Hybrid Beamforming for Relay-Aided mmWave Backhaul links

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Abstract. Massive multiple-input multiple-output (MIMO) and millimeter-wave (mmWave) technologies have emerged as a promising solution to enhance the backhaul wireless link in 5G Heterogeneous networks (HetNets). These mmWave backhaul links, however, are very susceptible to a significant path loss due to the blockage of the line-of-sight and massive antenna arrays may not be sufficient to alleviate such losses. To this end, relays are usually deployed to provide alternative routes that help boost links with high path loss. In this paper, therefore, we consider using relay base stations (RBS) in mmWave backhaul links between small cell base stations (SBS) and a macro-cell base station (MBS). It is assumed that the SBSs, the RBSs, and the MBS are all equipped with massive antenna arrays employing hybrid analog and digital beamforming. The analog beamformers are based on the selection of fixed multi-beams using a constrained eigenbeamforming scheme while the digital beamformers are based on the maximum ratio transmission and maximum ratio combining (MRT/MRC) schemes that maximize the transmit and receive SINRs of the effective channels created by the actual channel and the analog beamformer. The performance evaluation in terms of the beampatterns and the ergodic channel capacity shows that the proposed HBF scheme achieves near-optimal performance with only 4 RF chains and requires considerably less computational complexity.

Keywords: Hybrid beamforming, HetNets, Relays, Massive MIMO, mmWaves.

1 Introduction

Recently, millimeter-wave (mmWave) massive multiple-input multiple-output (MIMO) technologies [1],[2],[3],[4],[5][6] have emerged as a promising solution to enhance the backhaul wireless link in 5G Heterogeneous networks (HetNets) [5],[6],[7],[8],[9],[10],[11]. On the one hand, the mmWave backhaul links can provide the Gigahertz bandwidth that can be achieved by conventional optical fiber link without the restriction of deployment and installation of small cells. On the other hand, because of the small wavelength of mm-waves, a large number of antennas can be deployed and can provide a high gain to compensate for the pathloss of the mmWaves. However, mmWave massive antenna arrays work better in the presence of line-of-sight (LoS) and may not be sufficient to alleviate the severe losses due to the blockage of these LoSs. To overcome this problem, relay assisted backhaul link can be incorporated to efficiently transmit the signals between the small cell base stations (SBS) and the macro-cell base station (MBS). In this paper, therefore, we consider using relay base stations (RBS) in mmWave backhaul links between the SBSs and the MBS, where the SBSs, the RBSs, and the MBS are all

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equipped with massive antenna arrays. Moreover, in order to reduce the number of RF chains required by fully-digital beamforming massive arrays, we employ a combination of RF analog beamformers and baseband digital beamformers, known as hybrid beamforming (HBF) [12],[13],[14],[15],[16],[17],[18]. In such a hybrid configuration, the analog RF beamforming matrix, built from analog hardware like phase-shifters, is used to connect M_a antenna elements to N_{RF} RF chains, where $N_{RF} < M_a$. Previous studies on hybrid massive MIMO mainly focused on single-user systems and exploited the sparse nature of the mmWave to develop low-complexity hybrid precoding algorithms [12],[13],[14]. MU-MIMO cases were studied in [15],[16],[17]. In [15] a scheme called "Joint Spatial Division Multiplexing" (JSDM) was proposed to create multiple "virtual sectors" which reduces signaling overhead and computational complexity of downlink training and uplink feedback. In [16],[17] it was shown that the required number of RF chains only needs to be twice the number of data streams in order to achieve the same performance of any fully-digital beamforming scheme. These studies, however, did not consider HBF in the context of HetNets and focused primarily on macro-cellular systems. In this paper, we propose to extend HBF to relay-assisted backhaul links where the SBSs, the RBSs, and the MBS are all equipped with massive hybrid antenna arrays. On the one hand, the analog beamformers are based on the creation of the best fixed multi-beams by eigendecomposition of the backhaul channels. On the other hand, the digital beamformers are based on the maximum ratio transmission and maximum ratio combining (MRT/MRC) schemes [19] that maximizes the transmit and receive SINRs of the effective channels created by the cascade of the analog beamforming weights and the actual channel.

2 System Model

We consider the backhaul uplink in the HetNet of Figure 1, where K SBSs are connected to the MBS through an RBS using a two-hop relaying path. It is assumed that the RBS, the SBSs, and the MBS are equipped with $M_a - element$ transmitting/receiving massive hybrid antenna arrays. For the SBSs-to-relay link, it is assumed that the number of transmit/receive RF chains is identical and is equal to the number of data streams N_{RF}. On the other hand, it assumed that for the relay-to-MBS link, the number of transmit/receive RF chains is identical and is equal to the number of SBSs K.

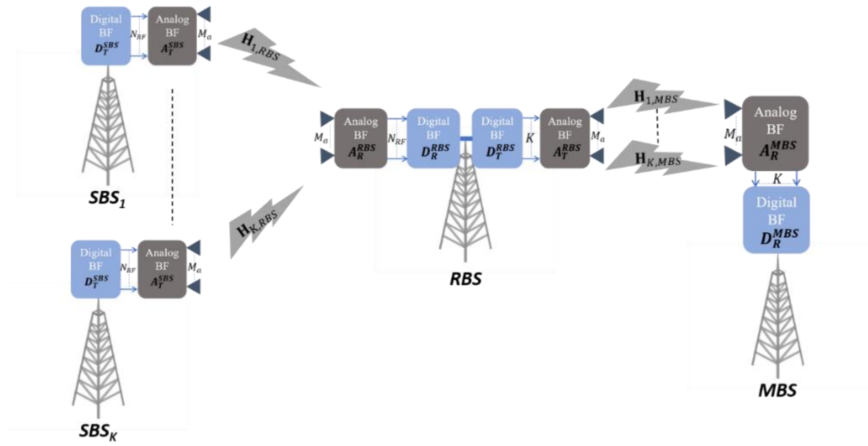

Fig. 1. System model: K SBSs connected to an MBS through two-hop relaying links.

2.1 SBSs-to-Relay Link

The k^{th} SBS applies its signal $\boldsymbol{s}_k^{SBS}$ of N_{RF} data streams to an $N_{RF} \times N_{RF}$ diagonal transmit digital beamforming weight matrix $\boldsymbol{D}_{T,k}^{SBS}$ followed by an $M_a \times N_{RF}$ transmit analog beamforming matrix $\boldsymbol{A}_{T,k}^{SBS}$. If we denote the combined digital-analog transmit beamformer for the k^{th} SBS as $\mathbf{w}_{T,k}^{SBS} = \boldsymbol{A}_{T,k}^{SBS}\boldsymbol{D}_{T,k}^{SBS}$, then the $M_a \times 1$ transmitted signal $\boldsymbol{x}_{T,k}^{SBS}$ at the output of the antenna array of the k^{th} SBS can expressed as

$$\boldsymbol{x}_{T,k}^{SBS} = \mathbf{w}_{T,k}^{SBS}\boldsymbol{s}_k^{SBS}, \tag{1}$$

and the array output of the RBS can be written as

$$\boldsymbol{y}_{RBS} = \sum_{k=1}^{K} \mathbf{H}_{k,RBS}\mathbf{w}_{T,k}^{\boldsymbol{SBS}}\,\boldsymbol{s}_k^{SBS} + \mathbf{n}_{RBS}, \tag{2}$$

where $\boldsymbol{y}_{RBS}$ is the $M_a \times 1$ vector containing the outputs of the $M_a -$ element antenna array at the RBS, $\mathbf{H}_{k,RBS}$ is the $M_a \times M_a$ channel matrix representing the transfer functions from the M_a −element antenna array of the k^{th} SBS to the M_a −element antenna array of the RBS, and $\mathbf{n}_{RBS}$ is the received $M_a \times 1$ complex additive white Gaussian noise vector at the RBS.

The RBS detects the k^{th} SBS signal by applying the output of the array $\boldsymbol{y}_{RBS}$ to the $N_{RF} \times M_a$ receiving analog weight matrix, $\boldsymbol{A}_{R,k}^{RBS}$, followed by a diagonal $N_{RF} \times N_{RF}$ receive digital beamforming weight matrix $\boldsymbol{D}_{R,k}^{RBS}$. If we denote the combined digital-analog receive beamformer for the k^{th} SBS as $\mathbf{w}_{R,k}^{RBS} = \boldsymbol{A}_{R,k}^{RBS}\boldsymbol{D}_{R,k}^{RBS}$, then the detection of the the k^{th} SBS signal by the RBS can be expressed as

$$\widehat{\boldsymbol{x}}_{k,RBS} = \left(\mathbf{w}_{R,k}^{RBS}\right)^H \boldsymbol{y}_{RBS} = \mathbf{S}_k^{RBS} + \mathbf{S}_{I_k}^{RBS} + \mathbf{N}_{RBS}, \tag{3}$$

where $\mathbf{S}_k^{RBS} = \left(\mathbf{w}_{R,k}^{RBS}\right)^H \mathbf{H}_{k,RBS}\mathbf{w}_{T,k}^{SBS}\boldsymbol{s}_k^{SBS}$ is the k^{th} SBS received signal, $\mathbf{S}_{I_k}^{RBS} = \left(\mathbf{w}_{R,k}^{RBS}\right)^H \sum_{i=1,i\neq k}^{K} \mathbf{H}_{i,RBS}\,\mathbf{w}_{T,i}^{SBS}\boldsymbol{s}_i^{SBS}$ is the multiple-access interference (MAI) from the $K-1$ other SBSs, and $\mathbf{N}_{RBS} = \left(\mathbf{w}_{R,k}^{RBS}\right)^H \mathbf{n}_{RBS}$ is the noise signal at the array output of the RBS.

Assuming that $\boldsymbol{s}_k^{SBS}$ are complex-valued random variables with normalized unit power, i.e., $\mathbb{E}\left[\boldsymbol{s}_k\,\boldsymbol{s}_k^H\right] = \mathrm{I}_{N_{RF}}$, we can express the SINR at the RBS for the k^{th} SBS as

$$\begin{aligned}\gamma_k^{RBS} &= \frac{\left(\boldsymbol{D}_{R,k}^{RBS}\right)^H \left(\boldsymbol{A}_{R,k}^{RBS}\right)^H \mathbf{H}_{k,RBS}\boldsymbol{A}_{T,k}^{SBS}\boldsymbol{D}_{T,k}^{SBS}\left(\boldsymbol{D}_{T,k}^{SBS}\right)^H\left(\boldsymbol{A}_{T,k}^{SBS}\right)^H \mathbf{H}_{k,RBS}^H \boldsymbol{A}_{R,k}^{RBS}\boldsymbol{D}_{R,k}^{RBS}}{\left(\mathbf{w}_{R,k}^{RBS}\right)^H \mathbf{B}_{RBS}\left(\mathbf{w}_{R,k}^{RBS}\right)} \\ &= \frac{\left|\left(\boldsymbol{D}_{R,k}^{RBS}\right)^H \boldsymbol{\mathcal{H}}_{k,RBS}\boldsymbol{D}_{T,k}^{SBS}\right|^2}{\left(\mathbf{w}_{R,k}^{RBS}\right)^H \mathbf{B}_{k,RBS}\left(\mathbf{w}_{R,k}^{RBS}\right)},\end{aligned} \tag{4}$$

where $\boldsymbol{\mathcal{H}}_{k,RBS} = \left(\boldsymbol{A}_{R,k}^{RBS}\right)^H \mathbf{H}_{k,RBS}\left(\boldsymbol{A}_{T,k}^{SBS}\right)$ represents the effective channel and $\mathbf{B}_{k,RBS} = \sum_{i=1,i\neq k}^{K} \mathbf{H}_{i,RBS}\mathbf{w}_{T,i}^{SBS}\left(\mathbf{w}_{T,i}^{SBS}\right)^H \mathbf{H}_{i,RBS}^H + \sigma_n^2 \mathbf{I}_{M_a}$ is the covariance matrix of the interference-plus-noise at the RBS.

2.2 Relay-to-MBS Link

The RBS applies the received k^{th} SBS signal, $\widehat{\boldsymbol{x}}_{k,RBS}$, to the k^{th} selected beam port of the transmit hybrid beamformer. For simplicity, we will assume that each SBS signal is forwarded to the MBS using a separate beam (i.e., a separate RF chain). Thus, if we reorganize the K SBSs' signals into a vector as $\hat{\boldsymbol{x}}_{RBS} = [\hat{\boldsymbol{x}}_{1,RBS}, \hat{\boldsymbol{x}}_{2,RBS}, \cdots, \hat{\boldsymbol{x}}_{K,RBS}]$ and we denote the RBS transmit analog beamformer as $\boldsymbol{A}_T^{RBS} = \left[\boldsymbol{a}_{T,1}^{RBS}, \boldsymbol{a}_{T,2}^{RBS}, \cdots, \boldsymbol{a}_{T,K}^{RBS}\right]$ and the digital beamformer as $\boldsymbol{D}_T^{RBS} = diag\left[d_{R,1}^{MBS}, d_{R,2}^{MBS} \ldots\ d_{R,K}^{MBS}\right]$, then the $M_a \times K$ transmitted signal, $\boldsymbol{s}_T^{RBS}$, at the output of the RBS antenna array can be expressed as

$$\boldsymbol{s}_T^{RBS} = \boldsymbol{A}_T^{RBS}\boldsymbol{D}_T^{RBS}\hat{\boldsymbol{x}}_{RBS}\,, \tag{5}$$

and the received signal at the array output of the MBS can be written as

$$\boldsymbol{y}_{MBS} = \mathbf{H}_{MBS}\boldsymbol{A}_T^{RBS}\boldsymbol{D}_T^{RBS}\hat{\boldsymbol{x}}_{RBS} + \mathbf{n}_{MBS}\,, \tag{6}$$

where $\boldsymbol{y}_{MBS}$ is the $M_a \times 1$ vector containing the outputs of the $M_a -$ element antenna array at the MBS, $\mathbf{H}_{MBS}$ is the $M_a \times M_a$ channel matrix between the RBS and the MBS, $\mathbf{n}_{MBS}$ is the received $M_a \times 1$ complex additive white Gaussian noise vector at the MBS.

The output of the array $\boldsymbol{y}_{MBS}$ is applied to the $M_a \times K$ receiving analog weight matrix of the MBS, $(\boldsymbol{A}_R^{MBS})^H$, followed by the $K \times K$ receive digital beamforming weight matrix $(\boldsymbol{D}_R^{MBS})^H$, then the detection of the K SBSs' signals by the MBS can be expressed as

$$\begin{aligned}\hat{\boldsymbol{x}}_{MBS} &= (\boldsymbol{D}_R^{MBS})^H(\boldsymbol{A}_R^{MBS})^H\boldsymbol{y}_{MBS} \\ &= (\boldsymbol{D}_R^{MBS})^H(\boldsymbol{A}_R^{MBS})^H\mathbf{H}_{MBS}(\boldsymbol{A}_T^{RBS})^H(\boldsymbol{D}_T^{RBS})^H\hat{\boldsymbol{x}}_{RBS} + (\boldsymbol{D}_R^{MBS})^H(\boldsymbol{A}_R^{MBS})^H\mathbf{n}_{MBS}\,,\end{aligned} \tag{7}$$

which results in the detection of the k^{th} SBS signal being expressed as

$$\hat{\boldsymbol{x}}_{k,MBS} = \left(d_{R,k}^{MBS}\right)^*\left(\boldsymbol{a}_{R,k}^{MBS}\right)^H\mathbf{H}_{MBS}\boldsymbol{a}_{T,k}^{RBS}\left(d_{T,k}^{RBS}\right)\hat{\boldsymbol{x}}_{k,RBS} + \left(d_{R,k}^{MBS}\right)^*\left(\boldsymbol{a}_{R,k}^{MBS}\right)^H\mathbf{n}_{MBS}\,, \tag{8}$$

Using (3), and denoting $\boldsymbol{\mathcal{H}}_{k,MBS} = \left(\boldsymbol{a}_{R,k}^{MBS}\right)^H\mathbf{H}_{MBS}\boldsymbol{a}_{T,k}^{RBS}$ as the effective channel, $\hat{\boldsymbol{x}}_{k,MBS}$ and the SINR of the k^{th} SBS at the MBS can be expressed, respectively, as

$$\begin{aligned}\hat{x}_{k,MBS} = \left(d_{R,k}^{MBS}\right)^*\left(d_{T,k}^{RBS}\right)\boldsymbol{\mathcal{H}}_{k,MBS}\left(\mathbf{S}_k^{RBS} + \mathbf{S}_{I_k}^{RBS} + \mathbf{N}_{RBS}\right) \\ + \left(d_{R,k}^{MBS}\right)^*\left(\boldsymbol{a}_{R,k}^{MBS}\right)^H\mathbf{n}_{MBS}\,,\end{aligned} \tag{9}$$

$$\gamma_k^{MBS} = \frac{\left|\left(d_{R,k}^{MBS}\right)^*\left(d_{T,k}^{RBS}\right)\boldsymbol{\mathcal{H}}_{k,MBS}\mathbf{S}_k^{RBS}\right|^{\mathbf{2}}}{\left(d_{R,k}^{MBS}\right)^*\mathbf{B}_{k,MBS}d_{R,k}^{MBS}} \tag{10}$$

where $\mathbf{B}_{k,MBS}$ is the covariance matrix of the interference-plus-noise at the MBS and is given by $\mathbf{B}_{k,MBS} = \mathbf{B}_{I_k} + \mathbf{B}_N$, with $\mathbf{B}_N = \left|\left(d_{T,k}^{MBS}\right)\right|^2\boldsymbol{\mathcal{H}}_{k,MBS}\mathbf{N}_{RBS}\mathbf{N}_{RBS}^H\boldsymbol{\mathcal{H}}_{k,MBS}^H + \sigma_{n_{MBS}}^2\left(\boldsymbol{a}_{k,R}^{MBS}\right)^H\boldsymbol{a}_{k,R}^{MBS}$ and $\mathbf{B}_{I_k} = \left|\left(d_{T,k}^{MBS}\right)\right|^2\boldsymbol{\mathcal{H}}_{k,MBS}\mathbf{S}_{I_k}^{RBS}\left(\mathbf{S}_{I_k}^{RBS}\right)^H\boldsymbol{\mathcal{H}}_{k,MBS}^H$.

Assuming that the transmit and receive digital beamformer are identical, (10) can be simplified as

$$\gamma_k^{MBS} = \mathbf{B}_{k,MBS}^{-\mathbf{1}}\left|\boldsymbol{\mathcal{H}}_{k,MBS}\left(\boldsymbol{D}_{R,k}^{RBS}\right)^H\boldsymbol{\mathcal{H}}_{k,RBS}\boldsymbol{D}_{T,k}^{SBS}\right|^{\mathbf{2}}\,, \tag{11}$$

2.3 Channel Model

For the two-hop relaying links, we consider mmWave propagation channels with limited scattering, which can be modelled by the narrowband clustered channel representation, based on the extended Saleh-Valenzuela model [13]. We assume a scattering environment with N_{cl} scattering clusters randomly distributed in space and within each cluster, there are N_{ray} closely located scatterers.

The channel matrix between the k^{th} SBS and the RBS and between the RBS and the MBS can be expressed, respectively, as

$$\mathbf{H}_{k,RBS} = \sqrt{\frac{M_a^2}{N_{cl}N_{ray}}}\sum_{i}^{N_{cl}}\sum_{j=1}^{N_{ray}} \alpha_{ij}\, \boldsymbol{a}_{RBS}(\emptyset_{i,j}^{r}, \theta_{i,j}^{r})\boldsymbol{a}_{k,SBS}^{*}(\emptyset_{i,j}^{t}, \theta_{i,j}^{t}) \,, \tag{12}$$

$$\mathbf{H}_{MBS} = \sqrt{\frac{M_a^2}{N_{cl}N_{ray}}}\sum_{i}^{N_{cl}}\sum_{j=1}^{N_{ray}} \alpha_{ij}\, \boldsymbol{a}_{MBS}(\emptyset_{i,j}^{r}, \theta_{i,j}^{r})\boldsymbol{a}_{RBS}^{*}(\emptyset_{i,j}^{t}, \theta_{i,j}^{t}) \,, \tag{13}$$

where α_{ij} are the complex gains of the j^{th} ray in the i^{th} scattering cluster and are assumed i.i.d $\mathcal{CN}(0, \sigma_{\alpha,i}^2)$ with $\sigma_{\alpha,i}^2$ representing the average power of the i^{th} cluster, $\emptyset_{i,j}^{r}$ and $\emptyset_{i,j}^{t}$ are the azimuth angles of arrival and departure respectively, $\theta_{i,j}^{r}$ and $\theta_{i,j}^{t}$ are the elevation angles of arrival and departure respectively, $\boldsymbol{a}_{RBS}(\emptyset_{i,j}^{r}, \theta_{i,j}^{r})$, $\boldsymbol{a}_{MBS}(\emptyset_{i,j}^{r}, \theta_{i,j}^{r})$, and $\boldsymbol{a}_{k,SBS}(\emptyset_{i,j}^{t}, \theta_{i,j}^{t})$ represent the normalized array response vectors of the RBS, MBS, and the k^{th} SBS respectively.

It is assumed that the N_{ray} azimuth and elevation angles, $\emptyset_{i,j}^{r,t}$ and $\theta_{i,j}^{r,t}$ are randomly distributed with a uniformly-random mean cluster angle of $\emptyset_{i}^{r,t}$ and $\theta_{i}^{r,t}$ respectively, and a constant angular spread of $\sigma_{\emptyset^{r,t}}$ and $\sigma_{\theta^{r,t}}$ respectively.

3 Proposed Hybrid Beamforming

The proposed hybrid beamforming is performed in two stages. First, the analog beamformers at the SBSs-to-RBS and RBS-to-MBS links select a set of beams using eigenbeamforming and imposing the phase-only constraint on each selected eigenvector. Beam selection can be realized by a network of RF switches that feed the data streams to the best ports (selected eigenvectors) of a Butler matrix. Once the analog beamformer is known, the transmit and receive digital weight vectors are obtained using the SINR-based MRT/MRC schemes.

3.1 SBSs-to-RBS

The transmit analog weight vectors of the k^{th} SBS are based on eigen-beamforming scheme and are given by

$$\begin{array}{c} \boldsymbol{A}_{T,k}^{SBS} = \left[\boldsymbol{a}_{T,k,1}^{SBS}, \boldsymbol{a}_{T,k,2}^{SBS}, \cdots, \boldsymbol{a}_{T,k,L_d}^{SBS}\right] \\ subject\ to\ \left|\boldsymbol{A}_{T,k}^{SBS}(i,j)\right|^2 = 1 \end{array} , \tag{14}$$

where $\boldsymbol{a}_{T,k,i}^{SBS}$ denote the i^{th} selected $N_{RF} \times 1$ eigenvector corresponding to the i^{th} maximum eigenvalue of $\boldsymbol{H}_{k,\text{RBS}}^{H}\boldsymbol{H}_{k,\text{RBS}}$.

Assuming channel reciprocity, the receive analog weight vectors of the MBS could be chosen as $\boldsymbol{A}_{R,k}^{MBS} = \boldsymbol{A}_{T,k}^{SBS}$.

For fixed analog beamforming weights, $\boldsymbol{A}_{T,k}^{SBS}$ and $\boldsymbol{A}_{R,k}^{MBS}$, the transmit optimal digital weight vector of the k^{th} SBS, $\boldsymbol{D}_{T,k}^{SBS}$, and the receive optimal digital weight vector of the MBS, $\boldsymbol{D}_{R,k}^{MBS}$, are obtained by the MRT/MRC scheme that maximizes (4) and are given by

$$\boldsymbol{D}_{T,k}^{SBS} = \boldsymbol{D}_{R,k}^{MBS} = \boldsymbol{B}_{k,RBS}^{-1}\boldsymbol{\mathcal{H}}_{k,RBS}\boldsymbol{V}_{BL} , \tag{15}$$

where $\boldsymbol{V}_{BL}$ is the eigenvector corresponding to the maximum eigenvalue of $\left(\boldsymbol{\mathcal{H}}_{k,RBS}\right)^{\boldsymbol{H}}\boldsymbol{\mathcal{H}}_{k,RBS}$

3.2 RBS-to-MBS

For the RBS-to-MBS link, the transmit analog weights of the RBS and the receive analog weight vectors of the MBS are based on the singular value decomposition (SVD) of the channel matrix, $\mathbf{H}_{MBS}$:

$$\mathbf{H}_{MBS} = \boldsymbol{U}_{MBS}\, \boldsymbol{\Sigma}\, \boldsymbol{U}_{RBS}^{H} \tag{16}$$

where $\boldsymbol{U}_{MBS} \in \mathbb{C}^{M_a \times K}$ and $\boldsymbol{U}_{RBS} \in \mathbb{C}^{M_a \times K}$ are semi-unitary matrices and $\boldsymbol{\Sigma}$ is an $K \times K$ diagonal matrix with the largest K singular values $\sigma_1, \cdots, \sigma_K$ on its diagonal.

The transmit and receive analog weight matrices of the RBS, and the MBS can then be expressed, respectively, as

$$\begin{gathered}\boldsymbol{A}_{T}^{RBS} = \left[\boldsymbol{a}_{T,1}^{RBS}, \boldsymbol{a}_{T,2}^{RBS}, \cdots, \boldsymbol{a}_{T,K}^{RBS}\right] = \boldsymbol{U}_{RBS} \quad , \\ \boldsymbol{A}_{R}^{MBS} = \left[\boldsymbol{a}_{R,1}^{MBS}, \boldsymbol{a}_{R,2}^{MBS}, \cdots, \boldsymbol{a}_{R,K}^{MBS}\right] = \boldsymbol{U}_{MBS} \ , \\ subject\ to\ |\boldsymbol{A}_{T}^{RBS}(i,j)|^2 = |\boldsymbol{A}_{R}^{MBS}(i,j)|^2 = 1 \ .\end{gathered} \tag{17}$$

Using (7) and (8), $\widehat{\boldsymbol{x}}_{MBS}$ and $\widehat{\boldsymbol{x}}_{k,MBS}$ can be expressed as

$$\widehat{\boldsymbol{x}}_{MBS} = (\boldsymbol{D}_{R}^{MBS})^{H}\, \boldsymbol{\Sigma}\, \boldsymbol{D}_{T}^{RBS}\widehat{\boldsymbol{x}}_{RBS} + (\boldsymbol{D}_{R}^{MBS})^{H}(\boldsymbol{A}_{R}^{MBS})^{H}\mathbf{n}_{MBS} , \tag{18}$$

$$\begin{aligned}\hat{x}_{k,MBS} &= \sigma_k\left(d_{R,k}^{MBS}\right)^{*}\left(d_{T,k}^{RBS}\right)\widehat{\boldsymbol{x}}_{k,RBS} + \left(d_{R,k}^{MBS}\right)^{*}\left(\boldsymbol{a}_{R,k}^{MBS}\right)^{H}\mathbf{n}_{MBS} \\ &= \sigma_k\left(d_{R,k}^{MBS}\right)^{*}\left(d_{T,k}^{RBS}\right)\left(\mathbf{S}_{k}^{RBS} + \mathbf{S}_{I_k}^{RBS} + \mathbf{N}_{RBS}\right) + \left(d_{R,k}^{MBS}\right)^{*}\left(\boldsymbol{a}_{R,k}^{MBS}\right)^{H}\mathbf{n}_{MBS}\end{aligned} , \tag{19}$$

The SINR of the k^{th} SBS at the MBS, given in (11), can then be simplified as

$$\gamma_k^{MBS} = \mathbf{B}_{k,MBS}^{-1}\left|\sigma_k\left(\boldsymbol{D}_{R,k}^{RBS}\right)^{H}\boldsymbol{\mathcal{H}}_{k,RBS}\boldsymbol{D}_{T,k}^{SBS}\right|^{2} , \tag{20}$$

where $\mathbf{B}_{k,MBS} = \sigma_{\mathrm{k}}^2\left|\left(d_{T,k}^{RBS}\right)\right|^2\left(\mathbf{S}_{I_k}^{RBS}\left(\mathbf{S}_{I_k}^{RBS}\right)^{H} + \mathbf{N}_{RBS}\mathbf{N}_{RBS}^{H}\right) + \sigma_{n_{MBS}}^2\left|\left(d_{T,k}^{RBS}\right)\right|^2\left(\boldsymbol{a}_{k,R}^{MBS}\right)^{H}\boldsymbol{a}_{k,R}^{MBS}$,

Note that the SINR, γ_k^{MBS}, given in (20) is independent of the digital beamformers, $\boldsymbol{D}_{T}^{RBS}$ and $(\boldsymbol{D}_{R}^{MBS})^{H}$, of the RBS-to-MBS link. This property enables us to choose the optimal digital beamformers that satisfy $\boldsymbol{D}_{T}^{RBS}(\boldsymbol{D}_{R}^{MBS})^{H} \propto \mathrm{I}_K$ or simply choose $\boldsymbol{D}_{T}^{RBS} \propto \mathrm{I}_K$ and $\boldsymbol{D}_{R}^{MBS} \propto \mathrm{I}_K$.

The ergodic channel capacity for each user l_s is given by [20],

$$\mathcal{C} = \mathbb{E}[log_2\{1 + \gamma_k^{MBS}\}] , \tag{21}$$

where $\mathbb{E}$ [.] denotes the expectation operator.

4 Simulation Results

In our simulation setups, we consider six SBSs (K=6) connected to one macro-cell through one relay station. The SBSs, the RBS, and the MBS use the same number of antennas, $M_a = 64$. The number of RF chains for SBSs-to-RBS links is $N_{RF} = 2 \; or \; 4$. We assume QPSK modulation.

Figure 2 shows the beampattern of the proposed HBF with four RF chains and the optimal fully-digital one for the SBSs-to-RBS links. The optimal beamformer has about four dominant beams that are similar to the selected beams of the proposed HBF, which means that near-optimal performance could be achieved by transmitting data streams through those four beams. Figure 3, on the other hand, compares the ergodic channel capacity of the proposed HBF and the optimal fully-digital one. It is observed that as we increase the number of RF chains, the performance gap between the two schemes is reduced, and the near-optimal solution was achieved by the proposed HBF using four RF chains. Compared to the single cell MU-MIMO case presented in [12],[13],[14], near-optimal performance was obtained with only five RF and for the MU-MIMO case in [16],[17] it was shown that the required number of RF chains could be reduced to two to achieve the fully-digital beamforming performance. However, unlike our case, where we have focused on the backhaul link and assumed a two-hop relay link that connects multiple small cells to a macro cell, these studies focused primarily on macro-cellular systems.

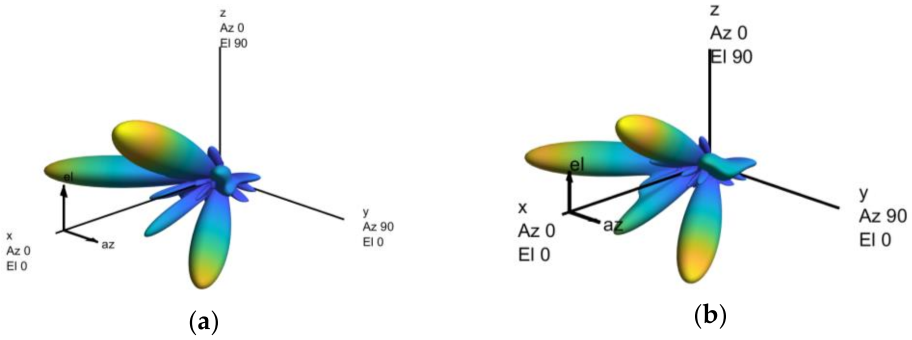

Fig. 2 Beampattern of the access link: (**a**) Proposed HBF, 4 RF chains; (**b**) Optimal beamforming.

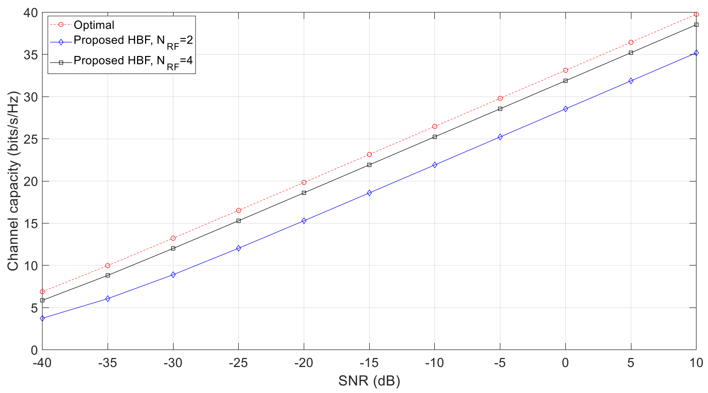

Fig. 3. Channel capacity for a different number of RF chains: Proposed HBF vs optimal

5 Conclusion

In this paper, we extended hybrid beamforming to relay-aided mmWave backhaul links where multiple small cell base stations (SBS) are connected to a macro-cell base station (MBS) through a two-hop backhaul with manageable interference between the SBSs. The performance evaluation in terms of the beampatterns and the ergodic channel capacity shows that the proposed HBF scheme achieves near-optimal performance with only four RF chains and requires considerably less computational complexity.

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