Hybrid Precoding for mmWave MIMO Systems With Overlapped Subarray Architecture

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ABSTRACT Traditional precoding is incompatible with millimetre wave (mmWave) multiple input multiple output (MIMO) systems due to hardware costs and power consumption. As a result, hybrid precoding is being considered as a promising technology for balancing hardware complexity and system performance. This paper proposes a hybrid precoding technique for overlapped subarrays (OSA) architecture in mmWave MIMO systems. It exploits the OSA’s structure to decompose the hybrid precoding problem into a series of $L_tN_s/2$ subproblems and then solves them iteratively, where $L_t$ and $N_s$ are the numbers of RF chains and transmitted data streams, respectively. First, the proposed scheme determines the analog and digital precoding submatrices of each OSA iteratively and then constructs the analog and digital precoding matrices of the whole OSA architecture. The digital precoding submatrix of each OSA is determined from each vector in the OSA submatrix. The results show that the proposed hybrid precoding for the OSA architecture outperforms the successive interference cancellation (SIC)-based hybrid precoding for non-overlapped SA (NOSA) and provides performance close to the fully-connected (FC) spatially sparse hybrid precoding, despite requiring less hardware and computational complexities.

INDEX TERMS Hybrid precoding, narrowband millimeter wave MIMO system, overlapping subarrays architecture.

I. INTRODUCTION
Millimetre wave (mmWave) communications are considered to be a vital technology for next-generation cellular systems [1], [2], due to the large amount of available bandwidth that can be supported. The mmWave frequency range enables the deployment of massive multiple input multiple output (MIMO) systems with a large number of antennas. However, new problems, including high power consumption and hardware costs, have made the classic fully-digital MIMO architecture infeasible. One solution to solve these problems is to use hybrid precoders, which combine analog and digital precoders to reduce complexity and power consumption [3]. The hybrid precoding is classified into two types: fully-connected (FC) [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14] and subarray (SA)-connected [15], [16], [17], [18], [19], [20], [21], [22], [23], in which each RF chain is connected to all antenna elements or only a subset of the antenna elements, respectively. As a result, the number of phase shifters (PSs) in a SA architecture can be greatly reduced when compared to an FC architecture, but this comes at the expense of beamforming gain loss in each RF chain.

The works in [3] and [13] proposed and investigated FC hybrid precoding and combining schemes that achieve near-optimal performance when compared to a fully-digital system. In [13], the authors were introduced and investigated proposed an iterative solution to solve the hybrid precoding and combining problems for an FC architecture. Because the fixed SA (FSA) architecture is divided into independent subarrays, the performance of the hybrid precoding in the FSA is lower than that in the FC [15], [16], [17], [18], [19], [20], [21], [22], [23]. The dynamic SA (DSA) [20], [21], the partially SA [22], [23] and the overlapped subarrays (OSA) [24], [25], [26] can enhance the performance and provide...
better performance than the FSA, but at the cost of higher hardware and computational complexities.

In the literature, there have been numerous studies devoted to fixed non-overlapped SA (NOSA) [14], [15], [16], [17], [18], [19], and DSA [20], [21]. In [16], an energy-efficient hybrid precoding technique based on successive interference cancellation (SIC) was introduced for the fixed NOSA architecture, and a diagonal digital precoder with real elements was assumed. In [19], two low-complexity hybrid precoding algorithms were proposed for NOSA architecture narrowband mmWave MIMO systems. DSA architectures, which use switches to modify the connections between RF chains and subarrays, were introduced and investigated in [20] and [21]. In [20] and [21], it is found that the DSA architectures perform better than fixed NOSA architecture, but with higher hardware complexity and power consumption due to the linear increase of the switches with the number of transmit antennas. To reduce the complexity of the DSA, the research works presented in [22] and [23] proposed a partially dynamic SA structure that assumed a dynamic connection between the subarrays and the RF chains. However, the partially dynamic precoders in [22] and [23] still result in greater computational and hardware complexities, as well as higher power consumption, compared to fixed NOSA precoders. A few papers [24], [25], [26] in the literature focused on the OSA architecture. An OSA structure was proposed and investigated in [24] and [25] to construct a hybrid precoding and combining scheme for a multiuser mmWave MIMO system. In [24] and [25], the digital precoder is dependent on both the analog precoder and the analog combiner. An energy-efficient hybrid precoding approach with adaptive OSA architecture for multiuser mmWave systems was suggested and investigated in [26]. It was demonstrated in [24], [25], and [26] that the OSA architecture can compensate for the fixed NOSA performance loss while maintaining a lower complexity than the FC architecture. The OSA structure is widely used in radars [27], [28], and [29].

In this paper, we consider the use of the OSA architecture for mmWave MIMO systems and the problem of the hybrid precoding is formulated and solved iteratively. We aim to achieve a better performance than the fixed NOSA architecture with lower complexity than the FC architecture.

To the best of our knowledge, the proposed scheme in this paper is the first to consider the issue of OSA in a single user scenario and propose an iterative solution to the problem of hybrid precoding in the OSA architecture. The main differences between the proposed scheme in this paper and those in [24], [25], and [26] are that the proposed scheme in this paper is for a single user scenario, whereas the schemes in [24], [25], and [26] are for a multiuser scenario, and finding the digital precoder in this paper is only dependent on the analog precoder, rather than both the analog precoder and combiner as in [24], [25], and [26].

The contributions of this paper are summarized as follows.

- An efficient OSA architecture to interconnect adjacent NOSAs is proposed and investigated, and its spectral efficiency is derived. In the suggested OSA architecture, each two adjacent RF chains connect with its own NOSA antennas and some antennas from the adjacent NOSA. The first RF chain, for example, connects to the antennas of the first NOSA as well as to some antennas from the second NOSA, whereas the second RF chain connects to the antennas of the second NOSA as well as to some antennas from the first NOSA. In addition, the third and fourth RF chains follow the same method to connect to the third and fourth NOSAs, and so on. The OSA architecture is depicted in Fig. 1 (b).

- The hybrid precoding optimization problem of the OSA architecture is formulated, decomposed into a series of $L_s N_s /2$ subproblems and solved iteratively, where $L_s$ and $N_s$ are the numbers of RF chains and transmitted data streams, respectively.

- A new low-complexity hybrid precoding algorithm is proposed and investigated for the OSA architecture in mmWave MIMO system. First, it assumes the initial analog precoding of the OSA submatrix equal to the normalized submatrix containing the first two columns of the optimum OSA submatrix and is multiplied by the overlapped matrix. The iterative algorithm is then used to find the optimum analog and digital precoding submatrices of each OSA. In each OSA, the digital precoding submatrix is determined from each vector in the OSA submatrix. Finally, the analog and the digital precoding matrices of the whole OSA architecture are constructed. The complexity of the proposed scheme is also derived and discussed.

- Simulation results and complexity analysis reveal that the proposed hybrid precoding has a spectral efficiency higher than that of the SIC-based hybrid precoding for a fixed NOSA described in [16], and closer to that of the FC spatially sparse hybrid precoding in [3], while requiring a lower complexity.

The main difference between the work in this paper and our work in [19] is that the hybrid precoding scheme in this paper is proposed for the OSA architecture while the work in [19] was proposed for the NOSA architecture.

The rest of this paper is organized as follows. In Sec. II, the channel model of the mmWave MIMO system is introduced. The system model of the hybrid precoding for OSA architecture is presented in Sec. III. The problem formulation and the proposed hybrid precoding are presented and investigated in Sec. IV. In Sec. V, we discuss the complexity of the proposed scheme. In Sec. VI, we provide the simulation results. Finally, the conclusions of this paper are drawn in Sec. VII.

Notations: Bold uppercase and bold lowercase are used to denote matrices and vectors, respectively. $(\cdot)^{-1}$, $(\cdot)^{*}$, $(\cdot)^{T}$, $(\cdot)^{H}$ and $|\cdot|$ denote the inverse, conjugate, transpose, Hermitian transpose and determinant of a matrix. $\|\cdot\|_2$ and $\|\cdot\|_F$ respectively denote the $l_2$-norm and the Frobenius norm of the matrix.
II. CHANNEL MODEL

In this paper, a mmWave channel model is assumed. $H$ can be written as [3]

$$H = \sqrt{N_tN_r/N_{cl}N_{ray}} \times \sum_{i=1}^{N_{cl}} \sum_{l=1}^{N_{ray}} [a_{il} \Lambda_i(\phi_{il}', \theta_{il}')] \times \Lambda_r(\phi_{il}', \theta_{il}') a_r(\phi_{il}', \theta_{il}') a_r(\phi_{il}', \theta_{il}')^T \tag{1}$$

where $N_t$ is the number of antennas at the transmitter and $N_r$ is the number of antennas at the receiver. The numbers of clusters and paths are denoted by $N_{cl}$ and $N_{ray}$, respectively. $a_{il}$ is the complex gain of the $l$th path in the $i$th cluster.

$\phi_{il}'$ and $\theta_{il}'$ are the azimuth (elevation) angles of departure and arrival of the $l$th path in the $i$th cluster. The transmit and receive antenna element gains at their departure and arrival angles are denoted by $\Lambda_i(\phi_{il}', \theta_{il}')$ and $\Lambda_r(\phi_{il}', \theta_{il}')$, respectively. $a_r(\phi_{il}', \theta_{il}')$ and $a_r(\phi_{il}', \theta_{il}')$ are the antenna array responses at the transmitter and receiver, respectively. The array response vector in a uniform planar array can be defined as [3]

$$a_{UPA}(\phi, \theta) = \frac{1}{\sqrt{N_t}} [1, \ldots, e^{jkd(x\sin(\phi)\sin(\theta) + y\cos(\theta))}, \ldots, e^{jkd(w-1)(x\sin(\phi)\sin(\theta) + (h-1)\cos(\theta))}]^T \tag{2}$$

where $k = \frac{2\pi}{\lambda}$, $1 \leq x \leq (w-1)$ and $1 \leq y \leq (h-1)$, $d = \frac{\lambda}{2}$, $w$ and $h$ are the inter-antenna spacing, width and height of the antenna array. The transmitter’s array size is $N_t = wh$. In this paper, we assume perfect channel estimation at the transmitter and receiver.

III. SYSTEM MODEL OF THE HYBRID PRECODER FOR OSA ARCHITECTURE

In this section, we consider the system model of hybrid precoding for the OSA architecture as shown in Fig. 1. We assume a single-user scenario in which $N_t$ data streams are sent from a transmitter with $N_t$ antennas and $L_t$ RF chains to a receiver with $N_r$ antennas. At the transmitter, a baseband digital precoder, $P_{DOSA}$, is first applied and the resultant signal is then precoded by the $P_{AOSA}$ analog precoder. At the receiver, the received signal can be written as

$$y = \sqrt{\rho} H (P_{ANOSA} \odot W_O) P_{DOSA}s + n \tag{3}$$

where $\rho$ is the average power of the received signal, $H \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix, $P_{ANOSA}$ and $P_{AOSA}$ are the $N_t \times L_t$ matrices that indicate the NOSA and the OSA analog precoding matrices, respectively, $P_{DOSA}$ is the $L_t \times N_t$ digital precoding matrix, $s$ is the $N_t \times 1$ vector of transmitted signal such that $E[ss^*] = \frac{1}{N_t} I_{N_t}$ and $n$ is the $N_r \times 1$ vector of independent and identical distribution $\mathbb{C}N(0, \sigma_n^2)$ additive white noise. $W_O$ is the $N_t \times L_t$ overlapped matrix and $\odot$ is the element-wise multiplication. The number of antennas in each NOSA is $N_{NOSA} = N_t/L_t$ and the number of the overlapped antennas in each NOSA is denoted by $K$. $P_{ANOSA}$ and $W_O$
can be expressed as

\[ P_{\text{ANOSAI}} = \begin{bmatrix} P_{\text{ANOSAI}12} & 0_{\text{NOSA} \times 2} & \cdots & 0_{\text{NOSA} \times 2} \\ 0_{\text{NOSA} \times 2} & P_{\text{ANOSAI}34} & \cdots & 0_{\text{NOSA} \times 2} \\ \vdots & \vdots & \ddots & \vdots \\ 0_{\text{NOSA} \times 2} & \cdots & 0_{\text{NOSA} \times 2} & P_{\text{ANOSAI}(L-1)L} \end{bmatrix} \]  

(4)

and

\[ W_o = \begin{bmatrix} W_{O12} & 0_{\text{NOSA} \times 2} & \cdots & 0_{\text{NOSA} \times 2} \\ 0_{\text{NOSA} \times 2} & W_{O34} & \cdots & 0_{\text{NOSA} \times 2} \\ \vdots & \vdots & \ddots & \vdots \\ 0_{\text{NOSA} \times 2} & \cdots & 0_{\text{NOSA} \times 2} & W_{O(L-1)L} \end{bmatrix} \]  

(5)

where \( N_{\text{OSA}} = 2N_{\text{NOSA}}, P_{\text{ANOSAI}(l+1)} \) \((l = 1, 3, 5, \ldots, L_t - 1)\) is an \( N_{\text{NOSA}} \times 2 \) analog precoding submatrix and \( 0_{\text{NOSA} \times 2} \) is an \( N_{\text{NOSA}} \times 2 \) matrix of zeros. \( W_{O(l+1)} \) \((l = 1, 3, 5, \ldots, L_t - 1)\) is an \( N_{\text{OSA}} \times 2 \) overlapped submatrix. \( P_{\text{ANOSAI}(l+1)} \) and \( W_{O(l+1)} \) can be written as

\[ P_{\text{ANOSAI}(l+1)} = \begin{bmatrix} p_l & p_{(l+1)} \\ p_{(l+1)l} & p_{(l+1)(l+1)} \end{bmatrix} \]  

(6)

and

\[ W_{O(l+1)} = \begin{bmatrix} 1_{N_{\text{OSA}} \times 1} & w_{(l+1)} \\ w_{(l+1)l} & 1_{N_{\text{NOSA}} \times 1} \end{bmatrix} \]  

(7)

where \( p_{in} \) is the \( N_{\text{NOSA}} \times 1 \) analog precoding vector of the \( l\)th NOSA when \((l = n)\) and the analog precoding vector of the OSA when \((l \neq n)\). \( w_{jl+1} \) and \( w_{(l+1)j} \) are the \( N_{\text{NOSA}} \times 1 \) overlapped vectors and the number of elements in these vectors that are equal to ones is \( K \), where \( K = 0 \) for the NOSA architecture and \( K \neq 0 \) for the OSA architecture. \( 1_{N_{\text{NOSA}} \times 1} \) is an \( N_{\text{NOSA}} \times 1 \) column vector of ones. From (4) and (5), the analog precoding matrix of the whole OSA architecture \( P_{\text{OSA}} \) can be expressed as

\[ P_{\text{OSA}} = \begin{bmatrix} P_{\text{ANOSAI}12} & 0_{\text{NOSA} \times 2} & \cdots & 0_{\text{NOSA} \times 2} \\ 0_{\text{NOSA} \times 2} & P_{\text{ANOSAI}34} & \cdots & 0_{\text{NOSA} \times 2} \\ \vdots & \vdots & \ddots & \vdots \\ 0_{\text{NOSA} \times 2} & \cdots & 0_{\text{NOSA} \times 2} & P_{\text{ANOSAI}(L-1)L} \end{bmatrix} \]  

(8)

where \( P_{\text{ANOSAI}(l+1)} \) \((l = 1, 3, 5, \ldots, L_t - 1)\) is an \( N_{\text{NOSA}} \times 2 \) analog precoding OSA submatrix that describes the overlapping between the \( l\)th and the \((l + 1)\)th NOSAs. It is given as

\[ P_{\text{ANOSAI}(l+1)} = \begin{bmatrix} p_l & p_{(l+1)} \\ p_{(l+1)l} & w_{(l+1)l} \end{bmatrix} \]  

(9)

The digital precoding matrix of the whole OSA architecture can be expressed as

\[ P_{\text{DOSAI}} = \begin{bmatrix} P_{\text{DOSAI}12} \\ P_{\text{DOSAI}34} \\ \vdots \\ P_{\text{DOSAI}(L-1)L} \end{bmatrix} \]  

(10)

where \( P_{\text{DOSAI}(l+1)} \) \((l = 1, 3, \ldots, L_t - 1)\) is a \( 2 \times N_s \) submatrix and it is given as

\[ P_{\text{DOSAI}(l+1)} = \begin{bmatrix} d_{l1} & \cdots & d_{ln} \\ d_{l(l+1)1} & \cdots & d_{l(l+1)n_s} \end{bmatrix} \]  

(11)

To focus on the precoding process, we consider an optimal combining matrix as in [20]. Therefore, the spectral efficiency of the OSA architecture can be written as

\[ R = \log_2 \left( \left| I_{n_r} + \frac{\rho}{N_s \sigma_n^2} HP_{\text{DOSAI}}P_{\text{DOSAI}}^H P_{\text{AOSA}}^H P_{\text{DOSAI}}^H \right| \right) \]  

(12)

The singular value decomposition (SVD) of \( H \) can be defined as [3] and [13]

\[ H = U \Sigma V^H \]  

(13)

where \( U = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \) is an \( N_r \times \text{rank}(H) \) unitary matrix, \( V = \begin{bmatrix} V_1 & V_2 \end{bmatrix} \) is an \( N_t \times \text{rank}(H) \) unitary matrix, and \( \Sigma = \text{diag}([\Sigma_1, \Sigma_2]) \) is an \( \text{rank}(H) \times \text{rank}(H) \) diagonal matrix containing the singular values of \( H \) in decreasing order. \( \Sigma_1 \) is an \( N_t \times N_t \) diagonal matrix, \( V_1 \) is an \( N_t \times N_t \) matrix and \( U_1 \) is an \( N_t \times N_t \) matrix.

The solution of the optimal unconstrained hybrid precoding is given by \( P_{\text{OPT}} = V_1 [3], [13] \). Using the SVD in (13), we can approximate and write (12) as

\[ R \approx \log_2 \left( \left| I_{n_r} + \frac{\rho}{N_s \sigma_n^2} \Sigma_1^2 V_1^H P_{\text{DOSAI}} P_{\text{DOSAI}}^H P_{\text{AOSA}}^H P_{\text{DOSAI}} V_1 \right| \right) \]  

(14)

By using the formula \((I - XY)(I - (I + X)^{-1}X(I - Y))\) and employing the high SNR approximation, \( R \) in (14) can be simplified as [16]

\[ R \approx \log_2 \left( \left| I_{n_r} + \frac{\rho}{N_s \sigma_n^2} \Sigma_1^2 \right| \right) + \log_2 \left( \left| V_1^H P_{\text{DOSAI}} P_{\text{DOSAI}}^H P_{\text{AOSA}} V_1 \right| \right) \]  

(15)

IV. PROBLEM FORMULATION AND THE PROPOSED HYBRID PRECODER

According to the structure of analog precoding matrix in the OSA architecture in (8), there are two constraints for the design of \( P_{\text{OSA}} = P_{\text{OSAI}} P_{\text{DOSAI}} \) in the OSA architecture.

**Constraint 1:** All non-zero elements in \( P_{\text{OSAI}(l+1)} \) have the same amplitude, which is equal to \( 1/\sqrt{N_{\text{NOSA}}} + K \), where \( K \) is the number of overlapped antennas.

**Constraint 2:** To meet the total transmit power, the Frobenius norm of \( P_{\text{OSA}} \) should satisfy \( \|P_{\text{OSA}} P_{\text{DOSA}}\|^2_F = N_t \).

According to (15), maximizing \( R \) is equivalent to maximizing

\[ V_1^H P_{\text{AOSA}} P_{\text{DOSAI}} P_{\text{DOSAI}}^H P_{\text{AOSA}}^H V_1 = \left| V_1^H P_{\text{AOSA}} P_{\text{DOSAI}} \right|^2_F \]

As a result, solving for the \( P_{\text{OSA}} \) and...
$P_{DOSA}$ to maximize $R$ in (15) is equivalent to solving the following optimization problem.

$$\begin{align*}
(P_{\text{opt}}^{\text{AOSA}}, P_{\text{opt}}^{\text{DOSA}}) &= \arg \min_{P_{\text{AOSA}}, P_{\text{DOSA}}} \left\| P_{\text{opt}}^{\text{AOSA}} - P_{\text{AOSA}} P_{\text{DOSA}} \right\|_F^2 \\
\text{st.} & \quad P_{\text{AOSA}}(l+1) \gamma_{\text{AOSA}}, \\
& \quad \left\| P_{\text{AOSA}} P_{\text{DOSA}} \right\|_F^2 = N_s
\end{align*}$$

(16)

where $\gamma_{\text{AOSA}}$ includes all possible $N_{\text{OSA}} \times 2$ matrices that satisfy constraint 1. However, the block diagonal structure of $P_{\text{AOSA}}$ in (8) and the constant entries of $P_{\text{AOSA}}(l+1)$ in (9) makes directly solving (16) impossible in the OSA architecture. Therefore, we decompose the OSA hybrid precoding problem into $L_N/2$ hybrid precoding subproblems and then solve them one by one iteratively. To illustrate that, the hybrid precoding matrix of the OSA architecture $P_{\text{OSA}}$ can be expressed as

$$P_{\text{OSA}} = \begin{bmatrix}
P_{\text{AOSA}12} & P_{\text{AOSA}13} & \cdots & P_{\text{AOSA}1L}
P_{\text{AOSA}24} & P_{\text{AOSA}34} & \cdots & P_{\text{AOSA}2L}
\vdots & \vdots & \ddots & \vdots
P_{\text{AOSA}(L-1)L} & P_{\text{DOSA}1L} & \cdots & P_{\text{DOSA}(L-1)L}
\end{bmatrix}$$

(17)

where $P_{\text{AOSA}(l+1)}$ and $P_{\text{DOSA}(l+1)}$ are given as in (9) and (11), respectively. We can also rewrite the optimal precoding matrix as

$$P_{\text{opt}}^{\text{AOSA}} = \begin{bmatrix}
P_{\text{opt} \text{OSA}12} & \cdots & P_{\text{opt} \text{OSA}1L}
P_{\text{opt} \text{OSA}23} & \cdots & P_{\text{opt} \text{OSA}2L}
\vdots & \ddots & \vdots
P_{\text{opt} \text{OSA}(L-1)L} & \cdots & P_{\text{opt} \text{DOSA}(L-1)L}
\end{bmatrix}$$

(18)

where $P_{\text{opt} \text{OSA}(l+1)}(l = 1, 3, \ldots, L - 1)$ is an $N_{\text{OSA}} \times 2$ optimal submatrix of the OSA that represents the overlapping between the $l$th and the $(l + 1)$th OSAs. Based on the structure of $P_{\text{OSA}}$ in (17), we can reformulate $\left\| V_1^H P_{\text{AOSA}} P_{\text{DOSA}} \right\|_F^2$ for all OSAs as

$$\begin{align*}
\left\| V_1^H P_{\text{AOSA}} P_{\text{DOSA}} \right\|_F^2 &= \sum_{l=1,3}^{L-1} \left\| V_{l+1}^H P_{\text{AOSA}(l+1)} P_{\text{DOSA}(l+1)} \right\|_F^2
\end{align*}$$

(19)

where $V_1 = [V_{12} V_{34} \cdots V_{(L-1)L}]^T$ and $V_{l+1}^H$ is the $N_{\text{OSA}} \times N_s$ submatrix representing the overlapping between the $l$th and the $(l + 1)$th OSAs. To obtain the columns’ vectors of $P_{\text{DOSA}(l+1)}$ vector by vector, we can further decompose (19) as

$$\begin{align*}
\left\| V_1^H P_{\text{AOSA}} P_{\text{DOSA}} \right\|_F^2 &= \sum_{l=1,3}^{L-1} \sum_{n=1}^{N_s} \left\| v_n^H P_{\text{AOSA}(l+1)} p_n \right\|_2^2
\end{align*}$$

(20)

where $p_n = [d_{l+1,n}]$ is the $n$th column of $P_{\text{DOSA}(l+1)}$ and $v_n$ is the $n$th column of $V_{l+1}^H$.

From (19) and (20), we note that maximizing $V_1^H P_{\text{AOSA}} P_{\text{DOSA}}$ is equivalent to maximizing $V_{l+1}^H P_{\text{AOSA}(l+1)} P_{\text{DOSA}(l+1)}$ in each OSA or to maximizing $v_n^H P_{\text{AOSA}(l+1)} p_n$ for each vector in the OSAs. So, the optimization problem in (16) is equivalent to the following subproblem

$$\begin{align*}
(P_{\text{opt} \text{AOSA}(l+1)}, p_n) &= \arg \min_{P_{\text{AOSA}(l+1)}, p_n} \left\| v_n^H P_{\text{AOSA}(l+1)} p_n \right\|_2^2 \\
\text{st.} & \quad P_{\text{AOSA}(l+1)} \in \mathcal{A}_{\text{AOSA}}, \\
& \quad \left\| P_{\text{AOSA}} P_{\text{DOSA}} \right\|_F^2 = N_s
\end{align*}$$

(21)

Now, the hybrid precoding problem in (21) can be solved iteratively as described in the following steps.

1. The initial value of the OSA submatrix $P_{\text{AOSA}(l+1)}$ is chosen as

$$P_{\text{AOSA}(l+1)} = \left[ V_{\text{AOSA}(l+1)} \otimes \left( \left| V_{\text{AOSA}(l+1)} \right| \times \sqrt{N_{\text{OSA}}} + K \right) \right] \otimes W_O \tag{22}$$

2. The digital precoder vectors are determined by maximal ratio combining as

$$p_n = P_{\text{AOSA}(l+1)}^H v_n \tag{23}$$

3. After that, the iterative algorithm for this OSA is applied to calculate the optimal $P_{\text{AOSA}(l+1)}$ as follows [13]

$$P_{\text{AOSA}(l+1)} = P_{\text{AOSA}(l+1)} + P_{\text{fred}(l+1)} P_{\text{DOSA}(l+1)}^H \tag{24}$$

4. The obtained $P_{\text{AOSA}(l+1)}$ in (24) is then normalized and multiplied by $W_O$ as follows:

$$P_{\text{AOSA}(l+1)} = \left[ P_{\text{AOSA}(l+1)} \otimes \left( \left| P_{\text{AOSA}(l+1)} \right| \times \sqrt{N_{\text{OSA}}} + K \right) \right] \otimes W_O \tag{25}$$

5. The digital precoder $p_n$ is then calculated as in (23) and steps 3 to 5 are repeated $N_{\text{iter}}$ times to obtain the optimal values of $P_{\text{AOSA}(l+1)}$ and $p_n$ that minimize

$$\left\| v_n^H - P_{\text{AOSA}(l+1)} p_n \right\|_2^2 \tag{26}$$

6. Steps 3 to 5 are repeated to obtain $P_{\text{AOSA}(l+1)}$ and $p_n$ for the remaining OSAs.

7. Finally, the $P_{\text{OSA}}$ and $P_{\text{DOSA}}$ of the whole OSA architecture are reconstructed.

Algorithm 1 summarizes the pseudo-code of the proposed hybrid precoding for the OSA architecture. From steps 3 to 18 of algorithm 1, the iterative solution minimizes the objective function $\left\| V_{l+1}^H P_{\text{AOSA}(l+1)} P_{\text{DOSA}(l+1)} \right\|_F^2$ and ensures the convergence of $P_{\text{AOSA}(l+1)}$ to a local optimal point.
Algorithm 1 The Proposed Hybrid Precoding Scheme for the OSA Architecture

1. Input $P_{AOSAl}^{opt}$, $W_O$, $N_{iter}$ and $K$
2. Decompose $P_{AOSAl}^{opt}$ as in (18).
3. For $l = 1, 3, \ldots, L - 1$
4. Choose $P_{AOSAl(i+1)}$ as

$$P_{AOSAl(i+1)} = \left( |V_{AOSAl(i+1)}| \times \sqrt{N_{OSA} + K} \right) \odot W_O$$

5. For $1 \leq n \leq N_s$
6. $P_{Dn} = P_{AOSAl(i+1)}^Hn^{opt}$
7. End for
8. Construct $P_{DOSAl(i+1)}$ as in (11).
9. For $1 \leq j \leq N_{iter}$
10. $P_{fed(i+1)} = P_{AOSAl(i+1)} - P_{DOSAl(i+1)}P_{DOSAl(i+1)}^H$
11. $P_{AOSAl(i+1)} = P_{AOSAl(i+1)} + P_{fed(i+1)}P_{DOSAl(i+1)}^H$
12. Update $P_{AOSAl(i+1)}$ as

$$P_{AOSAl(i+1)} = \left( |P_{AOSAl(i+1)}| \times \sqrt{N_{OSA} + K} \right) \odot W_O$$

13. For $1 \leq n \leq N_s$
14. Update $P_{Dn} = P_{AOSAl(i+1)}^Hn^{opt}$
15. End for
16. Construct $P_{DOSAl(i+1)}$ as in (11).
17. End for
18. End for
19. Construct $P_{AOSA}$ as in (8) and $P_{DOSA}$ as in (10).
20. Normalize $P_{DOSA}$ as

$$P_{DOSA} = \frac{\sqrt{N_S}}{\|P_{AOSA}P_{DOSA}\|_F}P_{DOSA}$$
21. Return $P_{AOSA}$ and $P_{DOSA}$

The idea of the proposed hybrid precoding algorithm for the OSA architecture in this paper can also be extended to the combining stage at the receiver side and to the multiuser scenario. Discussion about the multiuser scenario and hybrid combining for the OSA architecture will be left for future work.

V. COMPLEXITY EVALUATION

In this section, we analyze the complexity of the proposed hybrid precoding design using Algorithm 1 as compared to previous FC sparse hybrid precoding in [3] and fixed NOSA SIC-based hybrid precoding in [16] from the literature. Table 1 presents the complexity analysis for each hybrid precoding approach. Table 1 shows that there are no constraints in the proposed algorithm other than that in (21) and the number of the required PSs in the NOSA is lower than that in [3] and equal to that in the [16]. Table 1 also indicates that the number of required PSs in the OSA is lower that in [3] and higher than that in the NOSA and [16] by about $L_f K$.

| Method | Number of PSs | Constraints | Complexity |
|--------|--------------|-------------|------------|
| Sparse hybrid precoding (PC) [3] | $L_fN_s$ | RF precoder | $O(N_{iter}^2N_{iter}N_s)$ |
| SIC-based hybrid precoding (NOSA) [16] | $L_fN_{NOSA}$ | $L_f = N_s$ and diagonal digital precoding with real elements | $O(N_{iter}^2N_{iter}N_s)$ |
| Proposed hybrid precoding for OSA architecture ($K = 0$) | $L_fN_{NOSA}$ | None | $O(N_{iter}^2N_{iter}N_s)$ |
| Proposed hybrid precoding for OSA architecture ($K \neq 0$) | $L_f(N_{NOSA} + K)$ | None | $O(N_{iter}^2N_{iter}N_s)$ |

which is acceptable when compared with the improvements in the spectral efficiency as we will see in Sec. VI. Moreover, the proposed hybrid precoding scheme does not depend on the selection of the RF precoding like that in [3].

VI. SIMULATION RESULTS

In this section, we compare the performance of the proposed hybrid precoding with the optimal unconstrained hybrid precoding, the FC spatially sparse hybrid precoding in [3], as well as the SIC-based hybrid precoding [16]. To make a fair comparison between the proposed hybrid scheme and the other hybrid schemes, only the precoding stage is considered for all schemes and the spectral efficiency is calculated using (12). Simulation parameters are presented in Table 2. We simulate a narrowband mmWave MIMO channel and assume equal power for all clusters. The sector angle of the transmitter is $60^\circ$-wide in azimuth and $20^\circ$-wide in elevation. ULAs are used in both the transmit and receive antenna arrays.

Fig. 2 shows the spectral efficiency of the proposed hybrid precoder with different numbers of iterations $N_{iter}$ when $K = 0$ (without overlapping) and $K = 16$ (with overlapping). We assume a $256 \times 64$ mmWave MIMO system and $N_t = 4$. We can see that by increasing the number of iterations, the overall performance of the proposed scheme is improved, even without overlapping. Moreover, it is clear that the best number of $N_{iter}$ for both cases should be between 10 and 20. At a $SNR = 5$ dB, the proposed hybrid precoding with overlapping and $N_{iter} = 20$ provides about 6.5 $(\text{bits/s/Hz})$ improvement when compared with that with overlapping and $N_{iter} = 0$, whereas the proposed hybrid precoding without overlapping and $N_{iter} = 20$ provides about 4.5 $(\text{bits/s/Hz})$ improvement when compared with that without overlapping.
TABLE 2. Simulation parameters.

| Parameter                               | Value                        |
|-----------------------------------------|------------------------------|
| Channel type               | mmWave MIMO system           |
| Number of antennas at the transmitter | $N_t = 256$ and $64$          |
| Number of antennas at the receiver     | $N_r = 64$ and $16$           |
| Number of RF chains at the transmitter | $L_t = 4$ and $16$            |
| Number of data streams                | $N_c = 4$ and $8$             |
| Number of overlapping antennas        | $K = 4, 8, 12$ and $16$       |
| Number of antennas in each NOSA        | $N_{NOISA} = 16$              |
| Number of antennas in each OSA         | $N_{OSA} = 32$                |
| Number of clusters                    | $N_{cl} = 8$                  |
| Number of rays in each cluster         | $N_{ray} = 10$                |
| Angular spread                         | $7.5^\circ$                  |
| Carrier frequency                      | 28 GHz                       |
| Spacing between antenna elements       | $\lambda/2$                  |
| Channel Estimation                    | Perfect                      |

and $N_{iter} = 0$. The performance improvement of the proposed hybrid precoding when a $\text{SNR} = 5$ dB and $N_{iter} = 20$ is about 4 dB as compared with that without overlapping.

In Fig. 3, we provide the spectral efficiency against the SNR of a $256 \times 64$ mmWave MIMO system when $N_s = 4$. $N_{iter} = 10$ is considered. With the increase in $K$, the performance of our proposed hybrid precoder for the OSA increases and approaches that of the FC hybrid precoder in [3]. Besides, the performances of our proposed hybrid precoder for the OSA architecture have larger spectral efficiency than that for the NOSA architecture, which means that our proposed hybrid precoder for the OSA is the best choice for mmWave MIMO systems. Note that with the increase of $K$, the performance of the proposed hybrid precoding increases and approaches that of the FC sparse hybrid precoding in [3]. At a $\text{SNR} = 0$ dB and $K = 16$, the performance improvement is about 4 (bits/s/Hz) for the OSA architecture when compared with that for the NOSA architecture.

In Fig. 4, the spectral efficiency of the proposed hybrid precoding technique is studied and compared for a $256 \times 64$ mmWave MIMO system, where $N_s = 8$ data streams are conveyed through 16 RF chains. $N_{iter} = 10$ is considered. As shown in Fig. 4, the performance of the proposed hybrid precoder increases as $K$ increases. When $K = 16$, the proposed hybrid precoder for the OSA architecture outperforms the one for the NOSA and approaches the spatially sparse hybrid precoding in [13].
At a $SNR = 5$ dB, the proposed hybrid precoding scheme for the OSA provides about 10 (bits/s/Hz) improvement when $K = 8$ and about 14 (bits/s/Hz) improvement when $K = 16$ when compared with the NOSA ($K = 0$).

In Fig. 5, the proposed hybrid precoder is also compared with the SIC-based hybrid precoder in [16] for the NOSA architecture when $N_{\text{iter}} = 1, 3, 5$ and 10. $K = 0$, $N_T = 64$, $N_f = 16$, $L_f = 4$ and $N_s = 4$ are assumed. It is shown that the proposed hybrid precoding achieves higher spectral efficiency than the SIC-based hybrid precoding in [16], especially when $N_{\text{iter}} = 10$. In Fig. 5, the spectral efficiency of the proposed hybrid precoding when $N_{\text{iter}} = 10$ is about 7 (bits/s/Hz) higher than that in [16] when $SNR = 5$ dB.

VII. CONCLUSION

In this paper, we have proposed a low-complexity iterative algorithm to solve the OSA hybrid precoding problem in mmWave MIMO systems. The optimization problem of the hybrid precoding for the OSA architecture is formulated, decomposed into $(L_f N_s/2)$ subproblems and solved iteratively. First, for each OSA, the initial analog precoding submatrix used in the iterative algorithm is taken as a normalized submatrix containing the first two columns of the optimal OSA submatrix multiplied by the overlapping matrix. After that, the iterative algorithm for each OSA is applied to determine the optimal analog and digital precoding submatrices. Finally, the optimal hybrid precoding matrix of the whole OSA architecture is constructed. Complexity evaluation and numerical results have shown that the proposed algorithm outperforms the SIC-based hybrid precoding in [16] and approaches the FC spatially sparse hybrid precoding in [3], especially when the number of transmitted streams is small and requires a lower complexity when compared with that in [3]. As a future research, this work will be extended to the combining stage at the receiver side and to multiuser MIMO mmWave systems.

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