Energy-Efficient Hybrid Precoding Based on Successive Interference Cancelation for Millimeter-Wave Massive MIMO Systems

Linglong Dai*, Xinyu Gao, Zhaocheng Wang
Tsinghua National Laboratory for Information Science and Technology,
Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
Email: daill@tsinghua.edu.cn

***Abstract*—Millimeter-wave massive MIMO usually utilizes the hybrid precoding to overcome the serious signal attenuation, where only a small number of RF chains is required. However, most of hybrid precoding schemes consider the complicated full-connected architecture. In this paper, we focus on the more energy-efficient sub-connected architecture, and propose a low-complexity hybrid precoding based on successive interference cancelation (SIC). The basic idea of SIC-based hybrid precoding is to decompose the total capacity optimization problem into a series of sub-problems, each of which only considers one sub-antenna array. Then, we can optimize the capacity of each sub-antenna array one by one until the last sub-antenna array is considered. Simulation results verify that SIC-based hybrid precoding can achieve the near-optimal performance.**

I. INTRODUCTION

Millimeter-wave (mmWave) massive multiple-input multiple-output (MIMO) can achieve orders of magnitude increase in spectral efficiency, which makes it as a promising technique for future 5G wireless communication systems [1]. MmWave massive MIMO usually employs the hybrid precoding to compensate for the severe attenuation of mmWave signals, which only requires a small number of expensive radio frequency (RF) chains. Specifically, the transmitted signals are first precoded by the digital precoding of small size to guarantee the performance, and then precoded again by the analog precoding of large size to reduce the hardware complexity. However, most of hybrid precoding are designed for the full-connected architecture [2][3], where each RF chain is connected to all base station (BS) antennas via phase shifters involving high energy consumption [2]. By contrast, the hybrid precoding with sub-connected architecture, where each RF chain is connected to only a subset of BS antennas, can significantly reduce the number of required phase shifters without obvious performance loss [2]. Unfortunately, how to design the optimal hybrid precoding with sub-connected architecture is still a challenging problem.

In this paper, we focus on the more energy-efficient sub-connected architecture and propose a successive interference cancelation (SIC)-based hybrid precoding. We first show that the achievable total capacity can be decomposed into a series of sub-problems, each of which only considers one sub-antenna array. After that, inspired by the idea of SIC for multi-user signal detection, we propose to optimize the capacity of each sub-antenna array by exploring a precoding vector sufficiently close to the unconstrained optimal solution. To the best of the authors' knowledge, this work is the first one that considers the hybrid precoding design with sub-connected architecture for mmWave massive MIMO systems.

II. SYSTEM MODEL OF MMWAVE MASSIVE MIMO

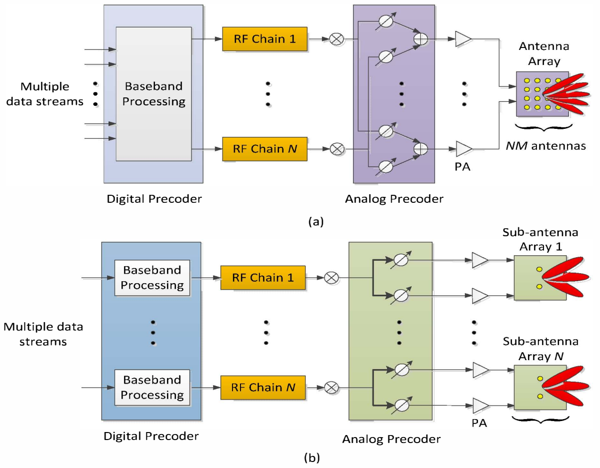

Figure 1: Hybrid precoding: (a) Full-connected architecture; (b) Sub-connected architecture.

Figure 1 illustrates two typical architectures of the hybrid precoding, where the BS has NM antennas but only N RF chains. For the sub-connected architecture as shown in Figure 1 (b), the N independent data streams in the baseband are firstly precoded by the digital precoder $\mathbf{D} = \mathrm{diag}\{d_1, \cdots, d_N\}$, where $d_n \in \mathbb{C}$ for $n = 1, \cdots, N$ [1]. After that, the signals are precoded again by the analog precoder $\mathbf{A} = \mathrm{diag}\{\bar{\mathbf{a}}_1, \cdots, \bar{\mathbf{a}}_N\}$, where $\bar{\mathbf{a}}_n \in \mathbb{C}^{M\times 1}$ whose elements have the same amplitude $1/\sqrt{M}$ but different phases [1]. Accordingly, the received signal vector $\mathbf{y} = [y_1, \cdots, y_K]^T$ at the user with K receive antennas can be presented as

$$\mathbf{y} = \rho\mathbf{HADs} + \mathbf{n} = \rho\mathbf{HPs} + \mathbf{n}, \qquad (1)$$

where ρ is the average received power; $\mathbf{H} \in \mathbb{C}^{K\times NM}$ denotes the mmWave channel matrix; $\mathbf{s} = [s_1, \cdots, s_N]^T$ presents the transmitted signal vector in the baseband with normalized signal power [2]; $\mathbf{P} = \mathbf{AD}$ presents the hybrid precoding matrix of size $NM \times N$; Finally, $\mathbf{n} = [n_1, \cdots, n_N]^T$ is the additive white Gaussian noise vector with zero mean and variance σ^2.

III. SIC-BASED HYBRID PRECODING

A. Structure of SIC-based hybrid precoding

The final aim of precoding is to maximize the total capacity R of mmWave massive MIMO systems:

$$R=\log_2\left(\left|\mathbf{I}_N+\frac{\rho}{N\sigma^2}\mathbf{H}\mathbf{P}\mathbf{P}^H\mathbf{H}^H\right|\right). \tag{2}$$

Since $\mathbf{P}=\mathbf{AD}=\mathrm{diag}\{\bar{\mathbf{a}}_1,\cdots,\bar{\mathbf{a}}_N\}\cdot\mathrm{diag}\{d_1,\cdots,d_N\}$ is a non-convex constraint, maximizing the total capacity R by designing $\mathbf{P}$ is very difficult to be solved. To this end, we propose to decompose the total capacity R into a series of sub-problems, each of which only considers one sub-antenna array. In particular, by dividing $\mathbf{P}$ as $\mathbf{P}=[\mathbf{p}_1,\cdots,\mathbf{p}_N]$, where $\mathbf{p}_n$ is the nth column of $\mathbf{P}$, we can rewrite (2) as

$$R=\sum_{n=1}^{N}\log_2\left(1+\frac{\rho}{N\sigma^2}\mathbf{p}_n^H\mathbf{H}^H\mathbf{T}_{n-1}^{-1}\mathbf{H}\mathbf{p}_n\right), \tag{3}$$

where $\mathbf{T}_n=\mathbf{I}_N+\left(\rho/N\sigma^2\right)\mathbf{H}\mathbf{P}_n\mathbf{P}_n^H\mathbf{H}^H$, and $\mathbf{T}_0=\mathbf{I}_N$. From (3), we can observe that the total capacity optimization problem can be transformed into a series of sub-problems of sub-antenna arrays, which can be optimized one by one. After that, inspired by the idea of SIC, we can optimize the achievable capacity of the first sub-antenna array and update the matrix $\mathbf{T}_1$. Then, the similar method can be utilized to optimize the capacity of the second sub-antenna array. Such procedure will be executed until the last sub-antenna array is considered.

B. Optimal solution to each sub-antenna array

According to (3), the capacity optimization problem of the nth sub-antenna array can be maximized by designing the nth optimal precoding vector $\mathbf{p}_n^{\mathrm{opt}}$ as

$$\mathbf{p}_n^{\mathrm{opt}}=\arg\max_{\mathbf{p}_n\in\mathcal{F}}\log_2\left(1+\frac{\rho}{N\sigma^2}\mathbf{p}_n^H\mathbf{G}_{n-1}\mathbf{p}_n\right), \tag{4}$$

where $\mathbf{G}_{n-1}$ is defined as $\mathbf{G}_{n-1}=\mathbf{H}^H\mathbf{T}_{n-1}^{-1}\mathbf{H}$, $\mathcal{F}$ is the set of all feasible precoding vectors. Note that $\mathbf{p}_n$ only has M non-zero elements. Therefore, the term $\mathbf{p}_n^H\mathbf{G}_{n-1}\mathbf{p}_n$ in (4) is equivalent to $\bar{\mathbf{p}}_n^H\bar{\mathbf{G}}_{n-1}\bar{\mathbf{p}}_n$, where $\bar{\mathbf{p}}_n$ of size $M\times 1$ is the non-zero vector of $\mathbf{p}_n$, and $\bar{\mathbf{G}}_{n-1}$ is the corresponding sub-matrix of $\mathbf{G}_{n-1}$ by only keeping the rows and columns of $\mathbf{G}_{n-1}$ from the ($M(n-1)+1$)th one to the (Mn)th one. It is known that the optimal solution to (4) is $\mathbf{v}_1$, the first right singular vector of $\bar{\mathbf{G}}_{n-1}$ [2]. However, since the elements of $\mathbf{v}_1$ do not obey the constraint as mentioned above, we cannot directly choose $\bar{\mathbf{p}}_n^{\mathrm{opt}}$ as $\mathbf{v}_1$. For this reason, we propose to explore a practical precoding vector sufficiently close to the optimal but unpractical precoding vector $\mathbf{v}_1$ as the optimal precoding vector $\bar{\mathbf{p}}_n^{\mathrm{opt}}$. Since $\bar{\mathbf{p}}_n=d_n\bar{\mathbf{a}}_n$ according to (1), the distance between $\bar{\mathbf{p}}_n$ and $\mathbf{v}_1$ can be presented as

$$\left\|\mathbf{v}_1-\bar{\mathbf{p}}_n\right\|_2^2=\left(d_n-\mathrm{Re}\left(\mathbf{v}_1^H\bar{\mathbf{a}}_n\right)\right)^2+\left(1-\left[\mathrm{Re}\left(\mathbf{v}_1^H\bar{\mathbf{a}}_n\right)\right]^2\right). \tag{5}$$

Based on (5), we know that the optimal analog, digital, and hybrid precoders for the nth sub-antenna array are $\bar{\mathbf{a}}_n^{\mathrm{opt}}=\left(1/\sqrt{M}\right)e^{j\mathrm{angle}(\mathbf{v}_1)}$, $d_n^{\mathrm{opt}}=\mathrm{Re}\left(\mathbf{v}_1^H\bar{\mathbf{a}}_n\right)=\left(1/\sqrt{M}\right)\left\|\mathbf{v}_1\right\|_1$, and $\bar{\mathbf{p}}_n^{\mathrm{opt}}=d_n^{\mathrm{opt}}\bar{\mathbf{a}}_n^{\mathrm{opt}}=\left(1/M\right)\left\|\mathbf{v}_1\right\|_1 e^{j\mathrm{angle}(\mathbf{v}_1)}$, respectively, where $\mathrm{angle}(\mathbf{v}_1)$ denotes the phase vector of $\mathbf{v}_1$, i.e., each element of $\bar{\mathbf{a}}_n^{\mathrm{opt}}$ shares the same phase as the corresponding element of $\mathbf{v}_1$.

IV. SIMULATION RESULTS

Figure 2 shows the capacity comparison in mmWave massive MIMO system, where $NM\times K=64\times 16$, $N=8$, the typical Saleh-Valenzuela channel model is adopted [2], and the signal-to-noise ratio (SNR) is defined as ρ/σ^2. We can observe that the proposed SIC-based hybrid precoding outperforms the conventional analog precoding [3] in the whole simulated SNR range. Meanwhile, Figure 2 also verifies the capacity-approaching performance of SIC-based hybrid precoding, since it can achieve about 99% of the capacity achieved by the optimal unconstrained precoding (i.e., $\bar{\mathbf{p}}_n^{\mathrm{opt}}=\mathbf{v}_1$) with sub-connected architecture.

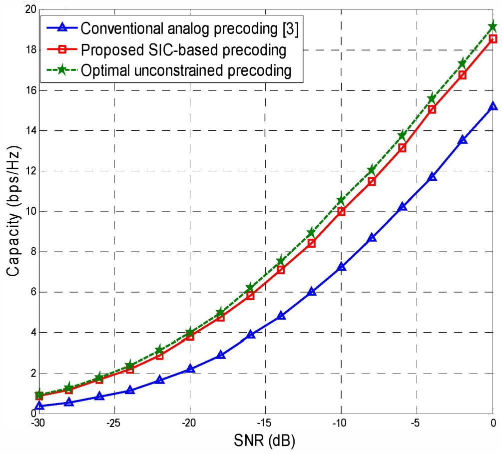

Figure 2: Capacity comparison for an $NM\times K=64\times 16$ ($N=8$) mmWave massive MIMO system.

V. CONCLUSIONS

In this paper, we have proposed a SIC-based hybrid precoding with sub-connected architecture, which is more energy-efficient. We first decompose the total capacity optimization problem into a series of sub-problems, each of which only considers one sub-antenna array. Then, we optimize the achievable capacity of each sub-antenna array by exploring a precoding vector sufficiently close to the unconstrained optimal solution. Simulation results have verified that the proposed SIC-based hybrid precoding can achieve the near-optimal performance with low complexity.

REFERENCES

[1] S. Han, C.-L. I, Z. Xu, and C. Rowell, “Large-scale antenna systems with hybrid precoding analog and digital beamforming for millimeter wave 5G,” *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 186–194, Jan. 2015.

[2] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. Heath, “Spatially sparse precoding in millimeter wave MIMO systems,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[3] O. El Ayach, R. W. Heath, S. Rajagopal, and Z. Pi, “Multimode precoding in millimeter wave MIMO transmitters with multiple antenna sub-arrays,” in *Proc. IEEE Global Communications Conference (GLOBECOM’13)*, Dec. 2013, pp. 3476–3480.