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A Novel User Selection Algorithm for Multiuser Hybrid Precoding in mmWave Systems

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***Abstract*—In this paper, a novel user selection algorithm is proposed for downlink multiuser mmWave systems. The base station exploits hybrid precoding and communicates with multiple users simultaneously via spatial multiplexing. The system performance degrades when the spatially multiplexed users are angularly close and thus results in residual interference which is hard to be cancelled out by the hybrid precoding. To obtain an efficient and computably tractable solution, a novel formulation of the user selection problem and the associated algorithm is presented in this paper. The proposed algorithm enables an optimal spatial multiplexing at the base station, where a predefined number of users is selected and simultaneously served to maximise the averaged spectral efficiency per user. Simulation results show that implementing the multiuser hybrid precoding with the proposed user selection algorithm achieves a performance close to the interference-free limit.**

I. Introduction

The large bandwidth in mmWave frequencies enables multi-Gpbs data rates for indoor wireless systems [1], [2], and makes mmWave communication a promising candidate for future outdoor cellular networks [3], [4]. In order to obtain high quality communication links, large antenna arrays are required at both the base station (BS) and users in mmWave systems. Fortunately, a large number of antennas can be built with reasonable form factors due to the short wavelength. The high array gain maintains a reasonable coverage even for outdoor communications. Further, with a constrained number of radio frequency (RF) chains, the large arrays enable the BS and users to multiplex independent data streams, which could improve the system spectral efficiency.

In single-user mmWave systems, analogue beamforming has been widely used, which adjusts the phase of the transmit signals at each antenna in the RF domain via a certain number of phase shifters [5]–[9]. In [5], [6], adaptive beamforming algorithms were developed with multi-resolution codebooks, where the transmitter and receiver jointly select the optimal beamforming vectors from the pre-defined codebooks to maximise the received signal power. These algorithms have been adopted in 60 GHz indoor communication standards, like the IEEE 802.15.3c standard [8] and the IEEE 802.11ad standard [9]. In [7], the beam selection process was formulated as an optimisation problem and an efficient and low-complexity beam training technique was proposed based on the Nelder-Mead simplex method. This technique achieves desirable performance in Line-of-Sight (LoS) scenarios. However, it was then modified in [10] in order to improve the performance robustness against Non-LoS channel models. An overall comparison on the performance of the abovementioned analogue beamforming algorithms was presented in [10].

In multiuser mmWave systems, to multiplex independent data streams and thus to improve the system spectral efficiency, hybrid precoding algorithms were presented in [11], [12], which divide the precoding process into analogue (RF) and digital (baseband) domains. In [11], a single-user hybrid precoding algorithm was developed, which exploits the sparse nature of mmWave channels and approximates the optimal unconstrained precoders and combiners using the principle of basis pursuit. In [12], a low-complexity multiuser hybrid precoding algorithm was proposed to design the hybrid precoder at the BS and analogue combiners at users with a small number of training and feedback overhead. The performance of the proposed algorithm was analysed in single-path channels, where the users have propagation paths with the angle of departure (AoD) randomly distributed over the interval $[0, 2\pi]$. For the case where the spatially multiplexed users are angularly close and therefore inseparable by the BS antenna array, the system performance would degrade due to the resulted residual interference. To obtain an efficient and computably tractable solution to such a challenge, a novel user selection problem is formulated and the associated algorithm is presented in this paper.

The rest of the paper is organised as follows. In Section II, the system and propagation channel models are described. Section III reviews the two-stage multiuser hybrid precoding algorithm and considers imperfect channel state information (CSI). In Section IV, the user selection problem is formulated and a novel algorithm is presented. Section V presents the simulation results to evaluate the performance of the proposed algorithm. Section VI concludes the paper.

II. mmWave System Model

A. System Model

Consider a multiuser mmWave system with a single BS and N users. The BS which has a large array of N_{BS} antennas and N_{RF} RF chains ($N_{BS} \gg N_{RF} > 1$) communicates simultaneously with K out of N users via independent data streams. Each user is equipped with a moderate number of antennas, N_{MS} ($N_{BS} \gg N_{MS}$), and a single RF chain. The BS exploits multiuser hybrid precoding while the users apply analogue-only beamforming. Given the assumption that the BS serves each user via only one stream, the total number of spatially multiplexed users is restricted by the number of

RF chains at the BS, i.e., $K \leq N_{RF}$. For simplicity, K is assumed to be equal with N_{RF} in the rest of this paper.

On the downlink of this mmWave transmission system, the BS modulates the data vector $\mathbf{d} = [d_1, d_2, \cdots d_K]^T$ with a hybrid precoding matrix $\mathbf{M}$ and then transmits the vector $\mathbf{s} = \mathbf{Md}$ to the K users simultaneously. The received signal vector $\mathbf{y}_k$ at the kth user is given as:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{M} \mathbf{d} + \mathbf{n}_k. \tag{1}$$

where $d \in \mathbb{C}^K$ is subject to the transmit power constraint P, i.e., $\mathbb{E}[\mathbf{d}\mathbf{d}^H] = \frac{P}{K}\mathbf{I}_K$, given uniform power allocation among users. $\mathbf{n}_k \sim \mathcal{N}(0, \sigma_d^2 \mathbf{I})$ is the downlink Gaussian noise. $\mathbf{H}_k$ denotes the $N_{MS} \times N_{BS}$ narrowband, block-fading channel model between the BS and the kth user. After being post-processed by the receive combining vector $\mathbf{w}_k$, the received signal is converted into an estimate $\hat{d}_k$ of the original data d_k, with:

$$\hat{d}_k = \mathbf{w}_k^H (\mathbf{H}_k \mathbf{M} \mathbf{d} + \mathbf{n}_k), \tag{2}$$

The $N_{BS} \times K$ hybrid precoding matrix $\mathbf{M}$ is given by $\mathbf{M} = \mathbf{BP}$, where the transmit beamforming matrix is $\mathbf{B} = [\mathbf{b}_1, \mathbf{b}_2, \cdots, \mathbf{b}_K]$ of a dimension $N_{BS} \times K$, implemented in RF domain using analogue phase shifters, and the MU-MIMO precoding matrix is $\mathbf{P} = [\mathbf{p}_1, \mathbf{p}_2, \cdots, \mathbf{p}_K]$ of a dimension $K \times K$, which processes the transmit data in the baseband domain. As a result, Equation (1) can be rewritten as:

$$\hat{d}_k = \mathbf{w}_k^H \mathbf{H}_k \sum_{i=1}^{K} \mathbf{B} \mathbf{p}_i \mathbf{d}_i + \mathbf{w}_k^H \mathbf{n}_k. \tag{3}$$

The digital precoding matrix $\mathbf{P}$ is designed to mitigate the inter-user interference, with column vectors $\mathbf{p}_k$ satisfying $\mathbf{w}_i^H \mathbf{H}_i \mathbf{B} \mathbf{p}_k = 0$, for all $i \neq k$. Each column vector $\mathbf{b}_k$, for $k = 1, \cdots K$, of the matrix $\mathbf{B}$ represents an antenna weighting vector, whose entries are of constant modulus and adjust the phase of the BS antennas in order to point the BS array to a specific direction. The $N_{MS} \times 1$ receive combing vector $\mathbf{w}_k$ at the kth user is also an antenna weighting vector and has the similar constraints as $\mathbf{b}_k$.

B. mmWave Channel Model

An important feature of mmWave propagation channels is the pronounced sparsity of multipath components, which arises from: 1) less prominent diffraction and 2) more power shift from the specular reflection into diffuse components. Channel models which incorporate the sparse scattering nature were developed for 60 GHz wireless local area networks (WLAN) and adopted by the IEEE 802. 11ad standard. Based on various indoor environments, the propagation channel models were described in detail in [13]. Using the clustered model, the channel matrix $\mathbf{H}_k$ can be expressed as:

$$\mathbf{H}_k = \sum_{l=1}^{L_k} \alpha_{l,k} \mathbf{a}_{MS,k}(\phi_{l,k}^{rx}, \theta_{l,k}^{rx}) \mathbf{a}_{BS}^H(\phi_{l,k}^{tx}, \theta_{l,k}^{tx}), \tag{4}$$

where $\alpha_{l,k}$ is the complex gain of the lth cluster at the kth user and L_k is the number of multipath clusters. $(\phi_{l,k}^{rx}, \theta_{l,k}^{rx})$ and $(\phi_{l,k}^{tx}, \theta_{l,k}^{tx})$ are the angle of arrival (AoA) and angle of departure (AoD) in the azimuth and elevation domain respectively. $\mathbf{a}_{BS}(\phi, \theta)$ and $\mathbf{a}_{MS,k}(\phi, \theta)$ denote the antenna array response vector of the BS and the kth user respectively. For a uniform linear arrays, $\mathbf{a}_{BS}(\phi)$ is defined as:

$$\mathbf{a}_{BS}(\phi) = \frac{1}{\sqrt{N_{BS}}}[1, e^{j\frac{2\pi}{\lambda}d\sin(\theta)}, \cdots, e^{j\frac{2\pi}{\lambda}d(N_{BS}-1)\sin(\theta)}]^T, \tag{5}$$

where λ is the signal wavelength and d is the antenna spacing. ϕ denotes the azimuth polar angle with respect to the x-axis when the array lies along the y-axis. Also, $\mathbf{a}_{MS,k}(\phi)$ is derived in a similar format.

III. Multiuser Hybrid Precoding

To design the optimal transmit matrix $\mathbf{M} = \mathbf{BP}$ at the BS and the receive vector $\mathbf{w}_k$ at each user, a commonly adopted performance metric is the system spectral efficiency. Given the post-processed signal defined in Equation (2), the achievable spectral efficiency for the kth user is expressed as:

$$R_k = \log_2 (1 + \frac{\frac{P}{K}|\mathbf{w}_k^H \mathbf{H}_k \mathbf{B} \mathbf{p}_k|^2}{\frac{P}{K}\sum_{i \neq k} |\mathbf{w}_k^H \mathbf{H}_k \mathbf{B} \mathbf{p}_i|^2 + \mathbf{w}_k \sigma^2}). \tag{6}$$

Therefore, the spectral efficiency of the overall system is $R_{sum} = \sum_{k=1}^{K} R_k$. Maximising R_{sum} requires a joint optimisation over the matrices $\mathbf{B}$, $\mathbf{P}$ and vectors $\mathbf{w}_k$ for $k = 1, \cdots, K$. Due to the constraints on analogue beamforming vectors, e.g., $\mathbf{b}_k$ and $\mathbf{w}_k$, as described in Section II-A, finding the global optimum of $\mathbf{M}$ and $\mathbf{w}_k$ is usually computationally intractable.

To obtain an efficient solution to the optimal design of the transmit matrices and receive vectors, i.e., $\mathbf{B}$, $\mathbf{P}$ and $\mathbf{w}_k$, which maximise the spectral efficiency, a mixed integer programming problem formulation and a two-stage hybrid precoding algorithm were presented in [12]. The optimisation problem is formulated as:

$$\begin{aligned} \{\mathbf{P}^{opt} | \{\mathbf{b}_k^{opt}, \mathbf{w}_k^{opt}\}_{k=1}^K\} &= \arg\max \sum_{k=1}^{K} R_k \\ \text{subject to} \quad & \mathbf{b}_k \in \mathbf{W}_{BS}, k = 1, \cdots, K, \\ & \mathbf{w}_k \in \mathbf{W}_{MS}, k = 1, \cdots, K, \end{aligned} \tag{7}$$

where $\mathbf{W}_{BS}$ and $\mathbf{W}_{MS}$ denote the pre-defined beamforming codebook matrices at the BS and individual user respectively. An example of the codebook design was presented in [14] and adopted in 60 GHz WPAN systems. Each column vector of the codebook matrix represents an analogue beamforming vector, i.e., a candidate for $\mathbf{b}_k$ or $\mathbf{w}_k$.

The hybrid precoding algorithm presented in [12] makes use of a two-stage design process. In the first stage, the BS and each user k jointly design their analogue beamforming vectors, $\mathbf{b}_k$ and $\mathbf{w}_k$, to maximize the received signal power, while ignoring interference from other users. This is a typical single-user beam training problem which is solved by jointly searching over the codebook matrices $\mathbf{W}_{BS}$ and $\mathbf{W}_{MS}$ and then selecting the best combination $(\mathbf{b}_k^{opt}, \mathbf{w}_k^{opt})$ that maximises the value of $\mathbf{w}_k^H \mathbf{H}_k \mathbf{b}_k$.

The second stage comprises the design of a MU-MIMO precoder for spatial multiplexing on the effective channel $\bar{\mathbf{H}}$

obtained after the analogue beamforming stage:

$$\bar{\mathbf{H}} = \begin{bmatrix} \mathbf{w}_1^H \mathbf{H}_1 \mathbf{b}_1 & \cdots & \mathbf{w}_1^H \mathbf{H}_1 \mathbf{b}_K \\ \vdots & \cdots & \vdots \\ \mathbf{w}_K^H \mathbf{H}_K \mathbf{b}_1 & \cdots & \mathbf{w}_K^H \mathbf{H}_K \mathbf{b}_K. \end{bmatrix} \quad (8)$$

Thanks to the considerable dimensionality reduction arising from the first stage, the overhead required to estimate the instantaneous CSI of the effective channel $\bar{\mathbf{H}}$, with dimension $K \times K$, is much lower compared with that of the full-dimension channel matrices $\mathbf{H}_k$ for $k = 1, \cdots, K$, each with a dimension of $N_{MS} \times N_{BS}$. In order to acquire an estimate of $\bar{\mathbf{H}}$ at the BS, a part of the coherence time of the channel is used for uplink training, given the assumption of a reciprocity channel. During the training phase, all K users simultaneously transmit mutually orthogonal pilot sequences to the BS which are concatenated as a $K \times \tau$ matrix $\sqrt{\tau P_u}\mathbf{\Phi}$ satisfying $\mathbf{\Phi}\mathbf{\Phi}^H = \mathbf{I}_K$, where P_u is the uplink transmit power from each user. The $K \times \tau$ received signal matrix at the BS is:

$$\mathbf{Y}_P = \sqrt{\tau P_u}\bar{\mathbf{H}}^H \mathbf{\Phi} + \mathbf{N}_u, \quad (9)$$

where $\mathbf{N}_u \sim \mathcal{N}(0, \sigma_u^2 \mathbf{I})$ is the uplink Gaussian noise. The LS estimate of the effective channel $\bar{\mathbf{H}}$ is given as [15]:

$$\hat{\mathbf{H}} = \frac{\mathbf{\Phi}}{\sqrt{\tau P_u}} \mathbf{Y}_P^H = \bar{\mathbf{H}} + \frac{\mathbf{\Phi}\mathbf{N}_u}{\sqrt{\tau P_u}}, \quad (10)$$

Using the zero-forcing (ZF) and minimum mean square error (MMSE) techniques, the digital precoders designed for the effective MU-MIMO channel are defined in Equation (11) and (12) respectively:

$$\mathbf{P}_{ZF} = \hat{\mathbf{H}}^H (\hat{\mathbf{H}}\hat{\mathbf{H}}^H)^{-1}, \quad (11)$$

$$\mathbf{P}_{MMSE} = \hat{\mathbf{H}}^H (\frac{P}{K}\hat{\mathbf{H}}\hat{\mathbf{H}}^H + \sigma_d^2 \mathbf{I})^{-1}. \quad (12)$$

Each column vector $\mathbf{p}_k$, also the precoding vector, is normalised such that $\|\mathbf{p}_k\|_F^2 = 1$.

Consider an example of the multiuser mmWave system described in Section II-A, where the total number of users is $N = 20$ and the number of antennas at the BS and individual user are $N_{BS} = 32$ and $N_{MS} = 8$ respectively. The number of BS RF chains is $N_{RF} = 4$, which means that the BS can communicate with up to $K = N_{RF} = 4$ users simultaneously. The downlink propagation channels are generated using the ray-tracing model presented in [13] and Section II-B. The channel of each user is modelled based on a LoS scenario, with AoD on the LoS path $\phi_{LoS,n}^{tx}$, for $n = 1, \cdots, N$, randomly distributed over the interval $[0, 2\pi]$. Assume the use of the beamforming codebook presented in [14] and the exhaustive search in the analogue beamforming stage. Fig. 1 demonstrates a comparison on the averaged spectral efficiency per user provided by the multiuser hybrid precoding and analogue beamforming over 200 system realisations. With perfect knowledge of the effective channel $\bar{\mathbf{H}}$ at the BS, the proposed hybrid precoding algorithm largely improves the spectral efficiency as compared with the analogue beamforming, owning to efficient mitigation of the inter-user interference. The performance gain is up to 7.1 bps/Hz, equivalent to an increase of 141%, in the high SNR regime where $SNR = 20dB$ and the system is interference limited. However, a small performance gap still exists, with a value around 2 bps/Hz between the hybrid precoding solution and the interference-free upper bound archieved by a single-user system.

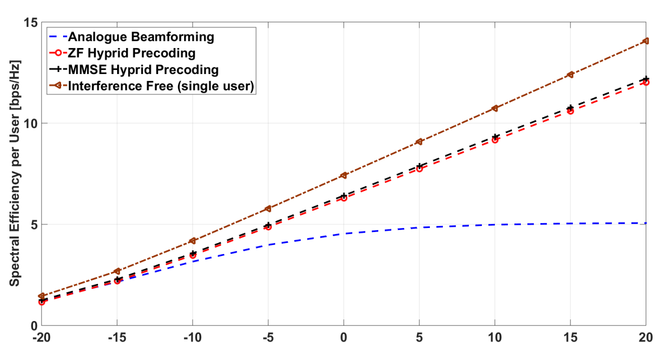

Fig. 1: Averaged spectral efficiency per user (in bits/s/Hz) achieved by multiuser hybrid precoding algorithm and analogue beamforming with random user selection

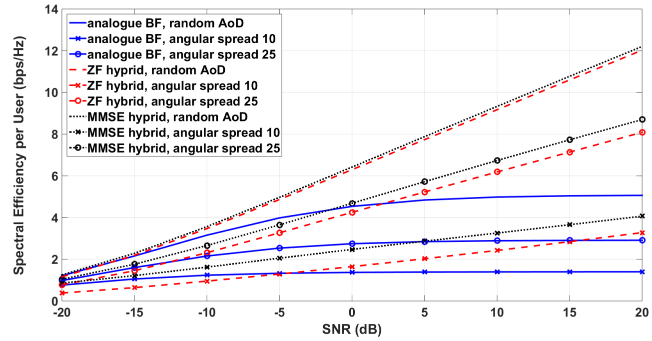

Fig. 2: Averaged spectral efficiency per user (in bits/s/Hz) achieved by multiuser hybrid precoding algorithm and analogue beamforming with users of different angular spread.

IV. User Selection Algorithm

A. User Selection Problem Formulation

The performance of the multiuser hybrid precoding algorithm depends on the K transmit vectors $\mathbf{b}_k$ designed in the analogue beamforming stage, which in turn depends on the propagation channel of the K users that are spatially multiplexed at the BS. Multiplexing users which selects the same or correlated transmit vectors could point the BS array towards directions that are angularly close, thus giving rise to an effective channel $\bar{\mathbf{H}}$ with unfavourable interference conditions. This is interpreted as a channel matrix $\bar{\mathbf{H}}$ with highly linearly dependent column vectors. Consider an example where the BS designs the same transmit vector b_e for both user 1 and user K. After the first stage, the produced effective channel $\bar{\mathbf{H}}$ is given as:

$$\bar{\mathbf{H}} = \begin{bmatrix} \mathbf{w}_1^H \mathbf{H}_1 \mathbf{b}_e & \mathbf{w}_1^H \mathbf{H}_1 \mathbf{b}_2 \cdots & \mathbf{w}_1^H \mathbf{H}_1 \mathbf{b}_{(K-1)} & \mathbf{w}_1^H \mathbf{H}_1 \mathbf{b}_e \\ \vdots & \vdots \quad \cdots & \vdots & \vdots \\ \mathbf{w}_K^H \mathbf{H}_K \mathbf{b}_e & \mathbf{w}_K^H \mathbf{H}_K \mathbf{b}_2 \cdots & \mathbf{w}_K^H \mathbf{H}_K \mathbf{b}_{(K-1)} & \mathbf{w}_K^H \mathbf{H}_K \mathbf{b}_e \end{bmatrix} \quad (13)$$

The matrix can not be diagonalised by the MU-MIMO precoder $\mathbf{P}$ designed in the second stage, which means that the inter-user interference, represented by the off-diagonal entries of $\bar{\mathbf{H}}$, can not be efficiently cancelled out.

This undesirable condition takes place when the AoD on the dominant path of the spatially multiplexed users (i.e.,

$\phi^{tx}_{LoS,k}$ for $k = 1, \cdots, K$) spans an interval that is narrow in angular domain and thus inseparable by the BS array. Fig 2 illustrates the averaged spectral efficiency per user achieved by a mmWave system in which the spatially multiplexed users have $\phi^{tx}_{LoS,k} \in [\bar{\phi} - \triangle\phi, \bar{\phi} + \triangle\phi]$, where $\bar{\phi} = 0$ and $\triangle\phi = \{10^\circ, 25^\circ\}$ represent the mean AoD and angular spread respectively. The performance of both the multiuser hybrid precoding and analogue beamforming degrades when users have narrow angular spread. For example, the spectral efficiency of the hybrid precoding solution decreases from 8.5 bps/Hz at $\triangle\phi = 25^\circ$ to 3.6 bps/Hz at $\triangle\phi = 10^\circ$, while the decrease for the analogue beamforming solution is around 1.5 bps/Hz, from 2.9 bps/Hz to 1.4 bps/Hz.

A feasible solution to this challenge involves implementing the proposed hybrid precoding algorithm with appropriate user selection. In order to obtain a favourable effective channel $\bar{\mathbf{H}}$, an easily computable (generally suboptimal) user selection algorithm is proposed in this paper. The algorithm evaluates the transmit vectors $\mathbf{b}_n$ designed for all of the N users after the beamforming stage and partitions the users into K non-overlapping groups according to the "angular distance" of the corresponding transmit vector. By selecting a single user from each group, the proposed algorithm prevents the BS from spatially multiplexing users with the same or correlated transmit vectors. To handle this selection, the pre-defined beamforming vectors in the BS codebook $\mathbf{W}_{BS}$ are indexed by consecutive integer q, ranging from 1 to $|\mathbf{W}_{BS}|$, the cardinality of the codebook. Consider the use of the beamforming codebook presented in [14] and Section III, where $|\mathbf{W}_{BS(MS)}| = 2 \times N_{BS(MS)}$. The associated index set is defined as $\mathcal{W} = 1, \cdots, |\mathbf{W}_{BS}|$, with its qth member indexing $[\mathbf{W}_{BS}]_{:,q}$, the qth column vector of the codebook matrix. The proposed user selection algorithm is presented below and summarised in Algorithm 1:

User Selection Algorithm:

- For each of the total N users:
  Select the beamforming vectors $\mathbf{b}^{opt}_n$ and $\mathbf{w}^{opt}_n$ from codebooks $\mathbf{W}_{BS}$ and $\mathbf{W}_{MS}$ respectively to maximise the desired received signal power:
  $$(\mathbf{b}^{opt}_n, \mathbf{w}^{opt}_n) = \underset{\substack{\forall \mathbf{b}_n \in \mathbf{W}_{BS} \\ \forall \mathbf{w}_n \in \mathbf{W}_{MS}}}{\arg\max} |\mathbf{w}^H_n \mathbf{H}_n \mathbf{b}_n|^2; \quad (14)$$
  For $[\mathbf{W}_{BS}]_{:,q} = \mathbf{b}^{opt}_n$, set $x_n = q$ and $r_n = |\mathbf{w}^{opt\,H}_n \mathbf{H}_n \mathbf{b}^{opt}_n|^2$ as the nth entry of the vectors $\mathbf{x}$ and $\mathbf{r}$;
  Note that x_n is the number indexing the transmit vector designed for user n and r_n is the received signal power of user n;
- Find the user with the maximum received signal power, e.g., indexed by n^{max}_1, and select this user as the first to be multiplexed by the BS: $\mathcal{S} = \{n^{max}_1\}$;
- Quantize the index set $\mathcal{W}$ for the BS codebook $\mathbf{W}_{BS}$ into $N_g = K$ disjoint subsets: $\mathcal{W}_1, \cdots, \mathcal{W}_{N_g}$, each of size $N_{sg} = \frac{|\mathbf{W}_{BS}|}{N_g}$, with members wrapped around those in $\mathcal{W}$ while satisfying that the centre member of $\mathcal{W}_1$ is $x^{max}_{n_1}$;
- Partition the N users into N_g groups by "putting" user n into group g if $x_n \in \mathcal{W}_g$, which means that the index of the transmit vector of user n is found within the gth index subset;
- For iteration g, $g = 2, \cdots, N_g$,:
  Evaluate the user n_g in the gth group, find the user that maximises the metric ξ_{n_g} defined in Equation (15) and (16), e.g., indexed by n^{max}_g, and select this user as the gth to be multiplexed by the BS: $\mathcal{S} = \mathcal{S} \bigcup \{n^{max}_g\}$;
  $$\xi_{n_g} = r_{n_g} \prod_{i=2}^{g} \sin\left(\frac{\triangle q_{(n_g,i-1)}}{2}\right), \quad (15)$$
  $$\triangle q_{(n_g,i-1)} = \frac{\pi}{|\mathbf{W}_{BS}|} |x_{n_g} - x_{n^{max}_{i-1}}|, \quad (16)$$
  where r_{n_g} is the received signal power for user n_g. $\triangle q_{(n_g,i-1)}$ is a measure of the angular distance between the direction pointed via the transmit vector designed for user n_g to that for user n^{max}_{i-1}, which is the user selected in the $(i-1)$th group;
- Spatially multiplex the $K = N_g$ users selected in the set $\mathcal{S} = \{n^{max}_1, \cdots, n^{max}_K\}$ at the BS and define the transmit beamforming matrix as $\mathbf{B} = [\mathbf{b}^{opt}_{n^{max}_1}, \cdots, \mathbf{b}^{opt}_{n^{max}_K}]$.

Algorithm 1 User Selection Algorithm

Input: N, N_{BS}, N_{MS}, N_{RF}, $K = N_{RF}$, $\mathbf{W}_{BS}$, $\mathbf{W}_{MS}$
Output: $\mathcal{S}$, $\mathbf{B}$
$\mathbf{x} = \mathbf{0}$, $\mathbf{r} = \mathbf{0}$, $\mathcal{S} = \emptyset$, $\mathcal{W} = 1, \cdots, |\mathbf{W}_{BS}|$, $N_g = K$, $N_{sg} = \frac{|\mathbf{W}_{BS}|}{N_g}$
for $n = 1$ to N **do**
  Design $\mathbf{b}^{opt}_n$ and $\mathbf{w}^{opt}_n$ using Equation (14)
  $x_n = q \Leftarrow [\mathbf{W}_{BS}]_{:,q} = \mathbf{b}^{opt}_n$
  $r_n = |\mathbf{w}^{opt\,H}_n \mathbf{H}_n \mathbf{b}^{opt}_n|^2$
end for
$n^{max}_1 = \underset{\forall n \in \{1,\cdots,N\}}{\arg\max}\; r_n$
$\mathcal{S} = \mathcal{S} \bigcup \{n^{max}_1\}$
$q^{beg}_1 = x^{max}_{n_1} - round(\frac{N_{sg}}{2})$, $q^{end}_1 = q^{beg}_1 + N_{sg} - 1$
$\mathcal{W}_1 = \{q^{beg}_1, \cdots, q^{end}_1\}$, $\mathcal{U}_1 = \emptyset$
for $g = 2$ to N_g **do**
  $q^{beg}_g = q^{beg}_{(g-1)} + N_{sg}$, $q^{end}_g = q^{end}_{(g-1)} + N_{sg}$
  $\mathcal{W}_g = \{q^{beg}_g, \cdots, q^{end}_g\}$, $\mathcal{U}_g = \emptyset$
end for
for $n = 1$ to N **do**
  if $x_n \in \mathcal{W}_g$ **then**
    $\mathcal{U}_g = \mathcal{U}_g \bigcup \{n\}$
  end if
end for
for $g = 2$ to N_g **do**
  for all $\mathcal{U}_g$ **do**
    Calculate ξ_{n_g} using Equation (15) and (16)
  end for
  $n^{max}_g = \arg\max \xi_{n_g}$
  $\mathcal{S} = \mathcal{S} \bigcup \{n^{max}_g\}$
end for
$\mathcal{S} = \{n^{max}_1, \cdots, n^{max}_K\}$
$\mathbf{B} = [\mathbf{b}^{opt}_{n^{max}_1}, \cdots, \mathbf{b}^{opt}_{n^{max}_K}]$

TABLE I: Simulation Parameters

Simulation Parameters	Value
Number of antennas at the BS N_{BS}	32
Number of antennas at users N_{MS}	8
Number of BS RF chains N_{RF}	4
Number of spatially nultiplexed users K	4
Number of system realizations	200
Channel model	LoS propagation channel [13]
Distance between the BS and user [m]	3
Codebook design $\mathbf{W}_{MS}$ and $\mathbf{W}_{MS}$	Codebook matrix in [14]
Analogue beamforming method	Exhaustive search

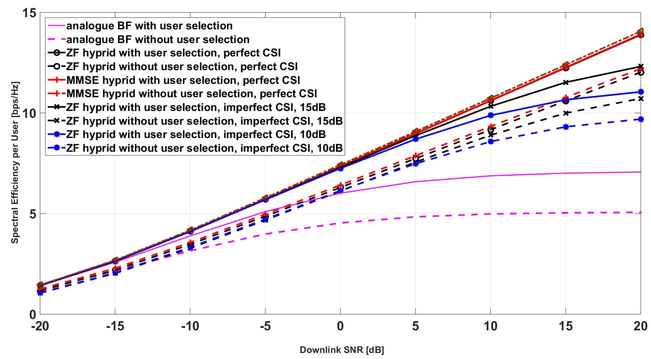

Fig. 3: Averaged spectral efficiency per user (in bits/s/Hz) archived by multiuser hybrid precoding algorithm and analogue beamforming with and without appropriate user selection

For the proposed user selection algorithm, the BS acquires a global knowledge of the transmit vectors designed for each of the N users after the analogue beamforming stage and selects the appropriate users without further feedback requirement from the users. Note that Equation (15) and (16) are valid only in the case where the BS beamforming vectors indexed by adjacent numbers point the array towards angular directions which are most close.

V. Simulation Results

This section presents the simulation results to compare the performance of the multiuser hybrid precoding and analogue beamforming with and without the proposed user selection algorithm. The comparison is carried out in terms of the averaged spectral efficiency per user, $R_{avr} = \sum_{k=1}^{K} \frac{R_k}{K}$ with R_k derived using Equation (6), over 200 system realisations. The numerical results are provided by considering the system model presented in Section II in the software simulation. The simulation parameters are listed in Table I.

Fig. 3 illustrates an overall comparison on the averaged spectral efficiency per user achieved with and without the proposed user selection algorithm. The SNR in the plot is defined as $SNR_{dl(ul)} = \frac{P\mathbb{E}[|\alpha_{l,k}|^2]}{K\sigma^2_{d(u)}}$. It is noted that, throughout all SNR values, the performance of both the multiuser hybrid precoding and analogue beamforming improves by implementing the user selection algorithm proposed in Section IV. In particular, the spectral efficiency given by the analogue beamforming solution increases up to 2 bps/Hz, i.e., from 5.1 bps/Hz to 7.1 bps/Hz, amount to an improvement of 39.5%, when downlink $SNR_{dl} = 20dB$. In the low SNR regime, the performance of the analogue beamforming with appropriate user selection even surpasses that of the hybrid precoding with random selection. The performance gain is thanks to the user selection algorithm producing a beamforming matrix $\mathbf{B}$ which points the BS array towards K well-separated angular directions without overlaps, thus, causing little co-channel interference.

Compared with the analogue beamforming solution, the performance of the hybrid precoding algorithm benefits from the MU-MIMO precoder designed in the digital domain. The performance improvement has been well demonstrated in all three figures. With the proposed user selection algorithm, the multiuser hybrid precoding achieves a performance close to the interference-free limit given by a single-user system where no interference exists. For the zero-forcing-based hybrid precoding, the spectral efficiency increases from 12.02 bps/Hz with random user selection to 13.88 bps/Hz with appropriate user selection, i.e., 15.48% improvement, at $SNR_{dl} = 20dB$. The MMSE-based hybrid precoding provides a similar performance gain, i.e., an increase from 12.20 bps/Hz to 13.91 bps/Hz, equivalent to an improvement of 14.01%. The performance gain achieved by the hybrid precoding and analogue beamforming solutions are equal in absolute value, i.e., around 2 bps/Hz, while varying in percentage, at 15% and 39% respectively. The reason is that, for analogue beamforming, the inter-user interference is mainly suppressed by the proposed user selection algorithm. However, the interference, for hybrid precoding, is also cancelled out by the digital precoder.

Fig. 3 also shows a comparison on the performance of the ZF-based multiuser hybrid precoding with perfect and imperfect knowledge of the effective channel $\bar{\mathbf{H}}$. For CSI estimation using uplink pilots, as described in section II, the pilot sequence is of length $\tau = K$. It is shown that the overall achievable spectral efficiency degrades with imperfect CSI, due to the channel estimation error from the uplink training. In particular, when downlink $SNR_{dl} = 20dB$, the spectral efficiency achieved with appropriate user selection is 12.31 bps/Hz at uplink $SNR_{ul} = 15dB$ and 11.05 bps/Hz at $SNR_{ul} = 15dB$, corresponding to a performance degradation of 1.57 bps/Hz and 2.83 bps/Hz respectively as compared with the perfect CSI case. Even though, the proposed user selection algorithm still provides a performance improvement when compared with its random counterpart, that is, an increase of 1.59 bps/Hz (15%) and 1.35 bps/Hz (14%) at $SNR_{ul} = 15dB$ and $SNR_{ul} = 10dB$ respectively.

The novel user selection algorithm proposed in Section IV enables the BS to optimally multiplex K out of N users in order to maximise the averaged spectral efficiency per user. This, however, is not a global optimisation for the overall system. A user selection algorithm that enables every single user in the system to be optimally multiplexed at the BS in the spatial domain is still under development.

VI. Conclusions

In this paper, a low-complexity user selection algorithm is proposed for downlink multiuser mmWave systems. The proposed user selection algorithm enables a multiplexing where the spatially multiplexed users cause little co-channel interference and thus maximises the averaged spectral efficiency per user. Simulation results show that the algorithm improves the performance provided by both the analogue beamforming and hybrid precoding solutions with or without perfect knowledge of the effective channel. When perfect CSI is available, the spectral efficiency achieved by implementing the multiuser hybrid precoding with the proposed user selection is close to the interference-free limit of a single-user system where no inter-user interference exists.

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