\theta_2\right)\right|$=0.1416 $<\frac{\lambda}{N_T d}=$ 0.25. Therefore, for the conventional SDMA scheme, the two UEs cannot be distinguished by directional beams due to the high inter-beam interference.

In Fig. 3, the BER performance comparison between two schemes is shown, from which we can see the proposed MU-HBF precoding scheme can achieve higher BER performance than the conventional SDMA scheme under user closely co-located scenarios. To give an overall perspective of performance, the path loss value range of the x-axis is set to (80,160)dB. Nevertheless, at the point with 120dB path loss, the communication distance reaches up to D=0.86km, which is already enough for mmWave communication systems [1], [7]. And at this point, as shown in Fig. 3, under the proposed scheme the corresponding BER is reduced from 0.24 to 0.002917. As aforementioned, for user closely co-located scenarios, UEs are interference-limited in the conventional SDMA scheme. Take UE 1 for example, whose SINR can be expressed as $SINR_1=\frac{\frac{p_{t,1}}{PL}\left\|\mathbf{w}_{R,1}\mathbf{H}_1(\mathbf{w}_{T1})^T\right\|^2}{\left\|\mathbf{w}_{R,1}\mathbf{n}_{0,1}\right\|^2+\frac{p_{t,2}}{PL}\left\|\mathbf{w}_{R,1}\mathbf{H}_1(\mathbf{w}_{T,2})^T\right\|^2}$, where p_t is the transmit power and PL is the large-scale path loss. According to [12], the interference between two beams is related to the angle differences between them. The closer the two UEs are , the higher the leaked signal power to each other is, i.e., the inter-beam interference. Under user closely co-located scenarios, the noise power is relatively lower than the interference power. As a result, the BER curve of the conventional SDMA scheme in Fig.3 does not obviously change along with the path loss and almost keeps at a constant level under low path loss.

Alternatively, to avoid inter-beam interference in user closely co-located scenarios, we may also use time division multiple access (TDMA) technology to serve UEs, that is, only an UE is served with a beam in a given time slot. Nevertheless, as shown in Fig. 4, compared with the proposed MU-HBF precoding scheme which allows UEs to concurrently reuse the same radio resources, the conventional scheme may result in lower spectrum efficiency. In the region with low path loss, for instance at the point of 80dB path loss, the performance improvement of the proposed scheme is 90.23%. As the large-scale path loss grows to 120dB, the performance improvement is still as high as 72.21%. With the large-scale path loss increasing continuously, the spectrum efficiency of two schemes reduce to zero.

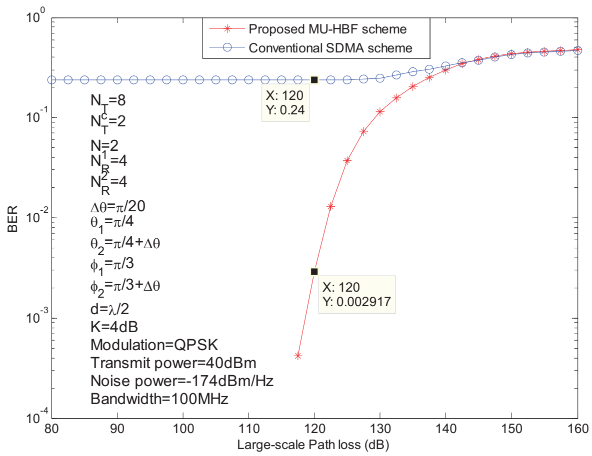

Fig. 3. BER performance comparison.

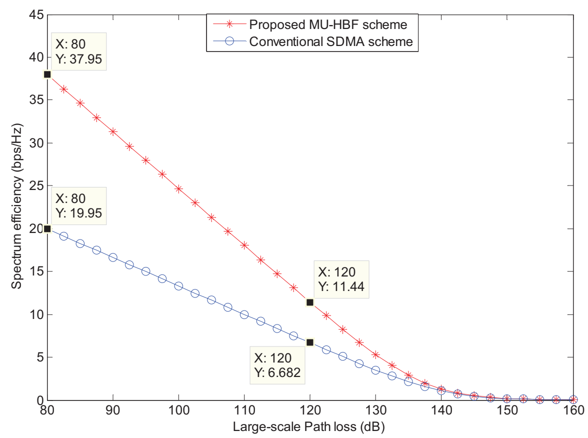

Fig. 4. Spectrum efficiency performance comparison.

V. Conclusion

In this paper, we have proposed an MU-HBF precoding scheme for user closely co-located mmWave beamforming scenarios. Analysis and simulations have demonstrated the performance improvements of the proposed scheme. Besides, the C/U-plane decoupled network architecture is used to avoid the blind effect of directional beamforming in feedback, in which omnidirectional cellular macro-cells help to forward important feedback via front-hauls. In our future work, to get the gain of multiple streams for each user, we will study the precoding scheme for the user closely co-located scenario where each user is equipped with multiple RF chains. Besides, the beam alignments and tracking under dense user scenarios are also good research directions.

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