Hybrid Beamforming for Single-User MIMO with Partially Connected RF Architecture

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Abstract—Hybrid analog-digital beamforming has been recognized as a promising solution for a practical implementation of massive multiple-input multiple-output (MIMO) systems based on millimeter-wave technology. In this paper, three hybrid beamforming algorithms are proposed for single-user MIMO systems with partially connected radio frequency (RF) architecture, including a singular value decomposition (SVD) matching algorithm, an iterative orthogonalization algorithm, and a transmit-receive zero forcing (ZF) algorithm. The rate performance of the proposed algorithms is compared with fully digital and analog beamforming in a realistic geometry-based stochastic channel model. The simulation results show that the transmit-receive ZF is superior among hybrid methods, and it provides performance relatively close to that of the digital beamforming. In conclusion, carefully designed partially connected hybrid beamforming can obtain an excellent balance between hardware complexity and performance.

Index Terms—hybrid precoding, massive MIMO, mm-wave communications, ZF beamforming.

I. INTRODUCTION

Current cellular networks suffer from the shortage of spectral resources to meet the capacity and performance requirements of the upcoming 5th generation (5G) systems. Millimeter-wave (mm-wave) technology has been proposed as a solution to provide a vast range of spectrum that can be leveraged in combination with massive multiple-input multiple-output (MIMO) systems [1], [2]. The shorter wavelength of mm-wave signals allows more small-sized antennas to be packed in the same area as in the case of former generations with lower frequencies. Consequently, massive MIMO technology utilizing a large number of antennas can be used to produce narrow beams with high array gains to combat severe propagation losses that occur in mm-wave frequencies. Massive MIMO enables reasonable link distances and high throughputs via beamforming and spatial multiplexing [3]–[5].

Beamforming is a transmission technique in which the transmitted data stream is weighted with different phases and powers at each antenna element in order to form a directed beam pattern. Conventional beamforming can be divided into analog and digital beamforming techniques. In analog beamforming, the transmitted stream is weighted using phase shifters and variable gain amplifiers. Analog beamforming can

support only one-stream transmission and is not viable for multi-stream case [6]. To exploit the full potential of both spatial multiplexing and beamforming in a MIMO system, fully digital beamforming architecture is leveraged [7], [8]. Implementing a fully digital MIMO beamformer requires one radio frequency (RF) chain per antenna element. Due to the high number of power-hungry RF components, such as digital-to-analog converters (DACs), in conventional digital beamforming, the practical implementation of a massive MIMO system requires new approaches to be realized [2], [6]. As a solution, the combination of both digital and analog beamforming, using a limited number of RF chains, known as hybrid beamforming (HBF) has been considered.

HBF splits the whole beamforming process into digital and analog parts, that enables multi-stream transmissions with a reduced complexity [6], [7]. Various HBF methods are proposed for fully and partially connected RF architectures in the literature [9]–[13], ranging from theoretical rate maximizing solutions to heuristic algorithms. In a fully connected HBF architecture, each RF chain is connected to all antennas [7], [10]. For a practical implementation of a mm-wave massive MIMO system, the fully connected structure may be too complex to be used due to very challenging and lossy RF signal division and combining processes. A more practical solution is to use partially connected RF architecture, in which each RF chain is connected only to a subset of the antenna array, called a sub-array [14], [15].

Partially connected RF architecture itself can be divided into two categories, i.e., full-array-based and sub-array-based processing structures. In full-array-based processing, all data streams are conveyed to all sub-arrays. Thus, each stream is transmitted via its corresponding beam which is generated by using all sub-arrays and their antennas. This implies that full beamforming gain is potentially available. However, the directions of different beams are interdependent due to the partial connectivity. This sets restrictions to the beam generation and leads to suboptimal beam directions. In sub-array-based processing, each sub-array transmits only a single data stream. This leads to a more efficient and flexible beam design process. However, the beamforming gain is limited by the number of antennas per sub-array.

Most of the HBF works in the literature use only phase shifting in the analog beamforming process [10]–[13]. However, employing analog amplitude control in addition to phase

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shifting is a feasible assumption [15]. Even though this will somewhat increase the hardware complexity, the hybrid beamforming design becomes more flexible and efficient leading to improved performance. As an example, fully connected HBF with only analog phase shifting can obtain the same performance as fully digital beamforming only if the number of RF chains is twice the number of data streams [7]. In comparison, HBF with both analog phase shifting and amplitude control can provide equal performance compared to fully digital beamforming when the number of RF chains and streams is the same. Due to the scarcity of algorithms and performance evaluations in the literature, partially connected HBF with both analog amplitude and phase control needs further studying, especially comparison between full-array and sub-array processing based approaches.

In this paper, three HBF algorithms are proposed for single-user (SU) MIMO systems with partially connected RF architecture. In the analog RF part at the transmitter, both phase shifting and amplitude control are assumed to be used. First two of the proposed HBF algorithms are designed for full-array-based processing structure while the third one is developed for sub-array-based processing. The first hybrid approach is a singular value decomposition (SVD) matching algorithm that minimizes the least squared error between the hybrid beamformers and the optimal digital SVD-based beamformers. The second method aims at orthogonalizing different transmitted streams in an iterative manner. The third one is an iterative transmit-receive zero forcing (ZF) algorithm that aims at canceling inter-stream interference using ZF beamforming at both transmitter and receiver. All the proposed algorithms employ waterfilling principle for power allocation. The rate performance of the hybrid algorithms is evaluated using a practical geometry-based stochastic channel model, and compared with the fully digital and analog beamforming solutions.

The rest of the paper is organized as follows. In Section II, the employed system model and the problem formulation is presented. Section III describes the proposed HBF algorithms for SU-MIMO systems with partially connected architecture. The simulation results are presented and discussed in Section IV. Finally, Section V concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A narrowband single-cell SU-MIMO system with a base station (BS) working in downlink (DL) mode is considered. The BS is assumed to be equipped with N antennas and N_A RF chains. HBF is considered only in the BS side and the user is assumed to use digital beamforming due to the relatively low number of receive antennas. Moreover, the employed HBF structure is considered to be partially connected in which each RF chain is connected to only one sub-array of antennas. Hence, N transmit antennas are divided into N_A subarrays, each with $n = N/N_A$ antennas. The user is considered to have M receive antennas and to require N_s data streams. It is assumed that the number of data streams is equal to the number of RF chains, i.e., $N_s = N_A$.

Fig. 1: High-level system model

The high-level system model is depicted in Fig. 1, in which data streams are first modified digitally at baseband using a digital precoder matrix, $V_D \in \mathbb{C}^{N_A \times N_s}$. As discussed in section I, partially connected hybrid architecture can be divided into two categories, i.e., full-array and sub-array-based processing structures. In the case of full-array-based processing method, where all data streams are connected to all RF chains, V_D can be expressed as

$$V_D = \begin{pmatrix} d_{11} & \dots & d_{1N_s} \\ \vdots & \ddots & \vdots \\ d_{N_A 1} & \dots & d_{N_A N_s} \end{pmatrix} \quad (1)$$

In the case of sub-array-based processing method, where each data stream is connected to only one RF chain, V_D becomes a diagonal matrix as $V_D = \text{diag}(d_{11}, d_{22}, \dots, d_{N_A N_s})$. Then after up-converting to carrier frequency by using N_A DACs, an analog RF precoder, $V_A \in \mathbb{C}^{N \times N_A}$, is employed to construct the transmitted signal. This analog RF precoder can be expressed as

$$V_A = \begin{pmatrix} \mathbf{a}_1 & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{a}_2 & \dots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{a}_{N_A} \end{pmatrix} \quad (2)$$

where $\mathbf{a}_i \in \mathbb{C}^{n \times 1}$, $i = 1, 2, \dots, N_A$, is the analog RF precoder of i th subarray, and $\mathbf{0} \in \mathbb{C}^{n \times 1}$ is a zero vector. The transmitted signal vector can be written as

$$\mathbf{x} = \mathbf{V}\mathbf{s} \quad (3)$$

where $\mathbf{s} \in \mathbb{C}^{N_s \times 1}$ is the vector of data symbols with $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \mathbf{I}_{N_s}$, and $\mathbf{V}$ is the hybrid precoder generated by $\mathbf{V} = \mathbf{V}_A \mathbf{V}_D$. The received signal vector by the user, after the digital combiner, $\mathbf{W} \in \mathbb{C}^{M \times N_s}$, can be modeled as

$$\mathbf{y} = \mathbf{W}^H \mathbf{H} \mathbf{x} + \mathbf{W}^H \mathbf{z} \quad (4)$$

where $\mathbf{H} \in \mathbb{C}^{M \times N}$ is the matrix of complex channel gains, and $\mathbf{z} \sim \mathcal{CN}(\mathbf{0}, N_0 \mathbf{I}_M)$ denotes additive white Gaussian noise vector. The overall rate of such a system, assuming Gaussian signalling is [8]

$$R = \log_2 |\mathbf{I} + \frac{1}{N_0} (\mathbf{W}^H \mathbf{W})^{-1} \mathbf{W}^H \mathbf{H} \mathbf{V} \mathbf{V}^H \mathbf{H}^H \mathbf{W}| \quad (5)$$

The most common optimization problem is to maximize the overall rate under total transmit power constraint at the BS,

assuming the perfect knowledge of the channel matrix $\mathbf{H}$. This optimization problem can be formulated as

$$\begin{aligned} & \underset{\{\mathbf{V}_A, \mathbf{V}_D, \mathbf{W}\}}{\text{maximize}} \quad R(\mathbf{V}_A, \mathbf{V}_D, \mathbf{W}) \\ & \text{s.t.} \quad \text{tr}(\mathbf{V}_A \mathbf{V}_D \mathbf{V}_D^H \mathbf{V}_A^H) \leq P \end{aligned} \quad (6)$$

where P is the total power budget at the BS. This problem is non-convex and cannot be solved in its original form. Suboptimal solutions can be derived by using convex approximation methods. However, the computational complexity of such suboptimal algorithms is usually very high. Therefore, in this paper, we focus on developing heuristic algorithms with lower complexity.

III. HYBRID BEAMFORMING ALGORITHMS

In this section, three HBF algorithms are proposed for SU-MIMO with partially connected RF architecture. The first two algorithms are designed for a full-array-based processing structure while the third one is developed for a sub-array-based processing approach.

A. Full-array-based Processing

1) *SVD Matching*: This algorithm formulates the HBF as a least squares problem where the goal is to minimize the sum of the squares of errors between the optimal SVD and hybrid beamformers. In addition to matching, digital beamforming coefficients can also be used to orthogonalize different streams. This optimization problem can be formulated as

$$\begin{aligned} & \underset{\{\mathbf{V}_A, \mathbf{V}_D\}}{\text{minimize}} \quad \|\mathbf{V}_{\text{opt}} - \mathbf{V}_A \mathbf{V}_D\|_F \\ & \text{s.t.} \quad (\mathbf{V}_A \mathbf{V}_D)_i^H (\mathbf{V}_A \mathbf{V}_D)_j \leq \tau \quad \forall i \neq j \end{aligned} \quad (7)$$

where the objective is to minimize the difference between the optimal SVD beamformer $\mathbf{V}_{\text{opt}}$ and the hybrid beamformer $\mathbf{V}_A \mathbf{V}_D$ subject to the requirement for orthogonality between different columns i and j of $\mathbf{V}_A \mathbf{V}_D$. In (7), τ is a fixed threshold for the level of orthogonality. Problem (7) is non-convex with respect to the joint analog and digital beamformers. However, it becomes convex with respect to the analog beamformer when the digital beamformer is fixed, and vice versa. The main idea behind this optimization method is to alternate between these two optimization phases until a certain level of convergence is reached. The optimization problem for the analog beamformer can be written as

$$\underset{\{\mathbf{V}_A\}}{\text{minimize}} \quad \|\mathbf{V}_{\text{opt}} - \mathbf{V}_A \mathbf{V}_D\|_F \quad (8)$$

where the only variable is the analog precoder $\mathbf{V}_A$. The digital beamforming coefficients are optimized as

$$\begin{aligned} & \underset{\{\mathbf{V}_D\}}{\text{minimize}} \quad \|\mathbf{V}_{\text{opt}} - \mathbf{V}_A \mathbf{V}_D\|_F \\ & \text{s.t.} \quad (\mathbf{V}_A \mathbf{V}_D)_i^H (\mathbf{V}_A \mathbf{V}_D)_j \leq \tau \quad \forall i \neq j \end{aligned} \quad (9)$$

The constraints in (9) guarantee a predefined level of orthogonality between the columns of the overall hybrid beamformer. This alternating optimization process is continued until the difference between two subsequent iterations is below a certain threshold or a maximum number of iterations is reached.

Algorithm 1 SVD Matching algorithm

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1: Initialize  $\mathbf{V}_D$ 
2: repeat
3:   Calculate  $\mathbf{V}_A$  while  $\mathbf{V}_D$  is fixed using (8)
4:   Calculate  $\mathbf{V}_D$  while  $\mathbf{V}_A$  is fixed using (9)
5: until meeting {Threshold | Max iterations}
6:  $\tilde{\mathbf{V}} \leftarrow \text{normalize } \mathbf{V}_A \mathbf{V}_D$ 
7:  $\mathbf{W} = \mathbf{H} \tilde{\mathbf{V}}$ 
8: Calculate power allocations  $\{P_i\}, i = 1, 2, \dots, N_s$  via WF using (10), (11)
9:  $\mathbf{V} \leftarrow \sqrt{P} \tilde{\mathbf{V}}$ 
10: return  $\mathbf{V}$  and  $\mathbf{W}$ 

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Then each column vector of the resulting overall transmit beamformer is normalized and the normalized overall beamformer $\tilde{\mathbf{V}}$ is employed to calculate the receive combiner as $\mathbf{W} = \mathbf{H} \tilde{\mathbf{V}}$, and each column of $\mathbf{W}$ is normalized, as well.

To maximize the overall rate, waterfilling (WF) algorithm is employed to allocate power P_i to the i th stream as

$$P_i = (\mu - \frac{N_0}{\epsilon_i})^+ \quad (10)$$

where μ is the water level constant, and the channel gain for the i th stream can be calculated as

$$\epsilon_i = |\mathbf{w}_i^H \mathbf{H} \tilde{\mathbf{v}}_i|^2 \quad (11)$$

where $\tilde{\mathbf{v}}_i$ and $\mathbf{w}_i$ are the i th column of the normalized overall precoder and the digital combiner, respectively. The total transmit power is limited by $\sum_{i=1}^{N_s} P_i = P$. The overall hybrid precoding matrix is formed as $\mathbf{V} = \sqrt{P} \tilde{\mathbf{V}}$ where $\mathbf{P} = \text{diag}(P_1, P_2, \dots, P_{N_s})$. The SVD matching algorithm is summarized in Algorithm 1.

2) *Iterative orthogonalization*: This algorithm aims at orthogonalizing all columns of the overall beamforming matrix in order to get rid of inter-stream interference. Since no convex optimization is required in this algorithm, its computational complexity is much lower in comparison with the SVD matching algorithm. To begin with, the analog beamformer is initialized with the first right singular vector of the fully digital SVD beamformer. Digital coefficients are used to orthogonalize different columns of the beamforming matrix by requiring the dot product between two columns to be zero. This orthogonality requirement can be expressed as

$$\mathbf{v}_i^H \mathbf{v}_j = 0 \quad \forall i \neq j \quad (12)$$

where $\mathbf{v}_i$ is the i th column of the overall precoder $\mathbf{V}$. Keeping the analog coefficients fixed, the digital ones are used to orthogonalize columns as

$$d_{i1} d_{j1} \sum_{k=1}^N |a_{k1}|^2 + \dots + d_{iN_s} d_{jN_s} \sum_{k=1}^N |a_{kN_s}|^2 = 0 \quad (13)$$

where a_{kl} , $l = 1, 2, \dots, N_A$, is the k th element of the l th column of the analog precoder $\mathbf{V}_A$. Since the coefficients ensuring orthogonality between two columns are calculated individually, the value of a coefficient becomes invalid after updating other fixed coefficients. Hence, the digital precoding

Algorithm 2 Iterative Orthogonalization algorithm

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1: SVD:  $\mathbf{H} = \mathbf{\Gamma}\mathbf{\Sigma}\mathbf{\Lambda}^H$ 
2: Block diagonal entries of  $\mathbf{V}_A \leftarrow$  first column of  $\mathbf{\Lambda}$ 
3:  $\mathbf{V}_D \leftarrow \mathbf{1}$ 
4: for  $ii = 2 : N_s$  do
5:   repeat
6:     for stream = 2 :  $ii$  do
7:       for subarray = 1 :  $ii$  do
8:         Calculate digital coefficients from (13)
9:       end for
10:    end for
11:  until meeting {Orth. threshold | Max iterations}
12:   $\tilde{\mathbf{V}} \leftarrow$  normalize  $\mathbf{V}_A \mathbf{V}_D$ 
13:   $\mathbf{W} = \mathbf{H}\tilde{\mathbf{V}}$ 
14:  Calculate power allocations  $\{P_i\}$ ,  $i = 1, 2, \dots, N_s$  via WF
    using (10), (11)
15:   $\mathbf{V} \leftarrow \sqrt{\mathbf{P}}\tilde{\mathbf{V}}$ 
16:  Calculate rate for  $ii$  number of streams using (5)
17: end for
18: return  $\mathbf{V}$  and  $\mathbf{W}$  with highest rate

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coefficients need to be solved iteratively. Iterations are continued until orthogonality between every two columns is smaller than a threshold, or until a maximum number of iterations is reached. Finally, WF algorithm is applied in the same way as in the SVD matching algorithm to allocate the total power P to different streams. The orthogonalized precoders and the corresponding powers are calculated for different number of streams. Then the number of streams that maximizes the overall rate and its corresponding precoder matrix are selected for transmission. The overall hybrid method is depicted in Algorithm 2.

B. Sub-array-based Processing

1) *Transmit-Receive ZF*: This algorithm aims at canceling the interference from other subarrays by using ZF beamforming in both transmitter and receiver. Since sub-array-based processing is assumed, the duty of the digital precoding part is to only route one stream to each sub-array, i.e., all digital coefficients are set to one in diagonal $\mathbf{V}_D$ matrix. Hence, beamforming is performed only at the analog RF part of each subarray, i.e., $\mathbf{V} = \mathbf{V}_A = \mathbf{V}_A \mathbf{V}_D$.

In the algorithm, the overall combiner $\mathbf{W}$ is first initialized with N_s left singular vectors of the SVD of the overall channel $\mathbf{H}$. Then ZF precoder is calculated separately for each subarray considering the effective channel $\mathbf{W}^H \mathbf{H}_i$ as

$$\mathbf{V}_i = \mathbf{H}_i^H \mathbf{W} (\mathbf{W}^H \mathbf{H}_i \mathbf{H}_i^H \mathbf{W})^{-1} \quad (14)$$

where $\mathbf{V}_i \in \mathbb{C}^{n \times N_s}$ is the overall precoder corresponding to the i th subarray, and $\mathbf{H}_i \in \mathbb{C}^{M \times n}$ is the channel matrix between the i th subarray and the user. Since sub-array-based processing is used, the i th column of $\mathbf{V}_i$ is picked and normalized as the precoder of the i th subarray. The normalized per-sub-array precoders are stacked into $\tilde{\mathbf{V}} \in \mathbb{C}^{N \times N_s}$, where the entries of other sub-arrays than i are set to zeros in the i th column. The next step is to calculate ZF combiner with effective channel $\mathbf{H}\tilde{\mathbf{V}}$ as

$$\mathbf{W}^H = (\tilde{\mathbf{V}}^H \mathbf{H}^H \mathbf{H} \tilde{\mathbf{V}})^{-1} \tilde{\mathbf{V}}^H \mathbf{H}^H \quad (15)$$

Algorithm 3 Transmit-Receive ZF algorithm

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1: SVD:  $\mathbf{H} = \mathbf{\Gamma}\mathbf{\Sigma}\mathbf{\Lambda}^H$ 
2:  $\mathbf{W} \leftarrow$  first  $N_s$  columns of  $\mathbf{\Gamma}$ 
3: repeat
4:   for  $i = 1 : N_s$  do
5:      $\mathbf{V}_i \leftarrow \mathbf{H}_i^H \mathbf{W} (\mathbf{W}^H \mathbf{H}_i \mathbf{H}_i^H \mathbf{W})^{-1}$ 
6:     Sub-array  $i$  entries of  $i$ th column of  $\tilde{\mathbf{V}} \leftarrow$  normalized  $i$ th
       column of  $\mathbf{V}_i$ 
7:   end for
8:    $\mathbf{W}^H \leftarrow (\tilde{\mathbf{V}}^H \mathbf{H}^H \mathbf{H} \tilde{\mathbf{V}})^{-1} \tilde{\mathbf{V}}^H \mathbf{H}^H$ 
9: until meeting { $R$  threshold | Max iterations}
10: Calculate power allocations  $\{P_i\}$ ,  $i = 1, 2, \dots, N_s$  via WF using
    (10), (11)
11:  $\mathbf{V} \leftarrow \sqrt{\mathbf{P}}\tilde{\mathbf{V}}$ 
12: return  $\mathbf{V}$  and  $\mathbf{W}$ 

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and normalize all columns of $\mathbf{W}$, one by one. Transmit-receive ZF process is repeated until a desired level of convergence is achieved in terms of rate. Then WF algorithm, similar to (10), (11), is employed to allocate powers to different streams. The overall transmit-receive ZF method is summarized in Algorithm 3.

IV. SIMULATION RESULTS

In this section, the performance of the proposed HBF algorithms is evaluated in a geometry-based stochastic channel model, and compared with the fully digital beamforming (i.e., SVD) and the fully analog beamforming (i.e., SVD Rank 1). In particular, it is studied that how the performance is affected by increasing the number of antennas and streams. The SU-MIMO simulation model consists of a BS serving a user in DL mode. A relatively large number of antennas is used at the transmitter side in order to reflect the nature of a massive MIMO type of setting. The rate performance is averaged over 100 channel realizations, and it is examined against SNR. The SNR is given by P/N_0 , and N_0 is normalized to 1. The channel is considered as frequency flat with a normalized pathloss.

The MIMO channel realizations are generated by using the Quasi Deterministic Radio channel Generator (QuaDRiGa) [16], which is an extension of Wireless World Initiative for New Radio (WINNER) channel model with new features to make it more realistic. QuaDRiGa follows a geometry-based stochastic modeling approach, in which the channel parameters are determined stochastically, based on statistical distributions extracted from channel measurements [16]. Moreover, QuaDRiGa is an antenna independent channel model, i.e. it supports different antenna configurations and patterns. In this paper, measurements conducted by Centre for Wireless Communications (CWC) at the University of Oulu, Oulu, Finland, for 10 GHz, presented in [17], [18] are inserted in the QuaDRiGa channel model. These measurements were carried out at the campus of the University of Oulu for both line-of-sight (LOS) and non-line-of-sight (NLOS) cases [17], [18].

Fig. 2 presents average rate as a function of SNR in Quadriga outdoor NLOS and LOS scenarios for $N = 64$, $M = 8$, $N_s = 4$. It can be seen that the transmit-receive

(a) Outdoor LOS

(b) Outdoor NLOS

Fig. 2: Average rate vs. SNR for $N = 64$, $M = 8$, $N_s = 4$

ZF is superior among hybrid algorithms at medium and high SNRs. The SVD matching algorithm is slightly better in low SNR region but starts to saturate at higher SNRs falling even behind the iterative orthogonalization method. All hybrid algorithms significantly outperform the analog beamforming solution. There is a moderate performance gap between the optimal digital solution and the transmit-receive ZF scheme. This is mainly due to sub-array-based beamforming providing lower array gains. The performance in NLOS channel is better than in LOS channel due to the better spatial separability properties of different streams.

In Fig. 3, the number of transmit antennas is increased to $N = 128$ while other parameters remain the same as in Fig. 2. The results show that the superiority of the transmit-receive ZF is slightly emphasized. For example, in NLOS channel, it is always better than other hybrid methods, even at low SNRs. The same behavior is seen for the increased number of receive antennas, i.e., $M = 16$, in Fig. 4, where the transmit-receive ZF outperforms others in both NLOS and LOS channels.

In Fig. 5, the entire system size is increased including the number of streams, i.e., $N = 128$, $M = 16$, $N_s = 8$. One can see that the transmit-receive ZF is superior in medium and high SNR regions while the SVD matching is the best at low SNRs. The iterative orthogonalization is the worst in all SNRs. The results also show that the performance gap between the optimal digital solution and hybrid beamforming is increased

(a) Outdoor LOS

(b) Outdoor NLOS

Fig. 3: Average rate vs. SNR for $N = 128$, $M = 8$, $N_s = 4$

due to the limited beamforming gain.

As a conclusion, it seems that the flexible beamforming design of the sub-array-based hybrid processing (i.e., transmit-receive ZF) plays a key role for achieving a proper performance, especially for providing similar performance scaling with the increasing SNR as the fully digital beamforming. Nevertheless, there is still room for improvements for hybrid beamforming design based on full-array processing.

V. CONCLUSION

In this paper, several HBF algorithms were proposed for SU-MIMO communications with partially connected RF architecture, including SVD matching, iterative orthogonalization, and transmit-receive ZF algorithms. The first two algorithms were developed for full-array-based processing strategy while the third one for sub-array-based processing. The rate performance of the hybrid algorithms was evaluated and compared to the fully digital and analog solutions using a realistic QuaDRiGa channel model with outdoor NLOS and LOS scenarios. For the chosen system settings, the transmit-receive ZF is superior among hybrid methods, especially at medium and high SNRs. A moderate performance gap compared to the optimal digital method is due to the limited array gain of sub-array-based beamforming. The results imply that partially connected HBF can provide a good balance between performance and hardware complexity. However, further research is still needed to

(a) Outdoor LOS

(b) Outdoor NLOS

Fig. 4: Average rate vs. SNR for $N = 64$, $M = 16$, $N_s = 4$

(a) Outdoor LOS

(b) Outdoor NLOS

Fig. 5: Average rate vs. SNR for $N = 128$, $M = 16$, $N_s = 8$

find most suitable hybrid methods for practical 5G channel conditions using relevant cm- and mm-wave frequencies with realistic pathloss models.

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