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Wideband hybrid precoder for mmWave multiuser MIMO-OFDM communications

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ABSTRACT

Using millimeter wave (mmWave) transmission for massive multiple input multiple output (MIMO) system can improve system performance and effectively reduce the size of the massive antennas array. However, A wideband beamformer design is needed to take advantage of this wideband channel. In this paper, a downlink multi-user massive MIMO orthogonal frequency division multiplexing (MIMO OFDM) system for mmWave communications is proposed. Each subcarrier channel can be approximated as a narrowband clustered channel, so a narrowband precoder can be applied for each subchannel. The hybrid precoder is implemented in a manner so the digital precoder is obtained for each subcarrier, whilst the analog precoder is common for all subcarriers. A modified “joint spatial division/multiplexing” (JSDM) scheme is used to design the precoder, where each user equipped with more than one antenna. The design of the analog precoder is based on the second order channel statistics to reduce the overhead information need to process and fed back and the subcarrier baseband precoder based on the instantaneous channel state information (CSI). Following the approach of Kronecker channel model, the iteration between the analog beamformers design at both end of link can be avoided. Finally testing the system using various numbers of antennas at base station.

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1. INTRODUCTION

Massive multiple input multiple output (MIMO) is the key technology of fifth generation (5G) wireless communication systems. Theoretically, massive MIMO employs a large number of antennas up to thousands, but only several dozens or hundreds of antennas are practically implemented [1], [2]. In massive MIMO, the base station is generally equipped with a large number of antennas to serve one or multiple users where each user equipped at least with one antenna [3], [4]. Using massive MIMO can provide many benefits for 5G wireless systems by increasing the spatial multiplexing gain and diversity gain which lead to increase system capacity and link reliability, also enhance the spectral efficiency and energy efficiency [5], [6]. By increasing antennas number of massive MIMO system, the physical size of massive MIMO array will be large and practically unfeasible. To overcome this difficulty, massive MIMO system along with millimeter wave transmission (mmWave) are used. Smaller wavelengths enable operations with more antenna elements per system within small area size [6]–[8]. For example, the size of massive MIMO with (8*8) uniform rectangular array (URA) operates at a frequency of 6 GHz is approximately 300 cm^2, while its size when operates at a frequency of 28 GHz is approximately 14 cm^2. For mmWave massive MIMO system, the uniform planar arrays are more considerable so more antenna elements can pack in a compact-sized array and allowing beamforming in the azimuth and elevation domains (3D beamforming) [8], [9].

Operating at mmWave frequencies puts new challenges for 5G massive MIMO such as high path loss due to atmosphere attenuation, propagation challenges due to penetration, and RF chain complexity. The mmWave channels have low rank and it is specular. They tend to have a less multipath components compared to microwave, so the channel matrix is sparse with a smaller number of components due to the geometric nature of the mmWave channel [9], [10].

The propagation issue due to penetration can be contained through adopt small size 5G network cell such as microcell or femtocell. High path loss at mmWave band can be reduced by using digital array signal processing involved spatial multiplexing and beamforming. In spatial multiplexing, multiple data streams are encoded (e.g. alamouti coding) then transmitted independently using array antenna elements. At each receiver, the dedicated original signal can be reconstructed effectively [11].

Beamforming is a technique steers the transmitted signals of a massive MIMO system to the desired angular direction. Beamforming of massive MIMO array can be implemented either at baseband stage, which called digital beamforming or at radio frequency (RF) stage, which called analog beamforming [12]. The basic mechanism behind analog beamforming depends on using phase shifters to control the phase of each transmitted signal in order to steer the main beam into the desired angle [12], [13]. While in digital beamforming, the beamforming process is done using digital signal processing. Digital beamforming provides more flexibility and accuracy of the beamforming process in comparison to analog beamforming because it is easily to control the direction of beam through weight factors at baseband stage [14]. However, digital beamforming requires a separate transmit (receive) module dedicated to each antenna element, this module contains digital/analog converter analog to digital converter (ADC) or digital to analog converter (DAC), mixer, and power amplifier it is called RF chain. Unfortunately, design RF chain at mmWave is complex and expensive especially for massive MIMO array because a large number of RF chains is necessary [15].

Hybrid beamforming provides a trade-off between design complexity and performance. Hybrid beamforming is a combination of digital and analog beamforming [16], [17]. The concept of hybrid beamforming is first proposed in [18].

The essential process of hybrid beamforming is based on divided array antenna elements into many sub-array groups, only one RF chain component is attached to each group. Each array antenna element is connected to one phase shifter. This structure, significantly reduces the number of required RF chains, cost, and system complexity. The performance degradation of the hybrid beamforming can be controlled by using a well-designed adaptive beamformer. It is proved, if the number of RF chains is at least twice the number of data stream, the performance gap between hybrid beamforming, and fully digital beamforming approaches zero [19], [20].

The analog precoder maps the outputs of RF chain to the antenna elements. According to this mapping, there are two main structures for hybrid beamforming which are fully-connected structure and partially-connected structure. In fully-connected structure all array antenna elements are connected to each RF chain, while in partially-connected structure each RF chain is connected only to a set of the antenna elements [20]–[22]. Note that the term "precoder" means beamformer at the transmitted side, while the term "combiner" means beamformer at the receiver side.

While the digital beamformer modify both the amplitude and phase of transmitted symbols, the analog beamformer has a constant amplitude $1/\sqrt{(N_t)}$, and N-resolution quantized phases in fact. The resolution of analog phase shifters is limited by the number of bits used in it. So, high resolution phase shifter provides fine resolution analog beamforming but increases power consumption and hardware complexity [23], [24].

In this paper, a hybrid precoder design is proposed for a MIMO orthogonal frequency division multiplexing (MIMO OFDM) system based on the second order channel statistics (transmit covariance matrix) to reduce the overhead information. The joint spatial division and multiplexing (JSDM) scheme is modified to design a precoder serves users with multiple antennas. Avoiding the coupling between the analog precoder design and the analog combiner design (the combiner design is beyond the scope of this paper) is achieved according to the approach of Kronecker channel model [22], [25]. A wideband precoder for wideband mmWave channel is obtained by modelling this wideband channel as multiple narrowband subcarrier channels, so the proposed narrowband precoder is applied to each OFDM subcarrier channel. Although JSDM does not provide an optimal beamforming, but spectral analysis shows a little degradation between the proposed precoder and fully digital one especially when large number of antennas used at the base station.

Notations: in this paper, the following notations is used, $(.)^T, (.)^H, \overline{(.)}, \|\ \ \|_F, \|\ \ \|_2, and\ \mathbb{E}[.]$ denote the transpose, conjugate transpose, conjugate, frobenius norm, l2-norm, and statistical expectation respectively. $\mathcal{CN}(\mu,\mathcal{K})$ is a circularly symmetric complex Gaussian distribution with mean μ and covariance matrix $\mathcal{K}$. $X\otimes Y$ is the Kronecker product of X,Y matrices. $Span(V), Span^{\perp}(V)$ denote the column space of (V), and its orthogonal complement respectively.

2. SYSTEM MODEL

Consider a downlink multi-user multi-stream mmWave massive MIMO system operates at 28 GHz, where the base station (BS) equipped with a uniform planar array (UPA) of N_t antennas, and communicates N_S independent data streams with N_U users each equipped with $N_{r,i}$ antennas, where i = 1, 2, ……, N_U. $N_{s,i}$ represents the number of independent data streams per user, N_{RF}^{t} is the number of RF chain at the base station, where $N_S = \sum_{i=1}^{N_u} N_{s,i}$, and $N_r = \sum_{i=1}^{N_u} N_{r,i}$. The users distributed within a range of 1000 meters from the base station. working at the mmWave frequency provide a narrower beam width, since the beam width is inversely proportional to the operating frequency, and this can enhance the beamforming process. Also, the large available mmWave bandwidth increases the transmission bit rate [8], [22]. However, a wideband beamforming is needed to take advantage of large mmWave channel bandwidth. OFDM technique is used to divided the wideband mmWave channel into many narrowband channels, which help in the design of beamforming process [26]. The block diagram of the system is shown in Figure 1.

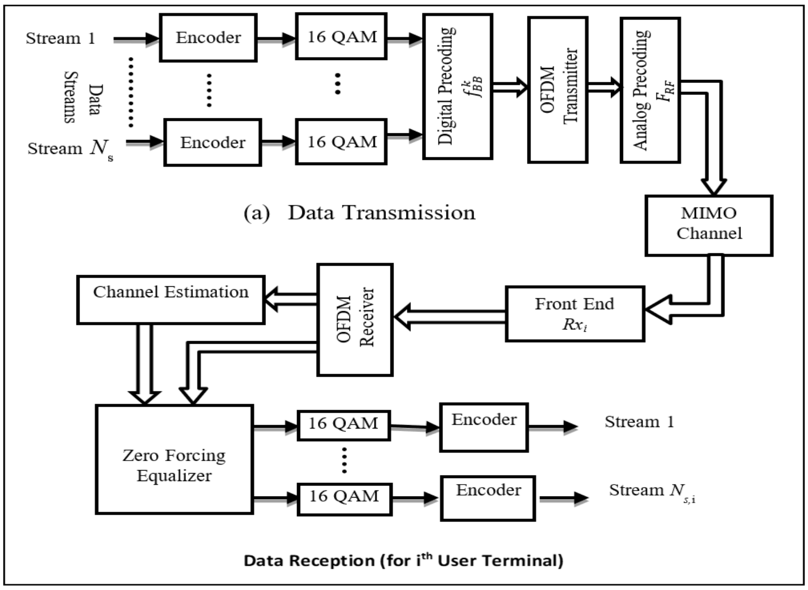

Figure 1. Massive MIMO-OFDM system block diagram

Hybrid beamforming is applied at the base station, the digital beamformer is used for each OFDM subcarrier and the analog beamformer is common to all OFDM subcarriers. The hybrid beamforming weights of the k^{th} OFDM subcarrier is of form $f_i^k = F_{RF,i} f_{BB,i}^k$, where $F_{RF,i} \in \mathbb{C}^{N_t * N_{RF,i}^t}$ is the analog precoder and it is common for all the subcarrier, and $f_{BB,i}^k \in \mathbb{C}^{N_{RF,i}^t * N_{S,i}}$ is the baseband precoder of the k^{th} subcarrier. In spite of that the users are equipped with multiple antennas, but no hybrid combiner is applied here, so the paper is focused only on the design of the hybrid precoder based on a modified JSDM for a wideband mmWave MIMO-OFDM system. However, it has been shown later that the design of hybrid precoder and combiner are independent of each other, also the hybrid combiner design can use the same model proposed here.

For each OFDM subcarrier, the symbol signal ($x_i^k \in \mathbb{C}^{N_{S,i} * 1}$) which is belong to i^{th} user is precoded using digital baseband precoder $f_{BB,i}^k$, then the precoder output is passed through OFDM, then is upconverted to RF stage using $N_{RF,i}^t$ RF chains. The fully-connected structure is used to connect the output of RF chains to the elements of the base station antenna array, so the analog precoder $F_{RF,i}$ uses $N_{RF,i}^t * N_t$ phase shifters. According to the above process, the transmitted signal ($y_i^k \in \mathbb{C}^{N_{t} * 1}$) is:

$$y_i^k = F_{RF,i} f_{BB,i}^k x_i^k \quad (1)$$

The received signal ($r_i^k \in \mathbb{C}^{N_{r,i*1}}$) at i^{th} user is:

$$r_i^k = \sqrt{\mathcal{P}_i}\, H_i^k F_{RF,i} f_{BB,i}^k x_i^k + \sum_{\substack{j=1\\ j\neq i}}^{N_U} \sqrt{\mathcal{P}_i}\, H_i^k F_{RF,j} f_{BB,j}^k x_j^k + n_i \tag{2}$$

$\mathcal{P}_i$ is the received average power at the i^{th} user, $n_i \in \mathbb{C}^{N_{r,i}*1}$ is the noise signal. n_i has complex gaussian distribution with zero mean and covariance matrix $\mathcal{R}n_i = \mathbb{E}[n_i n_i^H]$ (e.g., $n_i \sim \mathcal{CN}(0, \mathcal{R}n_i)$). $H_i^k \in \mathbb{C}^{N_{r,i}*N_t}$ is the channel matrix between the base station and the i^{th} user at k^{th} subcarrier. The Saleh-Valenzuela channel model [27] which adopted in this work to modelling the propagation of MIMO channel is:

$$H_i = \gamma \sum_{\ell=1}^{N_{c\ell,i}} \sum_{m=1}^{N_{\ell,i}} \alpha_{\ell,m,i} a_{r,i}\left(\phi_{\ell,m,i}^r, \theta_{\ell,m,i}^r\right)\, a_t^H(\phi_{\ell,m,i}^t, \theta_{\ell,m,i}^t) \tag{3}$$

This narrowband channel model assumed to be a sum of $N_{ray,i}$ rays divided into $N_{c\ell,i}$ clusters, and each cluster contains $N_{\ell,i}$ rays for $\ell = 1, 2\ldots, N_{c\ell,i}$. $\gamma = \sqrt{N_t N_r / N_{ray,i}}$, $N_{ray,i} = \sum_{\ell=1}^{N_{c\ell,i}} N_{\ell,i}$. $\alpha_{\ell,m,i}$ represents the complex gain of the m^{th} ray in the ℓ^{th} cluster and it is assumed to be zero mean independent random variable. $\phi_{\ell,\mathrm{m},i}^r, \theta_{\ell,\mathrm{m},i}^r$ are the azimuth and elevation angles of arrival (AoA) respectively, which are random variables with mean $\bar{\phi}_{\ell,i}^r, \bar{\theta}_{\ell,i}^r$. $\phi_{\ell,\mathrm{m},i}^t, \theta_{\ell,\mathrm{m},i}^t$ are the azimuth and elevation angles of departure (AoD) respectively, which are random variables with mean $\bar{\phi}_{\ell,i}^t, \bar{\theta}_{\ell,i}^t$. The AoD and AoA are assumed to be independent random variables. Finally, the $a_t\left(\phi_{\ell,\mathrm{m},i}^t, \theta_{\ell,\mathrm{m},i}^t\right)$ and $a_{r,i}\left(\phi_{\ell,\mathrm{m},i}^r, \theta_{\ell,\mathrm{m},i}^r\right)$ are the antenna array response vectors of the base station and the i^{th} user respectively. The channel model of the above equation is modified for wideband MIMO-OFDM mmWave channel model as in [28], so:

$$\mathcal{H}_i^k \approx \gamma_i \sum_{\ell}^{N_{cl,i}} \sum_{m}^{N_{\ell,i}} \beta_{\ell,m,k,i} a_{r,i}\left(\phi_{\ell,m,i}^r, \theta_{\ell,m,i}^r\right) a_t^H(\phi_{\ell,m,i}^t, \theta_{\ell,m,i}^t) \tag{4}$$

The right hand of the above equation is similar to the narrowband channel model of (3), where $\beta_{\ell,m,k,i} = \alpha_{\ell,\mathrm{m},i} \wp_{\ell,k,i}$ represents the complex gain of the m^{th} ray in the ℓ^{th} cluster for k^{th} subcarrier, $k = 1, 2, \ldots, N_{sc}$. $\wp_{\ell,k,i} = \sum_{n=0}^{N_{cp}} \wp(nT_s - \bar{\tau}_\ell)\, e^{-j2\pi kn/N_{sc}}$, N_{sc} is the number of OFDM subcarrier, and N_{cp} is the number of cyclic prefix (CP) and should be greater than the largest time delay of the channel to remove the intersymbol interference (ISI). $\wp(t)$ represents the function of transmitter (receiver) lumped pulse shaping. T_s is the sampling time, and $\bar{\tau}_\ell$ is the average time delay of the ℓ^{th} cluster. vec $\left(\mathcal{H}_i^k\right) \sim \mathbb{C}\,\mathcal{N}(0, \mathcal{K}_i^k)$ and $\mathcal{K}_i^k \in \mathbb{C}^{N_t N_{r,i} \times N_t N_{r,i}}$ represent the channel covariance matrix. Hence, each subchannel $\mathcal{H}_i^k$ can be considered as a narrowband Saleh-Valenzuela channel model, so any narrowband beamformer design algorithms can be implemented for each subchannel $\mathcal{H}_i^k$. Moreover, the Kronecker channel model [Ref. 170, Ref. 84] assumes that the transmit and receive correlation are separable, based on that assumption, the channel covariance matrix $\mathcal{K}_i^k$ can be expressed:

$$\mathcal{K}_i^k = \mathcal{K}_{t,i}^k \otimes \mathcal{K}_{r,i}^k \tag{5}$$

Where, $\mathcal{K}_{t,i}^k = \mathbb{E}\left[\mathcal{H}_i^{k^H} \mathcal{H}_i^k\right]$, and $\mathcal{K}_{r,i}^k = \mathbb{E}\left[\mathcal{H}_i^k \mathcal{H}_i^{k^H}\right]$ are the transmit and receive covariance matrices of the channel. based on (5), the design of analog precoders and combiners can be independent of each other. Without loss of generality, the following assumption are made: equal power distribution over all data streams, x_i^k has a normal distribution with zero mean covariance matrix $\mathcal{R}x_i = \mathbb{E}\left[x_i^k x_i^{k^H}\right] = \frac{1}{N_{s,i}} I_{N_{S,i}}$ (e.g., $x_i \sim \mathcal{N}(0, \mathcal{R}x_i)$). r_i^k transmitted through a narrowband block fading channel. This assumption can be feasible by using OFDM technique which converts wideband selective fading channel into several narrowband flat fading channels [28], [29]. $\{\left\|F_{RF,i} f_{BB,i}^k\right\|_F^2 = N_{S,i}, \forall\, k, i\}$ to satisfy the total power constraint.

3. PROBLEM FORMULATION

The main step of the hybrid beamforming design is to find the optimal values of precoder weights $(f_{BB,i}^k, F_{RF,i})$ that minimize the MSE between x_i^k and r_i^k over all users and subcarriers. The problem can be written as:

$$\min_{f_{BB,i}^k, F_{RF,i}} \sum_{i=1}^{N_U} \sum_{k=1}^{N_{DSC}} \mathbb{E}\left[\left\|x_i^k - r_i^k\right\|_2^2\right]$$

$$s.t. \left\|F_{RF,i} f_{BB,i}^{k}\right\|_F^2 = N_{S,i}, \forall i \tag{6}$$

$$F_{RF,i} \in \mathbb{F}_{RF}$$

A popular hybrid beamforming design method is JSDM is considered in this work. JSDM is designed for multiuser, each one with single antenna. JSDM is used to provide beamforming coefficients at base station only [30].

In this work, a modified version of JSDM is used to obtain precoder weights for multiuser, each with multiple antennas. For simplicity, one user per group is assumed and the users are well spatial separated. First, the analog precoder is designed based on the second order channel statistics (channel covariance matrix) and not on the instantaneous channel state information which reduce the overhead information needs to process and fed back because channel covariance matrix is varying slowly with respect to coherence time. At the beginning, each user estimates its channel and sending V_i^k to the BS. the singular decomposition value (SVD) of channel matrix ($\mathcal{H}_i^k$) is defined as:

$$\mathcal{H}_i^k = U_i^k \Sigma_i^k {V_i^k}^H \tag{7}$$

Where $U_i^k \in \mathbb{C}^{N_{r,i} * N_{r,i}}$, $V_i^k \in \mathbb{C}^{N_t * N_t}$ are the left-singular vectors and right-singular vectors respectively. $\Sigma_i^k \in \mathbb{R}^{N_{r,i} * N_t}$ is a diagonal matrix with $rank\ (\Sigma_i^k) = N_{r,i}$, and only non-negative real elements and these elements represent the square root of the eigenvalues of transmit covariance matrix $\mathcal{K}_i^k = \mathbb{E}\left[{\mathcal{H}_i^k}^H \mathcal{H}_i^k\right]$. Furthermore, the right-singular vectors matrix V_i^k can be obtain from eigenvalue decomposition (EVD) of transmit covariance matrix is:

$$\mathcal{K}_i^k = V_i^k{}_i {\Sigma_i^k}^2 {V_i^k}^H \tag{8}$$

Following the approach of [28], an approximate of EVD of $\mathcal{K}_i^k$ is defined as:

$$\mathcal{K}_i^k \approx \gamma^2 \mathbb{V}_i \mathbb{A}_i^k \mathbb{V}_i^H \tag{9}$$

Where $\mathbb{A}_i^k \in \mathbb{C}^{N_{r,i} * N_{r,i}}$ is a diagonal matrix, whose elements are $\sigma_{\alpha_{\ell,i}}^2 \left|\wp_{\ell,k,i}\right|^2 \mathbb{A}_\ell$, $\mathbb{A}_\ell$ is a diagonal matrix contains the dominant eigenvalues of transmit covariance matrix, and $\mathbb{V}_i \in \mathbb{C}^{N_t * N_{r,i}}$ is a semi-unitary matrix contains the eigenvectors corresponding to the dominant eigenvalues of $\mathbb{A}_\ell$. Note that only $\mathbb{A}_i^k$ depends on k^{th} subcarrier and $\mathbb{V}_i$ does not. $\mathbb{V}_i$ is an approximate of the first $N_{r,i}$ eigenvector columns of V_i^k. Based on the approach of [30], [31], Ξ_i is defined at the base station as:

$$\Xi_i = \left[\bar{\mathcal{V}}_1\ \bar{\mathcal{V}}_2\ \ \dots\ \bar{\mathcal{V}}_{i-1}\ \ \ \bar{\mathcal{V}}_{i+1}\ \dots\ \bar{\mathcal{V}}_{N_u-1}\ \bar{\mathcal{V}}_{N_u}\right]^T \tag{10}$$

Where $\bar{\mathcal{V}}_i$ is a complex conjugate of the first $N_{r,i}$ columns average of V_i^k over all subcarriers, Ξ_i matrix contains the eigenvectors of all users except that of i^{th} user. So $\Xi_i \in \mathbb{C}^{\bar{\mathcal{L}}_i * N_t}, and\ \bar{\mathcal{L}}_i = \sum_{j=1, j\neq i}^{N_u} N_{r,j}$. The SVD of Ξ_i is:

$$\Xi_i = \mathfrak{U}_i \mathcal{E}_i \mathfrak{V}_i^H \tag{11}$$

$\mathfrak{V}_i \in \mathbb{C}^{N_t \times N_t}$ and its rank=$\bar{\mathcal{L}}_i$. $\mathfrak{V}_i$ can be written as:

$$\mathfrak{V}_i = \left[\mathfrak{V}_i{}^{(1)}\ \ \ \mathfrak{V}_i{}^{(0)}\right] \tag{12}$$

Where, $\mathfrak{V}_i{}^{(1)} \in \mathbb{C}^{N_t \times \bar{\mathcal{L}}_i}$ contains the right eigenvectors corresponding to the dominant eigenvalues of Ξ_i, and $\mathfrak{V}_i{}^{(0)} \in \mathbb{C}^{N_t \times (N_t - \bar{\mathcal{L}}_i)}$ contains the right eigenvectors corresponding the weakest eigenvalues of Ξ_i, which represents the null space of Ξ_i such that $Span\left(\mathfrak{V}_i{}^{(0)}\right) = Span^{\perp}\left(\left\{\Xi_j : \forall j \neq i\right\}\right)$. The effective channel $\widetilde{\mathcal{H}}_i^k \in \mathbb{C}^{N_{r,i} \times (N_t - \bar{\mathcal{L}}_i)}$ is defined as:

$$\widetilde{\mathcal{H}}_i^k = \mathcal{H}_i^k \mathfrak{V}_i{}^{(0)} \tag{13}$$

The analog precoder $F_{RF,i}$ can be obtained by concatenating the right eigenvectors corresponding to the dominant eigenvalues of the effective channel $\tilde{\mathcal{H}}_i^k$ with the projection onto $Span(\mathfrak{V}_i^{(0)})$. $\tilde{\mathcal{V}}_i$ is the columns average of the eigenvectors $\tilde{V}_i^k$ over all subcarriers, where $\tilde{V}_i^k$ is obtained from the eigenvalue decomposition of the transmit covariance matrix $\tilde{\mathcal{K}}_i^k = \tilde{V}_i^k{}_i\tilde{\Sigma}_i^{k2}\tilde{V}_i^{kH}$ .Rewrite $\tilde{\mathcal{V}}_i$ $\mathbb{C}^{(N_t-\bar{\mathcal{L}}_i)\times N_{RF,i}^t}$ as:

$$\tilde{\mathcal{V}}_i = [\tilde{\mathcal{V}}_i^{(1)} \quad \tilde{\mathcal{V}}_i^{(0)}] \tag{14}$$

As mention above, the product of $\mathfrak{V}_i^{(0)}$and $\tilde{\mathcal{V}}_i^{(1)}$ produces $N_{RF,i}^t$ column vectors that maximize the transmission rate and eliminating inter-group interference for i^{th} user [32]. These column vectors represent the analog precoder $F_{RF,i}$.

$$F_{RF,i} = \mathfrak{V}_i^{(0)} * \tilde{\mathcal{V}}_i^{(1)} \tag{15}$$

Based on (15), the second term of the right-hand side of (2) can be eliminated since the effective channel ($\tilde{\mathcal{H}}_{ij}^k = \mathcal{H}_i^k\mathfrak{V}_j^{(0)} \approx 0$) for exact block diagonalization (BD), so (2) becomes:

$$r_i^k = \sqrt{\mathcal{P}_i}\, H_i^k F_{RF,i} f_{BB,i}^k x_i^k + + n_i \tag{16}$$

Moreover, $span\,(\mathcal{V}_i) \nsubseteq span\left(\{\mathcal{V}_j : j \neq i\}\right)$, $\dim(span(\mathcal{V}_i) \cap span^{\perp}(\{\mathcal{V}_j : j \neq i\}) \geq N_{s,i}$ should be satisfied to achieve exact BD, and the condition $span\left(F_{RF,i}\right) \subseteq span^{\perp}\,(\{\mathcal{V}_j : j \neq i\})$ is necessary for zero-forcing. The design of hybrid precoder is summarized as shown in. Given $F_{RF,i}$, the subcarrier digital precoder $f_{BB,i}^k$ can be obtained by define the effective channel $\hat{\mathcal{H}}_i^k \in \mathbb{C}^{N_{r,i}*N_{N_{RF,i}^t}}$ as:

$$\hat{\mathcal{H}}_i^k = \mathcal{H}_i^k F_{RF,i} \tag{17}$$

Algorithm 1 Analog Precoder $F_{RF,i}$ Design
1- Estimate $\mathcal{H}_i^k$ at each user.
2- Define $\mathcal{K}_i^k = \mathbb{E}[\mathcal{H}_i^{k\,H}\mathcal{H}_i^k]$.
3- Compute the EVD of ($\mathcal{K}_i^k$) to find the eigenvectors (V_i^k).
4- Each user feedback its eigenvectors (V_i^k) to the BS.
5- Define Ξ_i according to (10).
6- Find $\mathfrak{V}_i^{(0)}$ according to (11), and (12).
7- The BS broadcasting $\mathfrak{V}_i^{(0)}$ for users.
8- Define the effective channel ($\tilde{\mathcal{H}}_i^k$) according to (13).
9- Compute the EVD of ($\tilde{\mathcal{K}}_i^k$) to find the eigenvectors ($\tilde{\mathcal{V}}_i$).
10- Find $\tilde{\mathcal{V}}_i^{(1)}$ according to (14).
11- Finally, the analog precoder is defined according to (15).

Based on that $F_{RF,i}{}^H F_{RF,i}{}_i \approx cI_{N_{RF,i}^t}$for large BS antennas N_t [7], [28], the subcarrier digital precoder $f_{BB,i}^k$ is defined as the norm-normalized $N_{s,i}$ dominant eigenvectors of covariance matrix $F_{RF,i}{}^H\mathcal{K}_i^k F_{RF,i}{}_i$. So, the subcarrier precoder is the product of analog RF precoder by subcarrier baseband precoder.

4. SIMULATION RESULTS

An evaluation of the proposed system via simulation is presented in this section. A multi-users multi-streams OFDM massive MIMO system, shown in Figure 1, is considered. The users are randomly distributed within 1000 m diameter area around the base station in a manner ensure a well spatial separation between users. The base station communicates with the users over multi-clustered channel as in (4) with ten clusters each with ten rays, so the total number of rays is one hundred. The system using 256 subcarriers OFDM with 64 cyclic prefix to handle the wideband mm wave (28 GHz) channel. Channel sounding is used to estimate the channel by sending a preamble signal. Without loss of generality, each user is equipped with eight antennas and two data streams is dedicated for each user to ease the calculations.

First, the result of the proposed system is compared to that of fully digital precoding system with full channel state information for a variety number of base station antennas $N_t = 64, 128, 256$ and 512. The antennas are arranged in UPA. Figure 2(a) shows the average sum rate versus signal to noise ratio (SNR) for the proposed and fully digital system. The number of users is eight, so the total number of receivers' antennas is 64 therefore the minimum number of base station antennas must be more than 64. As shown in Figure 2(a), the gap between the proposed system and fully digital precoder system reduce as the number of transmitted antennas is increased, while the gap at 0 dB is about 8 for 64 antennas it does not exceed 0.7 for 512 antennas. The large degradation in the proposed system when the transmit array antennas is 64 is due to that the number of transmit array antennas should be more the total number of array antennas of all receivers, which is unverified condition here. Therefore, when the number of users is six and the total receive array antennas become 48, the gap for 64 transmit antennas is enhanced significantly in comparison to that for higher transmit antennas as shown in Figure 2(b). In Figure 3, the system is tested for the quantization effect of the phase shifters of the analog precoders. When using 1-bit phase shifters instead of unquantized phase shifters, the spectral efficiency degradation for 512 transmit array antennas is about 1.55 at 0 dB while it is about 0.43 for 128 transmit array antennas.

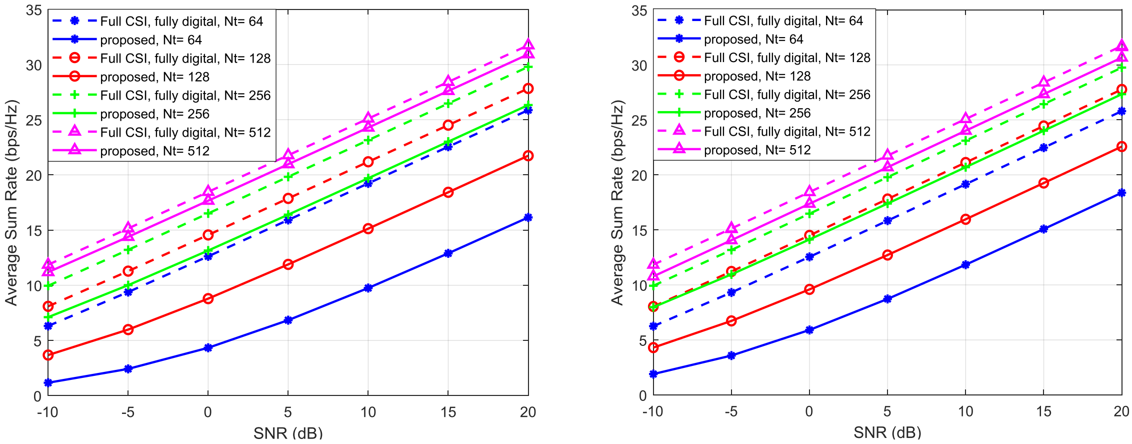

Figure 2. Spectral efficiency of the proposed system for (a) 8 users (b) 6 users. Each user equipped with 8 antennas, 2 data stream per user, and number of RF chains is 48 (three chains per data stream)

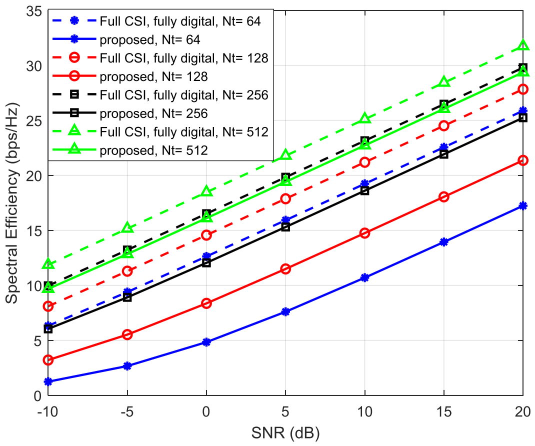

Figure 3. Spectral efficiency of the proposed system for 8 users each equipped with 8 antennas, 2 data stream per user, and number of RF chains is 48 (three chains per data stream), considering quantization effect on analog phase shifters (1 bit phase shifters)

A comparison of average sum rates at 0 dB for different number of transmit antennas when the number of users is 4 and 8 are listed in Table 1 considering the quantization effect of phaser shifters. The quantization of phase shifters has a limited effect on the system because the JSDM algorithm is not an optimal solution for the design of hybrid precoder. Figure 4 shows the effect of number of users on the average sum rates for different numbers of transmit antennas at 0 dB signal to noise ratio.

Table 1. Average sum rates for different transmit antenna number at 0 dB

		Unquantized phase shifter	1-bit phase shifter	2-bit phase shifter	3-bit phase shifter
NU=4	Nt=64	7.661	7.409	7.566	7.656
	Nt=128	11.578	10.850	11.395	11.535
	Nt=256	16.091	14.796	15.539	15.856
	Nt=512	20.452	18.735	19.721	20.126
NU=8	Nt =128	8.791	8.357	8.699	8.732
	Nt=256	13.147	12.043	12.704	12.974
	Nt=512	17.660	16.102	16.997	17.350

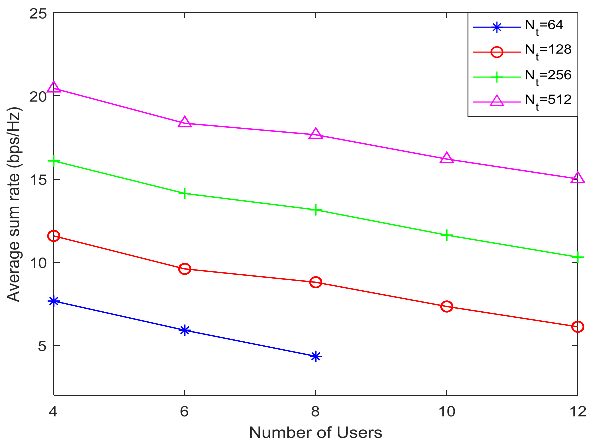

Figure 4. Average sum rates versus number of users for different transmit array size at (SNR=0 dB)

5. CONCLUSION

In this paper, a hybrid precoder is designed for multi-user multi-stream wideband MIMO-OFDM system based on JSDM for downlink transmission. The effect of transmit array size on the proposed system is discussed and the condition that the antennas number of transmit array must be more than the antennas number of all users array is verified. Also studied how sum rates effect by limiting the number of bits of the analog phase shifters which has small effect on the system because JSDM do not provide an optimal precoder, so the effects of the number of the phase shifter bits is limited. Even though the JSDM does not provide an optimal precoder but the results show a little degradation in the spectral efficiency. The proposed system provides a good computational efficiency because it does not depend on the instantons channel state information, also this will reduce the overhead information and the time to fed it back.

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